NEW ZEALAND GEOTECHNICAL SOCIETY INC
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SLOPE STABILITY GEOTECHNICAL GUIDANCE SERIES

UNIT 4

MITIGATION AND DESIGN PRINCIPLES

AN INDUSTRY REFERENCE DOCUMENT COMPILED AND PUBLISHED BY THE NEW ZEALAND GEOTECHNICAL SOCIETY (NZGS)

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DISCLAIMER

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Toka Tū Ake

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1 INTRODUCTION

1 PURPOSE AND SCOPE

The purpose of Unit 4 is to provide guidance on selecting and applying effective mitigation strategies for managing slope instability. Building on the principles outlined in Part 10 of Unit 1, this module offers both engineered and non-engineered approaches to slope stabilisation.

This Unit provides guidance on the selection and application of mitigation measures for slope instability, addressing both engineered and non-engineered solutions. The key areas covered include:

- **Slope Stability Design Considerations:** A discussion on the factors influencing slope stability and the design considerations necessary for effective mitigation.
- **Target Performance Criteria:** Guidance on establishing measurable performance criteria for mitigation measures, tailored to site-specific conditions and project requirements.
- **Considerations in Selecting Mitigation Strategies:** Key factors to consider when choosing mitigation strategies, including risk assessment, feasibility, and cost-effectiveness.
- **Mitigation Design Process:** A framework for designing effective mitigation measures with a focus on customising solutions to meet site-specific needs.

This Unit also covers:

- **Engineered Mitigation Measures:** A detailed exploration of engineered solutions, including stabilisation techniques for soil and rock slopes, rockfall mitigation, and debris flow management.
- **Non-engineered Mitigation Measures:** It discusses approaches for quick risk reduction, non-intervention methods, and bioengineering solutions, along with guidance on when these options are most appropriate.
- **Design Compliance and Safety by Design:** Emphasis on aligning mitigation measures with industry standards for safety, compliance, and long-term stability.
- **Sustainability by Design:** Integration of sustainable principles into the selection and design of mitigation measures.
- **Worked Examples:** Case studies illustrating the application of engineered and non-engineered mitigation measures, offering practical insights for real-world situations.

2 SLOPE STABILITY DESIGN CONSIDERATIONS

Understanding the underlying causes of instabilities is crucial to developing effective strategies for addressing slope failure or mitigating potential risks (Duncan et al., 2014). Unit 1 and Unit 2 modules outline how to identify and determine the various factors that can contribute to slope instability. These factors should be reviewed, but importantly, the design should consider how these factors may change over the life of the mitigation measures and what impact these changes may have on slope performance.

These factors influencing slope stability can generally be grouped into the following categories:

- **Weathering Processes**: Consideration must be given to how changes in weathering conditions, such as freeze-thaw cycles, chemical reactions, and biological activity, can weaken the soil or rock mass over time. These processes can reduce the shear strength of the material and create discontinuities within it, increasing its vulnerability to failure.
- **Changes in Soil or Rock Properties**: Alterations in soil or rock properties, such as a decrease in cohesion or friction angle due to changes in moisture content or other strength-reducing influences, can significantly reduce the slope stability. As outlined in Unit 1, the behavioural changes in clays across New Zealand must be carefully considered, as these changes can significantly affect slope performance.
- **Removal of Lateral (Toe) Support**: Design considerations should address both long-term geomorphological processes and short-term construction activities. Excavations at the slope toe, or toe erosion from water bodies such as rivers and streams, can reduce lateral support, thereby increasing the likelihood or scale of slope failure.
- **Change in Land Profile from Earthworks:** Design considerations should account for how past or future development (e.g., cut-to-fill operations) may impact slope stability and the effectiveness of mitigation measures.
- **Vegetation Removal**: The long-term effects of vegetation removal on the surrounding slopes should be assessed. Deforestation, or the removal of deep-rooted vegetation, can reduce slope stability, as roots help bind the soil and increase shear strength. Conversely, vegetation removal at the top of a slope may remove some driving load, potentially increasing the overall stability of the slope system.
- **Changes in Liquefaction Susceptibility:** While Unit 3 covers seismic impacts on slope stability, designers should also assess how liquefaction susceptibility may evolve following a seismic event over the life of a remedial solution.
- **Change in Land Use**: Consideration should be given to land use changes outside the immediate slope area that may impact stability or the effectiveness of mitigation measures, such as added surcharge from buildings, infrastructure, or stockpiled materials. Changes in groundwater conditions, surface run-off, or the development of reservoirs at or near the slope may also affect stability. Controls such as development setbacks or cut-off drains may help mitigate these risks.
- **Vibration or Earthquake Shaking**: Although seismic loading may be considered in the direct mitigation, consideration should also be given to the effects of ground shaking and/or cyclic loading. These can increase pore pressure, break bonds between soil particles, reduce strength, and trigger further instability.
- **Climate Change Impacts**: Climate change poses a significant risk by increasing the frequency and intensity of heavy or prolonged rainfall events. Such rainfall can saturate the soil, increasing its weight (driving force) and decreasing its effective shear strength (resisting force). It can also lead to an increase in pore water pressure, further decreasing the resisting forces and apparent cohesion in partially saturated soils (see Unit 3). As a result, rainfall is a critical trigger for many landslides, and consideration for how this may increase or intensify should be given during design. NIWA's High Intensity Rainfall Database (National Institute of Water and Atmospheric Research, 2017) provides a valuable source of future rainfall scenarios for use in risk assessment and design.
- **Changes in Groundwater Conditions**: Potential groundwater table fluctuations, caused by climate variability (e.g., La Nina versus El Nino), rainfall trends, or seasonal variations, can significantly impact slope stability by altering pore water pressures and soil properties. Vegetation changes, such as afforestation or deforestation, can also dramatically influence groundwater conditions. For example, pine plantation deforestation has been shown to raise near-surface unconfined groundwater levels by up to 4 m (Landcare Research New Zealand Limited, 2002).

Commonly, there are multiple and varying factors that contribute to a slope failure, which are well covered in other Units 1, 2, and 3. It is therefore important that design considerations include not only the site-specific causes of instability but also how these factors might evolve over time, in order to develop appropriate and effective mitigation strategies.

3 TARGET PERFORMANCE CRITERIA

Establishing target performance criteria is essential for the design and implementation of slope hazard mitigation measures. These criteria guide the design of mitigation measures and are site-specific, depending on several key considerations:

- **Annual Probability of Occurrence (likelihood)**: The probability that an event will occur and impact the asset (e.g., property, building, or road) within a given year.
- **Annual Exceedance Probability (likelihood of larger events):** The probability that an event greater than the design event will occur within a given year.
- **Probability of Occurrence over Design Life (likelihood within design life):** The probability the event will occur within the design life of the remedial solution (e.g., a 26% probability over 50 years for a 1-in-500-year event).
- **Impact of Failure (consequence):** The severity of consequences if an event occurs, including direct impacts (e.g., asset damage, casualties) and any cascading effects (e.g., a power pole being impacted, leading to overloading of adjacent lines and contributing to a wider outage).
- **Level of Uncertainty:** The degree of uncertainty associated with assessing the occurrence and impact of the event, based on the quality, quantity, and reliability of available information and investigations.

These factors can be evaluated using a Likelihood x Consequence x Uncertainty framework to determine the overall level of risk.

The slope performance criteria define the levels of acceptable risk that a specific slope event must meet. Three common approaches to setting target performance criteria are:

3.1 RISK-BASED PERFORMANCE CRITERIA

This section does not outline the recommended minimum risk-based performance criteria, as each site is likely to have site-specific requirements and risk tolerances. These are often agreed upon with the client, and in some scenarios, with Territorial Authorities (TAs) and Building Consent Authorities (BCAs). It should also be noted that the criteria will vary depending on whether only property is at risk or whether life safety is also a concern.

When applying risk-based performance criteria to assets or life safety, the following terms should be considered.

- **Tolerable Risk**: This is the level of risk that society is willing to accept in exchange for certain benefits. It represents a range of risk regarded as non-negotiable and subject to ongoing review and should be reduced further where reasonably practicable (AGS, 2007).
- **Acceptable Risk**: This is the level of risk that all affected parties are willing to accept. Typically, no further action is required to reduce the risk at this level (AGS, 2007). The threshold may vary depending on whether the asset is existing or newly proposed, as detailed in the Natural Hazard Risk Tolerance Literature Review published by Earthquake Commission[1] (2023).
- **So Far As Is Reasonably Practicable (SFAIRP):** This is the extent to which a risk can be reduced As Low As Reasonably Practicable (ALARP) such that the measures (cost, time, effort) relating to the available ways of eliminating or minimising the risk are proportionate to the level of risk (Health and Safety at Work Act 2015). This approach is weighted towards implementing a risk reduction measure that can achieve a lower residual risk.

In New Zealand, a range of qualitative and quantitative risk analysis tools is used to assess slope hazards that may affect public linear assets such as roads, railways, and trails. Commonly used tools include NZTA Assessed Risk Level (ARL), Rockfall Hazard Rating (RHR), Landslide Hazard Rating (LHR), KiwiRail Slope Risk Analysis (KRL), and GNS Natural Hazard Risk Analysis (NHRA).

Councils may also use their tools to assess risks associated with slope hazards affecting local road networks and other council-owned assets.

1 Presently known as the Natural Hazards Commission.

Table 3.1. Approaches to setting target performance criteria

Approach	Description
Risk-Based Approach	This approach evaluates whether residual risk levels are acceptable or tolerable based on a quantitative or qualitative risk framework.
Limit Equilibrium (Factor of Safety) Approach	This relies on achieving a minimum Factor of Safety (FoS) against slope failure under various loading conditions.
Performance-based Design Approach	This focuses on whether slope deformation or displacement criteria (e.g. tolerable movement) are met under different loading conditions.

For general slope instability assessments, particularly those outside of linear infrastructure, the Australian Geomechanics Society (AGS, 2007) guidelines are commonly adopted.

These tools share the common aim of providing a relative risk rating, with some directly or indirectly contributing to a qualitative assessment of life safety risk.

Risk to life is generally expressed in the following forms (AGS, 2007; De Vilder & Massey et al., 2024);

- **Individual Risk:** Expressed as **Annual Individual Fatality Risk (AIFR)**. This includes:
- **Local Personal Risk (LPR)**: The risk to the person most frequently exposed to the hazard (e.g., an occupier or worker),
- **Individual Risk (IR)**: The annual probability of fatality for a single individual (e.g., visitor).
  While AIFR for the LPR is typically the primary measure, it is important to differentiate between different categories of individuals where possible, as the tolerability of risk and the required risk controls may vary depending on the nature of the exposure and vulnerability.
- **Societal Risk:** Often expressed as the **Annual Likelihood of a Severe Event (ALSE)**, this considers multiple scenario-based assessments based on the potential scale and severity of the event. It is often communicated through a F-N curve or a risk tolerance chart, which illustrates the relationship between the likelihood (F) and the number of individuals killed or injured (N).

At the time of publication, there are no national guidelines in New Zealand for defining tolerable life-risk limits relating to AIFR. The Natural Hazard Risk Tolerance Literature Review published by the Earthquake Commission[1] (2023), outlines various life safety risk thresholds implemented at national, regional, and district levels across New Zealand as shown in Figure 3.1.

Table 3.2 presents examples of international risk thresholds alongside those established by the Minister for Canterbury Earthquake Recovery – Christchurch City Council, and the New Zealand Department of Conservation.

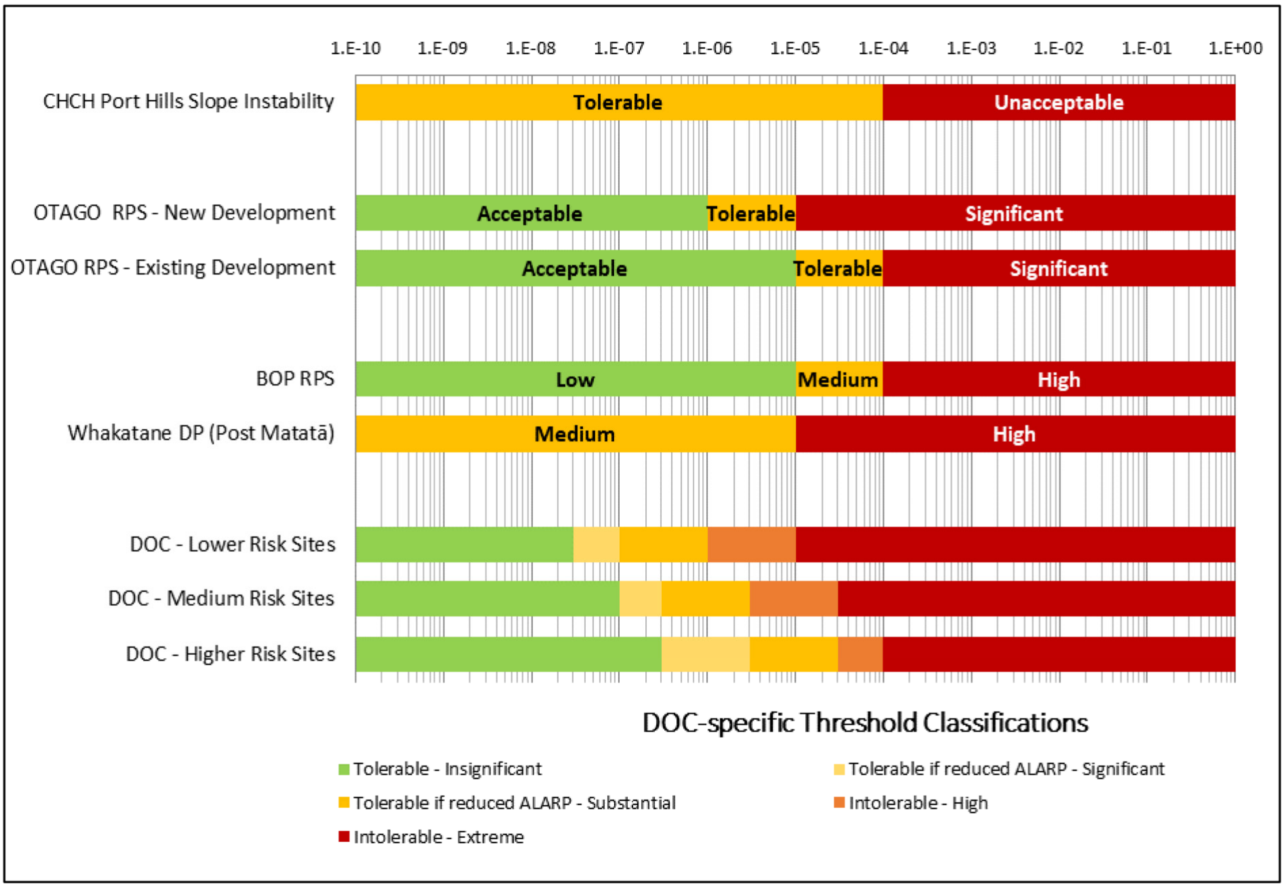


Figure 3.1. New Zealand examples of fatality risk thresholds (Source: Earthquake Commission1, 2023). Acronyms used in the figure: CHCH = Christchurch, RPS = Regional Policy Statement, BOP = Bay of Plenty, DP = District plan, DOC = Department of Conservation, and ALARP = As Low As Reasonably Practicable

Table 3.2. Comparison of risk thresholds (Adopted from Clarke et al., 2021, as cited by Earthquake Commission[1], 2023)

Organisation	Hazard	Threshold	Risk Tolerability (AIFR, unless noted otherwise)
Australian Geomechanics Society (AGS) Guidelines for Landslide Risk Management	Landslides (from engineered and natural slopes)	Suggested tolerable limit	AIFR: 10^{-4} per annum (public most at risk, existing slope) 10^{-5} per annum (public most at risk, new slopes) Annual property risk – suggest these are defined by the local authority
Hong Kong Special Administration Region Government	Landslides (from natural slopes)	Tolerable limit	10^{-4} per annum (public most at risk, existing slope) 10^{-5} per annum (public most at risk, new slopes)
Iceland Ministry for the Environment and Hazard Zoning	Avalanches and Landslides	'Acceptable' (tolerable) limit	3 x 10^{-5} per annum (residentials, schools, day-care centres, hospitals, community centres) 10^{-4} per annum (commercial buildings) 5x10^{-5} per annum (recreational homes)
NSW Australia, Roads and Traffic Authority	Highway Landslide Risk	Implied tolerable limit	10^{-3} per annum
Minister for Canterbury Earthquake Recovery – Christchurch City Council	Rockfall Protection Structures	Tolerable limit	10^{-4} for an existing dwelling or structure
New Zealand Department of Conservations (DOC)	Landslides and Rockfall	Tolerable limit	10^{-4} public most at risk for higher risk sites where users will be aware of heightened hazards. 10^{-5} public most at risk for lower risk sites.

Note: Risk Tolerability refers to the highest risk level considered with certain controls applied.

1 Presently known as the Natural Hazards Commission.

Based on this information, the designer should consider the appropriate level of tolerable risk aligned with the specific requirements of the client or governing body. To provide alignment with these requirements, the possible AIFR **Tolerable Risk Thresholds** could be summarised as follows;

- **1 x 10^{-3}** – A high individual fatality risk, generally considered tolerable only for informed and occupationally exposed individuals, such as road maintenance workers or truck drivers. This level of risk may be acceptable where individuals are aware of the hazard, exposure is voluntary or infrequent, and appropriate risk reduction measures are in place. This threshold aligns with tolerability thresholds from UK Health and Safety Executive (2001) and transportation agencies such as NSW Roads and Traffic Authority (NSW Department of Planning, 2011), where risks are managed to be as low as reasonably practicable (ALARP).
- **1 x 10^{-4}** – tolerable risk limit for public safety relating to an existing slope and developments, this was adopted by the Minister for Canterbury Earthquake Recovery in June 2013 specific for dwellings or structures protected by rockfall protection structures (Christchurch City Council, 2013).
- **1 x 10^{-5}** – tolerable risk limit for new slopes or developments, highlighting a lower tolerance for risk associated with newly developed areas. This value recognises that new developments should incorporate robust controls to mitigate risks to life.
- **1 x 10^{-6}** – acceptable risk limit for new developments, typically adopted as a minimum target for design in some international guidelines (e.g., AGS, 2007).

For societal risk, the ALSE for differing scenarios should consider the use of a F-N curve.

Figure 3.2 illustrates an example of F-N criteria specifically developed for Hong Kong. It is essential to recognise that societal risk tolerance differs significantly across regions and types of hazards, and tolerability criteria cannot always be directly applied from one location to another (De Vilder, Kelly et al., 2024).

It is important to consider that risk analysis tools can often identify and rate multiple hazards within a single site, and when applying risk-based performance criteria, considerations are needed to target the hazards which specifically do not meet tolerable risk levels, as well as considering the combined risk from all the identified geotechnical hazards from the potential slope failure. This is exemplified in Unit 1 Part 10, with experience following the Kaikōura Earthquake where slopes presented both isolated rockfall, debris slides, and rock avalanche hazards at a single site.

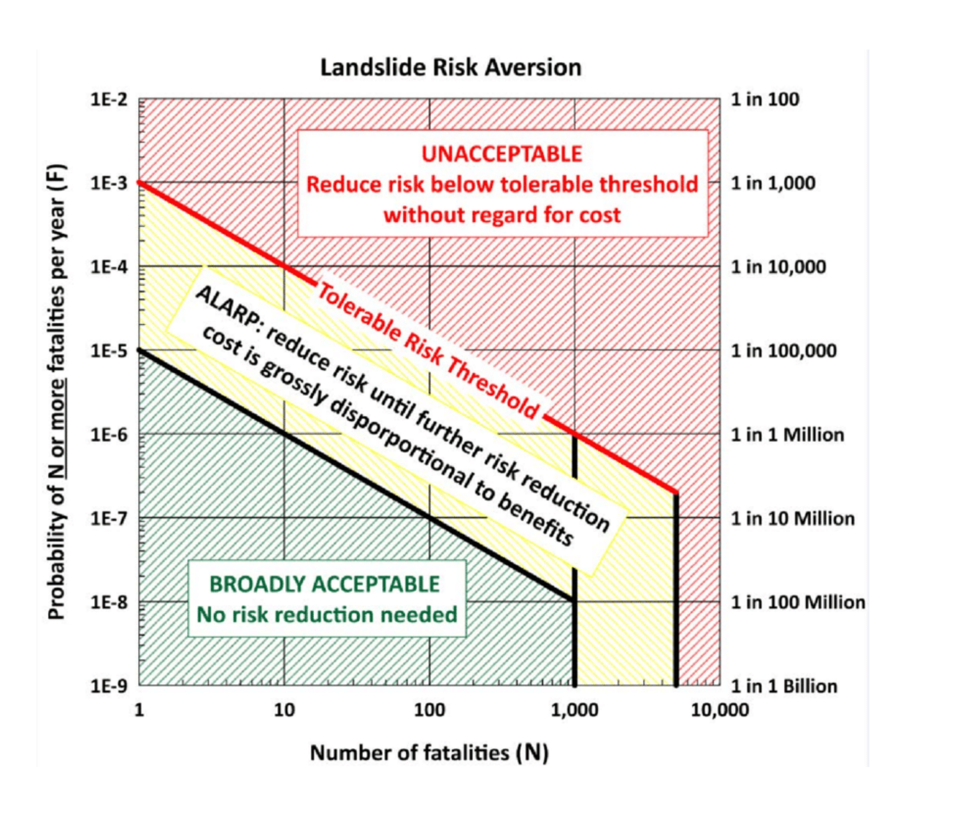


Figure 3.2. Risk tolerance chart for societal risk developed for use in Hongkong (Source: Strouth and McDougall, 2021). ALARP = As Low As Reasonably Practicable

Currently, there is no concise national or international guidance for risk tolerance in New Zealand, so in practice, all parties currently have an obligation to determine the appropriate risk thresholds through common or established practice. Some regional or territorial authorities may set thresholds specifically through regional policy statements or district plans, and the key to determining risk thresholds for a mitigation measure requires early engagement with stakeholders and governing parties to understand the risk appetite and risk tolerance specific to the site.

3.2 LIMIT EQUILIBRIUM (FACTOR OF SAFETY) AND PERFORMANCE-BASED DESIGN

Factors of Safety (FoS) and Performance-Based Design (PBD) approaches represent two different methods used in engineering design, including slope stability analysis, which are both well covered in Section 13 of Unit 3 – Slope Stability Analysis. The guidance covers selecting an appropriate methodology and proposes moving beyond the traditional reliance on a fixed value of 1.5 initially implied by Terzaghi in 1943, and selecting a performance-based approach, considering both the probability and consequences of failure and the level of geotechnical investigation and design.

In slope stability mitigation, it is important to understand these two approaches and how they can be considered compatible with each other.

Factor of Safety: This approach is largely deterministic, where design parameters (like soil properties) are considered as fixed values, and a FoS is calculated to account for uncertainties in material properties, loading scenarios, analysis methods, etc. A slope is considered stable if the calculated FoS exceeds a certain minimum value, often specified by codes or based on empirical evidence.

Performance-Based Design Criteria: This approach shifts from achieving a fixed FoS to meeting specific performance criteria (e.g., tolerable deformation or displacement) under various loading conditions, including extreme seismic events.

This approach often requires more sophisticated modelling to understand the slope behaviour, such as dynamic analysis to simulate earthquake loading. Uncertainties in the seismic loading are addressed by analysing a suite of representative ground motion records and evaluating a range of potential displacements, rather than relying on a single deterministic value. Uncertainties in the soil response are accounted for by means of a parametric assessment by using probable ranges of soil parameters.

Empirical methods, such as Newmark sliding block models, are also commonly used within this approach to estimate seismically induced slope displacements. These methods provide a practical and relatively simple means to estimate expected displacement, which can be compared to tolerable limits.

While the FoS, and the PBD approaches represent different philosophies, they can be used together to some extent in slope stability design, such that PBD methods can incorporate FoS calculations as part of the design process, considering the FoS as one of the performance measures. This provides a link between the traditional deterministic design and more modern probabilistic design frameworks.

Conversely, deterministic methods using a FoS approach can inform and guide the performance criteria adopted in PBD, and PBD methods can be used to verify the adequacy of the FoS approach by identifying any performance issues not captured by the FoS criteria.

Although FoS and PBD represent different approaches to design, they are not entirely incompatible, rather, they can be viewed as complementary methods, with the choice between them depending on the complexity of the situation and the desired confidence level regarding the structure's or slope's performance.

The key factors influencing a combination of the FoS and PDB selection include:

- **Loading Conditions:** Different scenarios like long-term static conditions, high groundwater, short-term loading, and seismic events require specific FoS considerations.
- **Consequence of Failure:** Higher consequence levels, like those involving potential loss of life, necessitate higher FoS values.
- **Level of Engineering (LoE):** More thorough site investigations, rigorous design, and robust construction oversight (higher LoE) could justify adopting lower FoS values.
- **Statistical Uncertainties:** Varying levels of uncertainty relating to material properties and groundwater levels.

FoS values based on various combinations of consequence categories and LoE levels can be appropriate to justify lower FoS values with proper communication of potential risks to stakeholders.

In addition, and more specifically to the design of ground anchors, the NZGS Ground Anchors: Design and Construction Guideline (2023), proposes a similar approach in Section 5.4.1.11 relating to the strength reduction factors used for the grout-ground bond. Notably, both guidance documents (Unit 3 and Ground Anchors) emphasise that the LoE or Risk Factor (K) must be critically and conservatively considered to avoid underestimating the risk or uncertainty.

A Performance Based Design approach could be considered more suitable for the design of slope stabilisation and remediation measures, considering the probability and consequences of failure, and resulting residual risk from the geotechnical hazard being addressed.Considerations in Selecting Mitigation Strategies

4 CONSIDERATIONS IN SELECTING MITIGATION STRATEGIES

4.1 KEY FACTORS IN SELECTING MITIGATION STRATEGIES

Effective slope mitigation begins with a clear understanding of the instability mechanism – whether it is a shallow landslide, deep-seated failure, rockfall, debris flow, or another hazard. Understanding the type, triggers, scale, and behaviour of the failure mechanism is essential to determining the most appropriate mitigation response. This understanding also helps identify the level of risk to life, property, infrastructure, and the environment and defines what "successful" mitigation looks like.

Once the problem is clearly defined, several key factors should be considered in selecting sustainable, effective solutions tailored to specific project needs:

- **Site Characteristics:** The unique characteristics of a site, such as topography, slope profile, geomorphology, existing landslides, vegetation, groundwater conditions, and local hydrology, are crucial in assessing slope stability. Site reconnaissance should identify these factors as well as existing infrastructure and assets. Vulnerability to instability may arise from site-specific conditions, including slope geometry, drainage, and localised geology or soil properties. Historical surveys, maps, and aerial photographs can reveal changes in topography, while ground instruments such as inclinometers, settlement plates, and piezometers can measure physical conditions. Human-caused factors may also be evident through records or past observations.
- **Geological Conditions:** Understanding subsurface conditions, material properties, and groundwater dynamics is essential as they significantly impact slope performance. Effective slope mitigation requires a multidisciplinary approach, drawing on geological knowledge and geotechnical principles to ensure accurate representation of ground conditions and to design practical stabilisation solutions.
- **Seismicity:** In regions with seismic activity, accounting for seismicity in slope design is essential, as earthquakes can destabilise slopes, resulting in landslides and rockfalls. Ground shaking can trigger slope movements by lowering soil stress or compromising rock formations. Seismically resilient solutions may involve reinforcement techniques, such as slope anchors, flexible retaining structures, or energy-absorbing barriers, designed to absorb seismic forces and preserve slope stability during and after seismic events. A site-specific understanding of seismic risk, including shaking intensity and potential earthquake frequency, enables the development of tailored solutions that enhance the resilience of critical infrastructure.
- **Performance Requirements:** Safety and performance standards shape the selection of mitigation strategies, setting expectations for effectiveness, durability, and reliability. These standards ensure that the solution meets site-specific goals, including safety, service life, and maintenance needs, while managing acceptable levels of risk. Well-defined performance criteria guide engineers in developing solutions that achieve long-term stability and safeguard surrounding assets and communities.
- **Design Life:** The lifespan of landslide mitigation measures is a very important consideration. The effectiveness and cost of a mitigation measure can be affected by lifespan limitation. Design life can be influenced and dictated by:
  - Durability of component materials
  - Environmental conditions (such as corrosion, rainfall, climate change, etc)
  - Loading conditions (earth pressure, seismic loading, fluctuating water loads such as tides, etc)
  - Maintenance requirements (some measures require frequent upkeep and maintenance in order to remain effective throughout their lifespan)
  - Sustainability (carbon footprint of measure all through its life cycle – i.e., design, installation, service life, maintenance, and decommissioning)
- Design life should be determined in accordance with the recommendations of NZS 1170.0 or the NZTA Bridge Manual, whichever is applicable, or as agreed with the client, taking into account the appropriate importance level. Below are summarised examples of design working life for some typical mitigation measures.

Table 4.1. Design working life for typical mitigation measures

Mitigation Measure	Typical Design Working Life
Retaining walls and reinforced slopes (depending on the materials used and the environmental conditions)	50 to 100 years
Properly design drainage systems	30 to 50 years
Wire mesh or cable net systems	20 to 30 years

- **Risk Assessment:** This helps identify the instability level and the intervention scale required. This assessment might involve visual inspections, geological surveys, and geotechnical analysis to determine (a) Potential landslide zones and frequency, (b) Likelihood and potential impact of landslides, (c) Financial implications, including damage repair and disruption costs, and (d) Risk to human safety. By evaluating residual risks, mitigation strategies can be selected that reduce the probability of landslides and ensure risks to life and property or assets remain within acceptable or tolerable risk limits.
- **Legal and Regulatory Requirements:** Regulatory requirements and land ownership considerations influence available strategies. Local authorities, regional councils, or national agencies may impose restrictions, especially for projects that affect protected lands or waterways. Neighbouring landowners may also restrict mitigation efforts that extend onto their property. Early identification of these legal limitations and stakeholder engagement is vital to ensure that selected solutions are both compliant and socially acceptable. Engaging affected parties—such as landowners, local councils, and Iwi—can also highlight any cultural or customary concerns, especially if mitigation work could impact access to important natural sites.
- **Cost Considerations:** Mitigation strategies should be financially justified, with the cost of implementation balanced against the reduction in risk achieved. For asset managers and local authorities, this often involves prioritising cost-effective strategies that meet safety needs without overextending resources. Budget constraints should not compromise design adequacy; in some cases, a temporary or lower-cost solution with a shorter lifespan may be a suitable alternative.
- **Construction Considerations**
  - **Timeframes:** If a quick turnaround is needed, solutions that can be rapidly deployed or implemented in stages may be preferable. Time-sensitive projects benefit from the early involvement of contractors and suppliers to identify potential supply chain limitations.
  - **Access, Constructability, and Safety:** Site accessibility for equipment and maintenance must be considered, as this can limit available solutions. A phased approach may sometimes be necessary to establish initial or temporary stabilisation before completing full mitigation measures.
  - **Availability of Resources and Expertise:** Certain mitigation methods require specific equipment, materials, or technical skills. Assessing resource availability within the project timeline helps ensure that the selected method can be effectively implemented.
  - **Time of year for Construction:** Construction methodologies or methods may change depending on the time of year that construction works are undertaken. Constructing within the drier, summer months may enable solutions to be implemented quicker and safer, without the need for as many temporary stability measures.
- **Environmental Considerations**
  - **Durability and Sustainability:** Materials and methods should be selected for their resilience against environmental conditions, durability, and sustainable sourcing.
  - **Environmental and Social Impact:** Mitigation efforts should aim to minimise ecological disruption, with a focus on maintaining cultural and community values. Consultation with Iwi may be required, and solutions with lower environmental footprints should be prioritised where possible.
  - **Climate Conditions:** Climate factors, especially rainfall patterns, play a significant role in slope stability. Proactive planning around runoff and groundwater impacts can help predict the frequency and severity of potential slope failures.
- **Maintenance and Monitoring:** The long-term maintenance needs vary widely among mitigation options. Maintenance costs and practicalities should be considered early on. Innovative solutions, such as self-cleaning or debris-intercepting designs, can help lower ongoing maintenance demands and costs.
- **Other Considerations**
  - **Technical Effectiveness:** Solutions must be evaluated for their level of risk reduction, with engineers communicating the effectiveness of each option to project stakeholders.
  - **Aesthetic Impact:** Some mitigation measures significantly alter the landscape's appearance. Projects should define aesthetic considerations early to address visual impacts effectively.
  - **Potential for damage and vandalism:** Consideration should be made for the ability of solutions to be damaged or vandalised by the public, and where necessary and appropriate, anti-damage and vandalism measures should be implemented.

4.2 MITIGATION OPTIONS ASSESSMENT PROCESS

Choosing an effective slope mitigation strategy begins with a comprehensive understanding of both the slope's characteristics and the project's goals and constraints. The selection process varies depending on the project's scale and complexity, as well as the severity of the hazard. For smaller projects, a simple table summarising the pros and cons of each mitigation option may suffice. In larger or more complex projects, a risk-based approach spanning the project's lifecycle is typically applied, often requiring insights from multiple disciplines.

Mitigation selection is not only a design decision but also involves input from construction and maintenance teams to ensure long-term viability. This selection process typically starts early in project planning and is refined as a clearer understanding of the instability and any unforeseen constraints emerges.

Figure 4.1 illustrates an example mitigation option assessment process that can serve as a guide for selecting mitigation strategies.

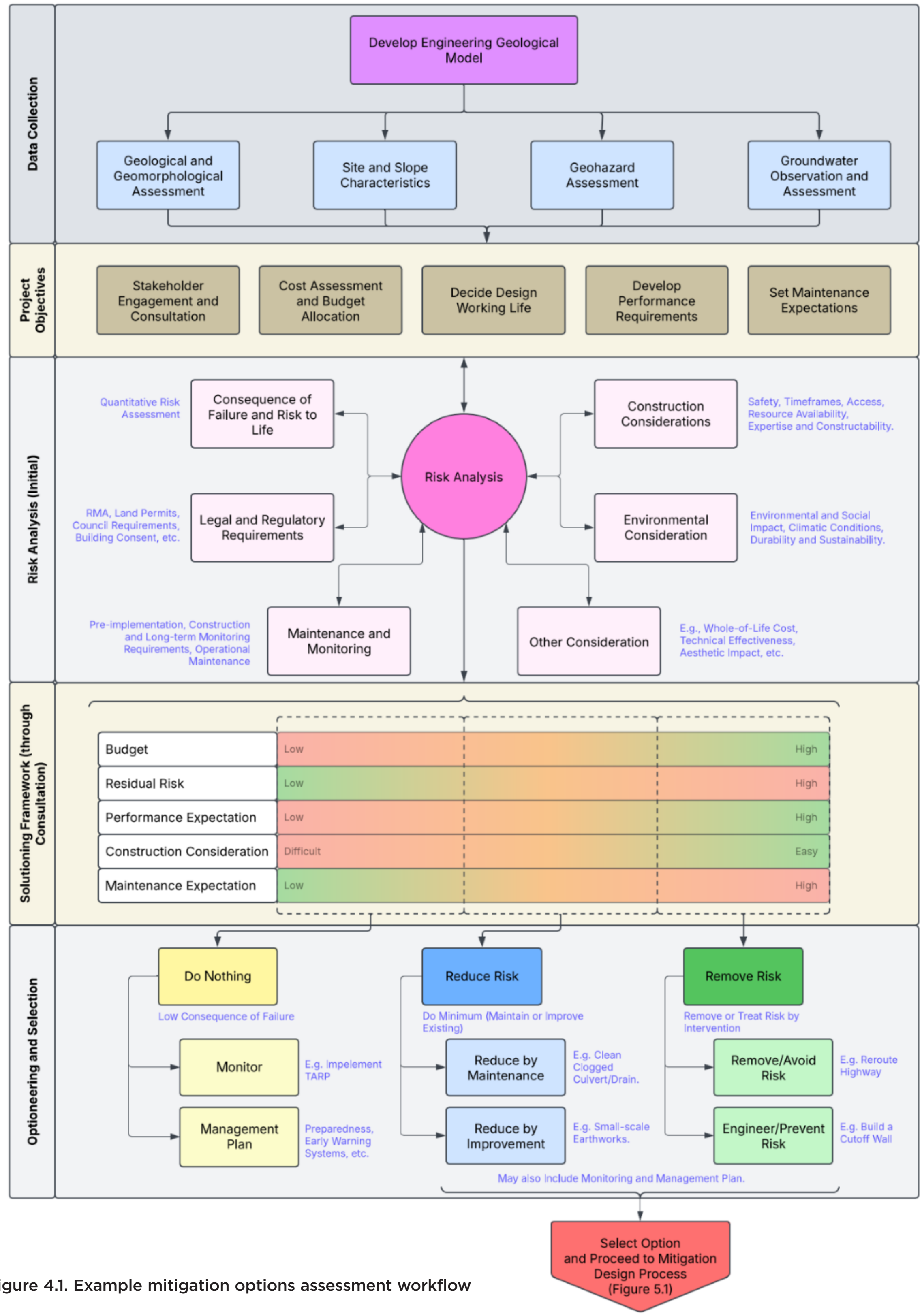


Figure 4.1. Example mitigation options assessment workflow

5 MITIGATION DESIGN PROCESS

When referring to slope stability and landslide mitigation methods and design, the typical understanding is that intervention design involves either engineered or non-engineered methods.
Intervention or engineered mitigation measures to actively reduce the likelihood of landslides. e.g., use retaining walls, rock bolts, and soil nails to provide physical support and prevent slope movement, or install surface and subsurface drainage to manage water flow and reduce hydrostatic pressure. Other options also include the use of reinforcement techniques, such as geosynthetics, rockfall barriers, and catchment nets, to stabilise slopes.

Non-engineered measures are solutions that implement a less direct method of addressing landslide risk, such as bioengineering or land-use planning. Bioengineering involves using vegetation to stabilise soil and reduce erosion, where appropriate. Effective land-use planning can include implementing zoning regulations to restrict development in high-risk areas and promote safe land-use practices.

In addition to these methods, other important considerations in the mitigation design are incorporating instrumentation and monitoring, and designing for future elements. Instrumentation and monitoring include the implementation of real-time monitoring systems and remote sensing to detect early signs of slope movement. Mitigation design should also incorporate elements that account for future landslide triggers or effects that may increase the likelihood of landslides (e.g., climate change and future adaptation). As a result, including an element of evaluation of how climate change (such as increased rainfall and temperature variations) may affect slope stability is reasonable. And considering flexible mitigation strategies that can be adjusted as climate conditions change helps to future-proof the design.

5.1 STEPS INVOLVED IN MITIGATION DESIGN

Mitigation design steps can vary depending on the impact or consequence of the risk, which could be quite variable for different projects. Broadly speaking, once the decision to implement mitigation has been made, mitigation design involves the following steps:

- **Hazard Identification and Characterisation**: This includes identifying the type, magnitude, frequency, and extent of the hazard(s), along with an understanding of site conditions and any residual risks following mitigation.
- **Agreeing on Performance Criteria:** Defining the expected level of acceptable safety, performance, reliability, and acceptable or tolerable risk levels.
- **Options Assessment:** This varies from simple concept sketches to detailed multi-criteria assessment (MCA), depending on factors such as project type, cost, and complexity.
- **Sustainability by Design:** Incorporates measures to reduce environmental and social impacts, improve durability, and enhance climate resilience.
- **Method Selection and Detailed Design:** This is based on site-specific constraints, performance requirements, constructability, cost, environmental and regulatory considerations, and long-term maintainability.
- **Safety by Design:** Includes consideration of the mitigation design features that may have an impact on health and safety, from construction all the way to decommissioning of the design features.

An example mitigation design workflow is presented in Figure 5.1.

5.2 MITIGATION DESIGN PHILOSOPHY

Generally, slope stability mitigation design falls into two categories: hazard reduction and consequence reduction.

5.2.1 Mitigation Design Philosophy for Reducing the Likelihood of Risk

Designs under this category focus on improving slope stability by reducing the potential for failure. These measures often target the root cause of instability, such as adverse groundwater conditions, weak materials, or unfavourable slope geometry. This strategy is most appropriate when there is a clear instability mechanism and where the failure likelihood is high or unacceptable under current conditions.

5.2.2 Mitigation Design Philosophy for Reducing the Consequences of Risk

Where the likelihood of slope failure cannot be feasibly reduced to an acceptable level (due to cost, access, environmental constraints, or uncertainty), designs may focus instead on reducing the consequences of failure. These measures aim to limit the impact on people, infrastructure, and the environment, even if failure occurs. This approach is typically adopted where uncertainty in hazard modelling is high or where infrastructure is located in unavoidably exposed positions.

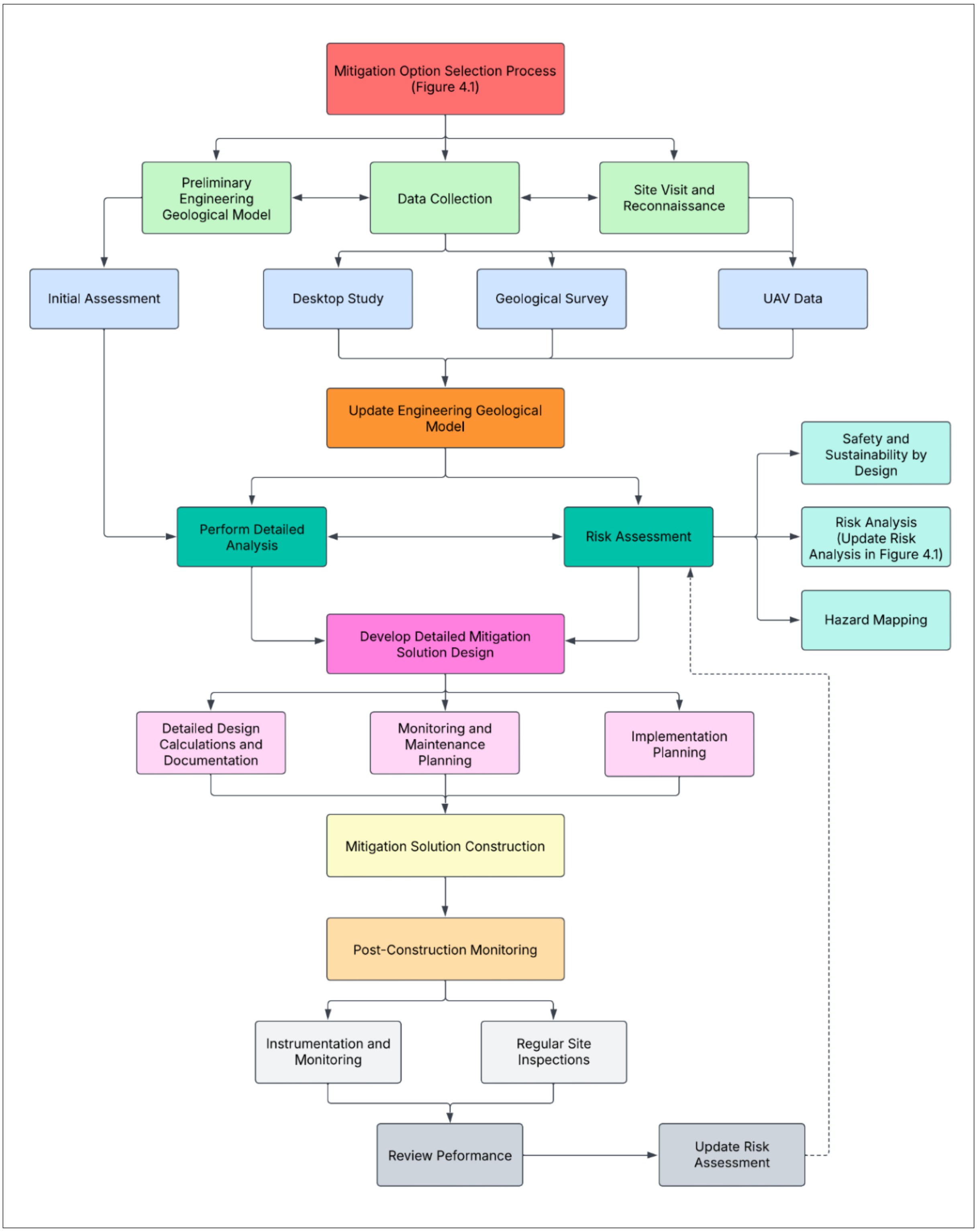


Figure 5.1. Example mitigation design workflow

6 ENGINEERED MITIGATION OPTIONS

6.1 SOIL/HIGHLY FRACTURED ROCK SLOPES

6.1.1 Introduction

This section provides engineering mitigation solutions for existing or proposed soil slopes (natural and constructed), where instability is identified and assessed through surface mapping and ground investigation.

Soil slopes occur naturally in the landscape or are modified during construction. Natural soil slopes are shaped by long-term geomorphological and weathering processes, with slope stability evolving over time due to changes in climate, vegetation, and groundwater conditions. Modified soil slopes are created through cut or fill earthworks and rely on engineering design and construction practices to maintain stability.

In general, soil slopes are formed at flatter angles than rock slopes due to the lower shear strength of soils compared to intact rock. Similarly, excavation and fill profiles in soil are generally more conservative than those in rock to account for pore water pressure effects, surface erosion, and time-dependent deformation. Unlike rock slopes, where discontinuities often control failure mechanisms, soil slope behaviour is primarily governed by effective stress conditions, which are influenced by drainage, pore water pressure, and the spatial variability of soil strength parameters.
The slope mitigation measures outlined in this section focus on the most common at-source treatments applied to soil slopes to improve stability, including drainage and dewatering, earthworks, retention systems, slope reinforcement techniques and ground improvement techniques.

6.1.2 Drainage and Dewatering

6.1.2.1 Description

Effective drainage and dewatering are essential for maintaining the stability of soil and highly fractured rock slopes. These systems manage both surface and subsurface water to reduce pore pressure, minimise erosion, and prevent water accumulation that could destabilise the slope. In soil slopes, particularly those composed of fine-grained, weathered, or colluvial materials, saturation and prolonged wetting are primary triggers for slope movement.

Some New Zealand guidance documents relevant to drainage and dewatering include:

- **NZTA Highway Surface Drainage Design Guide (2010)**: Focuses on managing surface water runoff to protect road infrastructure and adjacent slopes.
- **SCIRT Dewatering Guideline (2016):** Practical guidance on choosing dewatering techniques such as wellpoint systems and deep wells.
- **NZTA Stormwater Management Specification P46 (2021):** Standards for managing surface water and runoff in infrastructure design.

Drainage can be categorised as either surface drainage or subsurface drainage, each with a distinct function but often applied in a complementary manner. Dewatering methods further assist by lowering the phreatic surface or intercepting pressurised seepage paths, particularly in deep-seated landslides or large earthwork cuttings.

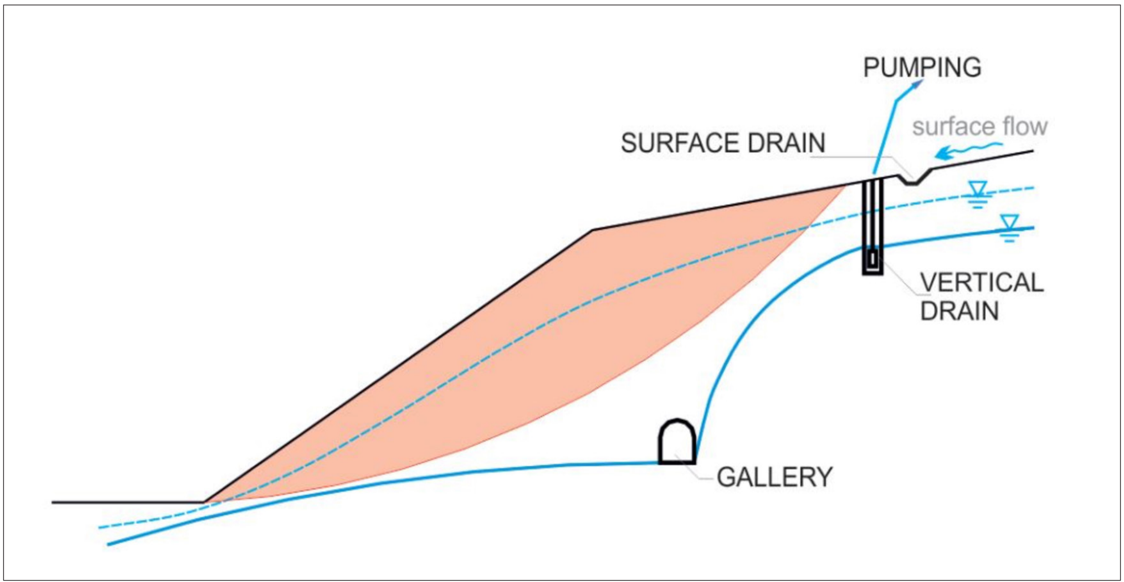


Figure 6.1. Slope stabilisation using drainage techniques (Adapted from Mihalić Arbanas and Arbanas, 2015)

Surface Drainage
Surface drainage prevents uncontrolled water from flowing over or infiltrating into the slope. This is particularly important in:

- Transport corridors,
- Industrial/residential subdivisions,
- Linear infrastructure routes (e.g., transmission lines, pipelines), and
- Areas subject to de-vegetation or deforestation.

Common surface drains include channels or culverts diverting surface water away from critical areas, minimising erosion, and reducing surface saturation. Factors that commonly influence or initiate slope instability events include:

- Uncontrolled stormwater/rainfall run-off or overland flow initiating scour and erosion,
- Inadequate or compromised surface drainage features such as table drains and culverts leading to infiltration, seepage problems, and/or near-surface saturation and shallow slumping, and
- Slopes subjected to periodic inundation and subsequent rapid drawdown.

In most cases where surface drainage has led to an instability event, appropriate mitigation involves fundamental improvements in basic civil engineering principles associated with the control and management of overland flow. This starts with an understanding of the hydrological conditions and the establishment of design rainfall event criteria. Identifying the catchment area via surveys, mapping, and aerial imagery is essential to assess run-off characteristics, ensuring the adequate design capacity of surface water control structures and safe discharge to prevent infiltration and scour issues on vulnerable slopes.

The most common surface drainage-related landslide events are initiated by erosion or scour effects on the landform. However, over time, ongoing or extreme erosion/scour events can trigger other instability mechanisms on geologically vulnerable controlled surfaces by over-steepening a marginally stable slope.

Improving drainage can serve as a preventative measure, but in circumstances where poor drainage has led to large-scale instability or mass movement, it is not uncommon to include additional slope stabilisation mitigation measures to reinforce and/or reinstate the affected slope.

Subsurface Drainage
It is common to encounter both man-made and natural slopes where attempts to address existing instability issues have been based on efforts to lower the groundwater level (phreatic surface) in the slope using sub-surface drainage measures to increase the effective stress on the active slip plane / shear surface.

Common subsurface drainage methods include:

- **Horizontal Drains or Counterfort Drains,** which intercept groundwater seepage and reduce the phreatic surface,
- **Raking Drains,** installed at shallow inclinations to target specific seepage zones,
- **Vertical Drains, Relief Wells or Dewatering Wells,** which actively pump out groundwater,
- **Drainage Galleries** with associated horizontal drains (used in large-scale or deep-seated instability),
- **Interceptor Trenches,** which cut across perched water tables or shallow seepage layers.

6.1.2.2 Intended Use and Benefits
Drainage and dewatering provide both immediate and long-term benefits in slope stabilisation as summarised in Table 6.1.

Table 6.1. Benefits of drainage measures

Drainage Type	Benefits
Surface Drainage	• Reduces surface erosion and scour • Limits infiltration and near-surface saturation • Diverts water from sensitive areas or infrastructure at the slope toe
Subsurface Drainage	• Lowers groundwater pressure in weak layers or along slip planes • Intercepts seepage before it reaches the slope face • Improves effective stress and slope stability • Reduces risk of drawdown-related failures and long-term creep movements

6.1.2.3 Effective Application
Effective drainage and dewatering are critical issues to consider in the stabilisation of soil and fractured rock slopes. Proper drainage systems manage groundwater flow, reduce pore pressure, and prevent destabilising water accumulation.

Table 6.2. Application of drainage measures

Surface Drainage	Subsurface Drainage
• Prevents slope instability by managing overland flow and reducing erosion and infiltration. • Commonly applied in transport corridors, industrial/residential subdivisions, linear infrastructure routes, and deforested areas.	• Targets internal groundwater pressures along slip planes or in weak soil layers. • Effective in deep-seated instability or slopes with high pore pressures.

6.1.2.4 Considerations and Limitations

While drainage is often an effective first-line defence against slope instability, its long-term success depends on design, installation quality, and maintenance. Key limitations include:

- **Clogging or deterioration** of sub-drain pipes,
- **Incorrect siting** or alignment of drains leading to ineffective interception of groundwater,
- **Incomplete catchment assessment**, leading to under-designed drainage infrastructure,
- **Reactivation of instability** if drains become blocked, groundwater regimes shift, or rainfall patterns intensify, and
- **Need for periodic inspection**, especially in high-risk or active landslide areas.

An example of large-scale treatment using subsurface drainage is described in the paper *Observations and predictions of the behaviour of large, slow-moving landslides in schist, Clyde Dam reservoir, New Zealand* (Macfarlane, 2009).

A simplified, theoretical example is defined in Figure 6.2 where a gallery drainage system is installed for stabilisation of an active landslide mechanism.

The theoretical basis for drainage-induced stabilisation is related to the effective shear resistance on the active slip plane or shear surface expressed as:

$$\tau = c' + (\sigma - u)^*\tan\phi' \qquad \text{Equation 6.1}$$

Where:

c' = effective cohesion on the shear surface
σ = total vertical stress on the shear surface
u = pore pressure on the shear surface
ϕ' = effective angle of shearing resistance on the shear surface.

In this example, the drainage system reduces the pore pressure from U_b to U_a.

The reduced pore pressure on the shear surface increases effective stress, improving the shear resistance (τ).

The margin of improvement in the Factor of Safety (FoS) for the landslide mechanism depends on the drainage system's effectiveness and the associated reduction in pore pressure.

The design must demonstrate that the proposed drainage system will lower the phreatic surface to achieve an acceptable margin of safety. However, in active landslide mechanisms, the shear strength characteristics in the sheared materials (c'/ϕ') may be impacted, and post-peak strength characteristics should be adopted in the design.

Design documentation for stabilising an active landslide mechanism using drainage must include monitoring and maintenance to ensure the continued effectiveness of the system.

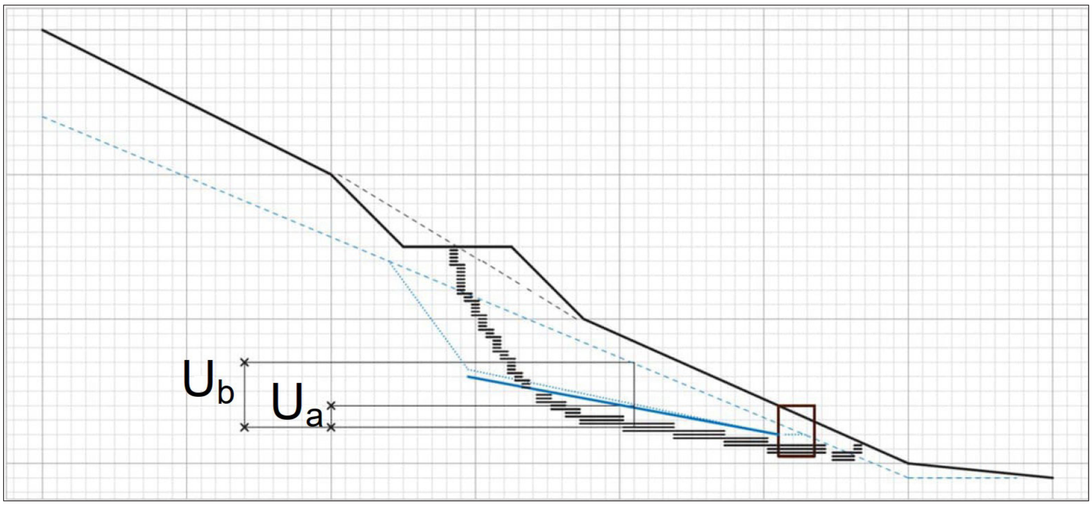


Figure 6.2. Gallery drainage system for stabilisation of an active landslide mechanism

Figure 6.3. Gallery drain treatment on State Highway (SH1) at Kaiwaka, showing the gallery drain well and collection chamber located downslope in the adjacent paddock

6.1.2.5 Example Applications

There are examples where sub-surface drainage measures have been installed, but over time, there can be some reactivation of the initial slope instability problem. Whilst this is often attributed to poor maintenance and/or degradation over time of the installed sub-surface drainage system, there are theoretical and practical limitations to the success of this mitigation methodology.

6.1.3 Earthworks

6.1.3 1 Description

Natural or man-made slopes can experience instability due to various factors, including erosion, weathering, changes in water content, and human activities. Earthworks controls are practical engineering solutions that can modify slope geometry to improve slope stability. These controls are commonly implemented in various forms depending on site conditions, slope characteristics, and project requirements.

Key earthworks strategies for enhancing the stability of slopes include:

- **Slope Reshaping and Gradient Reduction:** Slope reshaping involves reducing the steepness of a slope to decrease the driving forces acting on the potential sliding mass. Reducing the slope angle decreases the gravitational force component acting downslope, thereby improving stability. Excavation at the slope crest and backfilling near the toe of the slope can reduce the slope gradient. This method is often applied in conjunction with other stabiliSing measures to create a more stable profile without overloading the toe region.
- **Toe Buttress:** A toe buttress strengthens, or reinforces, the lower part of the slope (toe) by adding material, such as compacted fill or rock, to counteract downslope movement. Gravity retaining walls can be used to provide similar support.

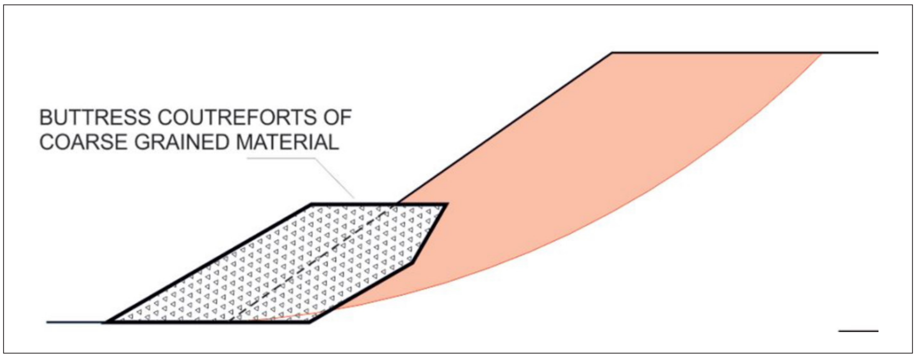


Figure 6.4. Toe buttress constructed with coarse-grained materials (Adapted from Mihalić Arbanas and Arbanas, 2015)

Guidance on earthworks measures for soil slope stabilisation is provided by several technical documents relevant to New Zealand conditions and internationally accepted engineering practices:

- **NZGS Slope Stability Guidance (2025a, Unit 3)** provides recommendations on slope reshaping, gradient reduction, and toe buttressing tailored for New Zealand conditions.
- **NZTA Highway Structures Design Guide (2016)** provides general and specific requirements for all highway structures, including earthworks for natural slopes, embankments, and cuttings.
- **NZTA Bridge Manual (SP/M/022)** outlines the criteria for the design and evaluation of all highway structures, and earthworks, including design philosophy, stability design requirements, and performance requirements for soil structures such as cut and fill slopes, and embankments.
- **Australian Geomechanics Society Landslide Risk Management Guidelines (2007)** provide practical advice on earthworks stabilisation techniques for slopes, supporting long-term performance and stability.

6.1.3.2 Intended Use and Benefits

The table below summarises the intended uses and benefits of the key earthwork strategies used for soil slope stabilisation:

Table 6.3. Benefits of earthworks

Mitigation Measure	Intended Use	Benefits
Slope Reshaping and Gradient Reduction	To reduce slope steepness and driving forces promoting slope failure.	Improves stability by lowering gravitational forces, mitigates shallow landslides and erosion, and supports integration with drainage and revegetation measures.
Toe Buttress	To reinforce the lower slope by adding mass to counteract downslope movement.	Increases resisting forces against deeper or rotational failures, effective for steep slopes where regrading is limited, and offers flexible construction options using fill, rock, or retaining walls.

6.1.3.3 Effective Application

The following table summarises the effective application of slope reshaping and gradient reduction, and toe buttress earthworks for soil slope stabilisation.

Table 6.4. Effective application of earthworks strategies

Strategy	Slope Reshaping and Gradient Reduction	Toe Buttress
When to Use	Suitable where slope gradients are steep and can be safely reduced.	Ideal for slopes needing additional support at the toe to resist movement.
Implementation Methods	Excavation at crest; placement of fill at toe; may be combined with drainage or reinforcement.	Placement of compacted fill or rock at the toe; gravity retaining walls may be used as buttress.
Typical Applications	Road cut slopes, embankments, landslide remediation where slope angle reduction is feasible.	Riverbank stabilisation, coastal cliffs, highway cut slopes with toe erosion.

6.1.3.4 Considerations and Limitations

Slope reshaping and toe buttressing are effective earthworks strategies, but their applicability depends on site-specific factors such as available space, material volumes, construction access, and environmental constraints. The key considerations and limitations for each method are outlined below.

Slope Reshaping and Gradient Reduction

- **Material Volume and Site Geometry**: Reducing the slope angle often requires extensive cut-and-fill operations, which may not be feasible for tall or long slopes due to the significant material volumes involved. This is particularly restrictive in constrained urban corridors, narrow gorges, or steep terrain.
- **Land Availability**: Flattening a slope requires more lateral space, which may not be available near boundaries, infrastructure, or sensitive ecological zones.
- **Stability of Temporary Cuts**: During construction, temporary cuts made at the crest may be unstable and require short-term support or staged excavation.
- **Drainage Control**: Reshaped slopes must be integrated with adequate surface drainage to prevent water ponding or erosion on the new slope face.
- **Aesthetic and Environmental Impact**: While effective, large-scale earthworks can alter the landscape significantly and may trigger resource management or environmental planning considerations.

Toe Buttress

- **Importation of Fill**: Toe buttressing generally requires the importation of engineered fill (granular or rock), which can add cost and construction complexity, particularly in remote or soft ground areas.
- **Foundation Bearing Capacity**: The buttress must be founded on competent ground to avoid additional instability or settlement issues. Weak toe ground may require improvement or staged loading.
- **Space Constraints**: Buttressing can occupy significant space at the slope toe, which may conflict with infrastructure, waterways, or property boundaries.
- **Drainage Requirements**: Incorporating drainage elements within or behind the buttress may be necessary to manage groundwater or pore pressures, particularly if the slope is known to have seepage issues.
- **Seismic and Long-term Performance**: The geometry and mass of a toe buttress must be designed to withstand not just static loads but potential seismic forces and long-term degradation (e.g., internal erosion or weathering of fill materials).

Overall, earthworks solutions must be tailored to the site context, informed by ground investigation, slope modelling, and construction feasibility assessments. These interventions are often integrated with other stabilisation measures (e.g., drainage, reinforcement) to achieve long-term performance and resilience.

6.1.3.5 Example Applications

A specific example in the literature was presented by Orgias, Tate, and Pranjoto (2017) at the NZGS Symposium in 2017, *ANZAC Cliffs –Geotechnical aspects of cliff stabilisation works.* The problem associated with the above example is as follows.

Active, periodic toe erosion has created an over-steep cliff face of gravel / sand deposits that is actively regressing (FoS < 1.0).

To improve the stability, the selected remedial treatment is management of the river channel to prevent toe erosion and buttressing of the over-steep exposed cliff face with engineered fill material placed at a stable angle of repose.

6.1.4 Retention Systems

6.1.4.1 Description

Retention systems stabilise slopes by directly resisting the lateral earth pressures associated with the instability mechanisms through structural support. These systems are typically used on steeper slopes or in areas with limited space. Key types of retention systems include:

- **Cantilever/Soldier Pile Walls:** Cantilever walls are vertical walls that resist lateral loads through the cantilever action of an embedded length in the ground (e.g., sheet piles). Soldier pile walls act in a similar manner but typically rely on the embedment of individual vertical piles (e.g., timber, concrete, or steel piles), installed at a uniform distance apart, with lagging (timber, concrete, or steel lagging) spanning between them.
- **Gravity Walls:** Gravity walls rely on their own weight to resist lateral earth pressures. These are typically constructed from pre-cast concrete blocks or rock-filled gabion baskets. They can be used as a toe-buttress to support an active landslide and are usually tapered to be wider at the base to improve overturning and sliding resistance.
- **Anchored/Tie-Back Walls:** Anchored walls are similar in concept to cantilever/soldier pile walls, with the provision of additional support by tie-back rods attached to deadman anchors or anchorages drilled and grouted into stable soil/rock to control deflections and reduce demand loads in the wall section.

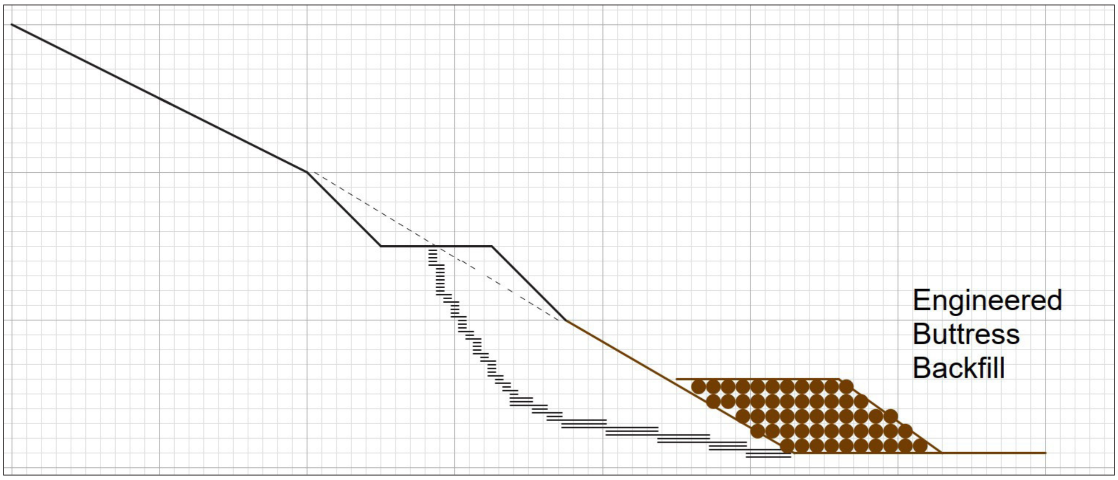


Figure 6.5. Buttress fill slope stabilisation example (generalised schematic representation)

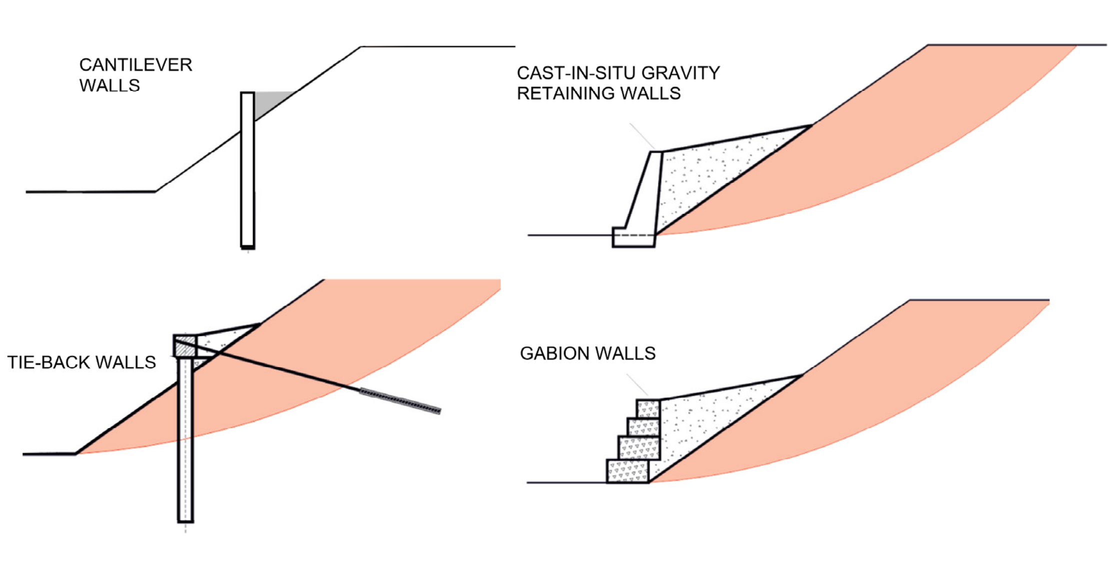


Figure 6.6. Common retention systems (Adapted from Mihalić Arbanas and Arbanas, 2015)

Guidance documents relevant to the design and application of retention systems include:

- **MBIE & NZGS *Earthquake Geotechnical Engineering Practice, Module 6: Earthquake Resistant Retaining Wall Design* (2021):** Retaining wall solutions for landslip stabilisation should be designed according to these guidelines and are often subject to design checks using proprietary slope stability analyses
- **NZTA Highway Structures Design Guide (2016)** outlines general and specific requirements for state highway structures, including design guidance for a wide range of retaining walls.
- **NZTA Bridge Manual (2022)** includes design requirements for bridge abutments and retaining structures. It addresses geotechnical, structural, and seismic aspects of embedded and gravity walls.

6.1.4.2 Intended Use and Benefits

Retention systems are typically used when passive or non-structural slope stabilisation measures are infeasible or insufficient. Their key intended uses and benefits are summarised in Table 6.5.

Table 6.5. Intended use and benefits of retention systems

Retention Systems	Intended Use	Key Benefits
Cantilever/ Soldier Pile Walls	Used in temporary or permanent earth retention where excavation or slope reshaping is not possible, such as tight urban sites, unstable cut slopes, or post-landslide stabilisation.	Moderate cost, relatively quick to install, adaptable to various soil conditions, minimal site footprint.
Gravity Walls	Suitable for sites with available space at the toe; ideal for shallow to moderate slope heights or when aesthetics or simplicity of construction are important.	Simple construction, no deep excavation required, inherently stable due to self-weight.
Anchored/ Tie-Back Walls	Effective for tall cuts, high loads, or when deflection control is critical. Common in deep excavations, landslide scarps, or when working above infrastructure.	Allows retention of high walls with minimal front-face footprint; significantly reduces structural demands on the wall.

6.1.4.3 Effective Application

The following table summarises the effective application of retention systems for soil slope stabilisation.

Table 6.6. Effective application of retention systems

Retention Systems	Effective Application
Cantilever/ Soldier Pile Walls	These walls are often used for temporary or permanent earth retention in urban construction/slope stabilisation projects where space constraints prevent slope reshaping, a landslide event has left an unsupported/unsafe slope or evacuated land has to be reinstated.
Gravity Walls	Gravity walls are commonly used for retaining moderate slope heights, especially in locations where there is sufficient space at the slope's toe for construction. They are suitable for applications where large retaining structures are needed, and where the wall's mass can be effectively utilised to resist earth pressure.
Anchored/ Tie-Back Walls	Anchored walls are typically used in scenarios with larger retained heights and higher earth pressures, or when space constraints prevent the use of cantilever or gravity walls. They are also employed in areas where the soil conditions or slope geometry make alternative wall systems impractical.

6.1.4.4 Considerations and Limitations

Each retention system has design limitations, suitability constraints, and site-specific considerations that must be evaluated during planning and design. The key considerations and limitations for each retention system are outlined below.

Cantilever/Soldier Pile Walls

When designing cantilever and soldier pile walls, several key factors must be taken into account to ensure the wall's stability and effectiveness in retaining the slope. These considerations focus on the structural integrity of the wall, the interaction between the soil and the piles, and the management of water pressure behind the wall. The following are essential aspects to consider during the design process:

- **Embedment Depth:** Ensuring adequate embedment of the wall to resist overturning and sliding forces that may occur due to lateral earth pressures.
- **Soil-Pile Interaction:** The characteristics of the soil surrounding the piles must be well understood. A proper assessment is needed to avoid excessive deflection, which could compromise the wall's structural integrity. The soil's stiffness, cohesion, and frictional properties will affect how the wall behaves under load.
- **Drainage:** Incorporating an effective drainage system behind the wall is critical to prevent the buildup of hydrostatic pressure. Water accumulation can weaken the wall and lead to failure. Proper drainage ensures that water is safely directed away from the wall, maintaining stability over time.
- **Cantilever walls are relatively economical** compared to other retention systems making them a popular choice for many applications. However, they may not be suitable for very high walls due to the demand loads generated by the cantilever action and associated deflection concerns. In such circumstances, anchored / tie-back walls should be considered as an alternative to provide additional stability and reduce deflection.

Gravity Walls

Several factors must be considered in the design of gravity walls to ensure their effectiveness and stability:

- **Wall Weight:** The wall's weight must be sufficient to counteract the lateral forces acting on it. The weight of the wall is the primary mechanism for resisting earth pressure, so it is crucial that the materials used provide adequate mass.
- **Base Width and Stability:** An adequate base width is essential to prevent sliding and overturning. A wider base enhances the stability of the wall, particularly in resisting the lateral forces acting on it.
- **Drainage:** Proper drainage must be incorporated to reduce hydrostatic pressure behind or beneath the wall. Weep holes or drainage systems can be used to direct water away from the wall, ensuring that water does not accumulate, which could weaken the wall's foundation and reduce its effectiveness.
- **Gravity walls are relatively simple to construct**, making them an attractive option for many projects. However, they require large quantities of heavy materials, which can make them less suitable for constrained or difficult-access sites. Additionally, their size and weight can make transportation and handling challenging in some locations.

Anchored/Tie-Back Walls

Several critical factors must be considered when designing anchored or tie-back walls to ensure their effectiveness and safety:

- **Embedment Depth:** The wall must be adequately embedded to generate passive restraint and prevent toe failure.
- **Tie-back spacing, length and deadman:** The spacing and length of the tiebacks, as well as the configuration of the deadman anchors, must be carefully designed to avoid any active wedge or landslide mechanism. The deadman should be placed such that it generates adequate passive restraint to support the wall.

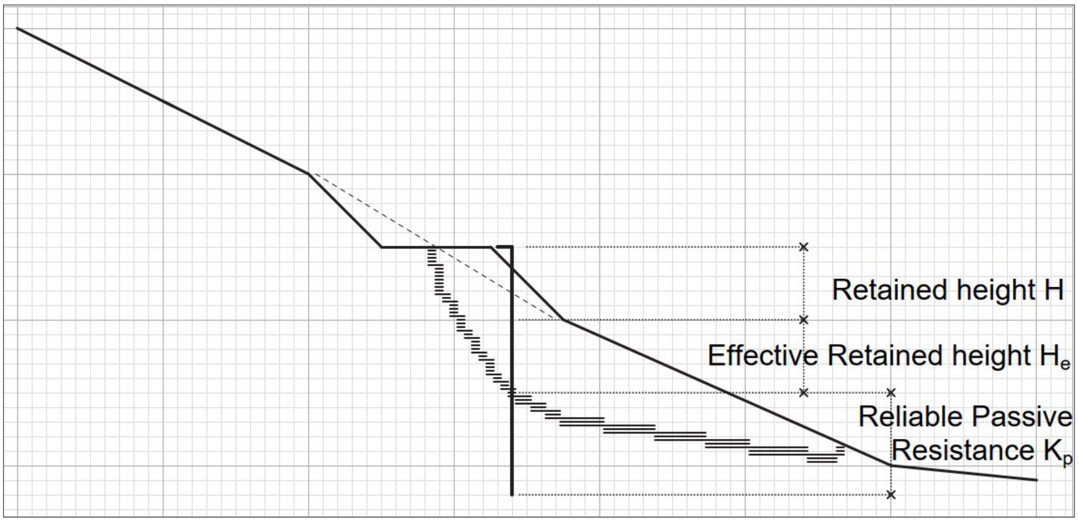


Figure 6.7. Schematic retaining wall solution to stabilise an active underslip showing design criteria

- **Anchorage Spacing, Length and Angle:** Anchorages should be long enough and set at an optimal angle to provide maximum effectiveness. They must be positioned beyond the active wedge or landslide mechanism to ensure long-term stability.
- **Anchorage Capacity:** The pull-out capacity and long-term performance of the anchorages should be assessed based on the soil or rock conditions. This ensures the anchors can withstand the forces over time without failure.
- **Corrosion Protection:** Steel anchorages must be protected from corrosion, especially in aggressive soil, water, or coastal environments. This may require sheathing, coatings or sacrificial anodes to ensure the anchors' durability.
- **Anchored walls provide a high-capacity, efficient structural solution** for retaining large heights and stabilising unstable ground. They are particularly useful in challenging conditions where other types of walls are not feasible. However, the installation process can be complex and costly, particularly in hard rock or deep soil layers, which may require advanced drilling and grouting techniques.

6.1.4.5 Example Applications

Retention systems are commonly used to stabilise existing or activated landslide mechanisms on NZ roads and highways. Following the cyclone events in February 2022, many local underslips were effectively treated and stabilised by retention systems.

Figure 6.7 illustrates a typical stability issue remediated using a retaining wall solution, which relies on the embedded wall being founded below the "active" slip mechanism in stable "passive" ground.

The challenge in designing retaining walls following MBIE guidelines in Module 6 is determining the effective retained height (He) and the passive earth pressure coefficient (K_p) for the embedded length within the "active" slip mechanism. For active landslides (FoS < 1.0), the depth at which the active mechanism intercepts the embedded wall supports should be considered the effective design retained height, as the active mechanism will move away from the wall over the structure's design life, creating a tension crack with no passive resistance.

When checking or reviewing retaining wall stabilisation solutions using limit equilibrium (LE) slope stability analysis techniques, the design and analysis principles are similar to those for rigid inclusions/piles.

Figure 6.8. SH23, Remutaka Hill Underslip Repair (Source: NZTA Waka Kotahi, November 2024)

6.1.5 Slope Reinforcement Techniques

6.1.5.1 Description

Slope reinforcement techniques aim to improve stability by introducing structural elements that enhance the shear resistance of slope materials and restrict slope movement. These methods are useful for slopes where large-scale earthworks or large retention structures are impractical due to space constraints, difficult terrain, or environmental considerations.

Tow common reinforcement techniques are discussed in the following subsections.

Soil Nails

Soil nails are passive reinforcement elements typically consisting of steel reinforcing bars inserted into pre-drilled holes in the slope and grouted in place. The nails act in tension to stabilise the slope by binding potentially unstable ground to more stable material behind the failure surface. Alternative soil nail materials include Glass Fibre Reinforced Plastic (GFRP) bars, circular hollow steel sections, duck-bill/platypus anchors, and screw piles. Whilst soil nails are typically drilled and grouted in place, they can be launched/driven into the ground – a method commonly referred to as ballistic or shot-fired soil nails.

Rigid Inclusions/Piles

In-ground piles or rigid inclusions (sometimes referred to as palisade walls) are drilled into the ground at discrete spacings to provide reinforcement by intercepting shear zones/active shear surfaces and transferring loads from mobilised, unstable near-surface soil/rock to deeper, stable layers. Pile types are commonly continuous flight auger piles, cased and cast-in-place reinforced concrete piles, drilled and cast-in-place columns (steel or timber), and reinforced or unreinforced soil/cement columns (deep soil mixing technology).

6.1.5.2 Intended Use and Benefits

This subsection summarises the typical applications and main advantages of each slope reinforcement technique in various geotechnical scenarios.

Table 6.7. Intended use and benefits of soil reinforcement techniques

Soil Reinforcement Technique	Intended Use and Benefits
Soil nails	• Provide stabilisation for steep or near-vertical cuttings and slopes. • Minimal excavation required, preserving existing ground and vegetation. • Rapid installation, particularly suitable for constrained or difficult-access sites. • Can be combined with facing systems (e.g., mesh, shotcrete, vegetation) for surface protection and erosion control.
Rigid Inclusions/ Piles	• Enable deep stabilisation by anchoring unstable ground to stable substrata. • High load-carrying capacity allows use on large, active, or complex landslides. • Applicable to both natural and engineered slopes. • Can be designed to resist lateral and vertical loads.

6.1.5.3 Effective Application

This subsection identifies the conditions under which soil reinforcement techniques are most effectively applied, considering slope geometry, soil conditions, and stability requirements.

Table 6.8. Effective application of soil reinforcement techniques

Soil Reinforcement Technique	Effective Application
Soil nails	Soil nails are particularly suited for stabilising high and/or steep slopes or cuttings. They are often used in situations where access is limited and space is constrained, making other forms of retention impractical.
Rigid Inclusions/Piles	Rigid inclusions or piles are typically used on slopes where weak surface layers, that may extend to some depth, overlay competent soil or rock. These systems are employed when the demand loads from potential, or active, landslide mechanisms require mobilisation of significant stabilising forces to prevent further movement and maintain slope stability.

6.1.5.4 Considerations and Limitations

This subsection discusses critical design considerations and limitations associated with each reinforcement technique to guide appropriate selection and implementation.

Soil Nails

When designing a soil nail system, the following factors must be taken into account to ensure its effectiveness:

- **Nail Size, Spacing, Installation Angle and Length:** The spacing and length of the soil nails should be optimised to provide effective reinforcement and slope stabilisation. The angle of installation also plays a significant role in maximising the nails' effectiveness.
- **Face stability/treatment:** It is important to assess the local stability of the shallow slope surface between soil nails. Additionally, surface treatments should be considered, such as bio-engineered matting, shotcrete, steel mesh, geogrid, or geotextile, to improve the surface's stability.
- **Effective stabilising contribution:** The design should consider the effective stabilising contribution of the soil nails, taking into account the assumed or potential instability mechanism of the slope.
- **Bond Strength:** It is essential to verify the design bond capacity per unit length of the soil nail that can be reliably mobilised throughout the design life of the nail.
- **Corrosion Protection:** The durability of the soil nail components should be confirmed, ensuring that they are protected from corrosion and capable of withstanding environmental conditions for the entire design life of the reinforcement.
- **Soil nails offer a cost-effective and relatively quick solution** for slope stabilisation. They are easy to install with minimal disruption, often requiring only lightweight equipment. However, the effective depth of treatment may be a limitation in certain situations, especially for very deep or large slopes.

Rigid Inclusions/Piles

The following are several factors that must be taken into account when designing rigid inclusions or piles:

- **Pile Diameter, Spacing and Length:** Pile characteristics such as the size, length, and spacing of the piles should be selected to meet the demand loads imposed by the active or potentially unstable mechanisms and efficiently distribute those loads.
- **Soil Structure Interaction:** Ensuring adequate connectivity between the pile and the surrounding ground is critical. This interaction helps mobilise the effective stabilising contribution of the pile, allowing it to transfer loads effectively to deeper stable layers.
- **Effective stabilising contribution:** Resolving the effective stabilising contribution that can be relied upon from the pile for any assumed or potential instability mechanism.
- **Connection to Slope:** Pile caps and/or tie beams are used to connect the piles for uniform load distribution.
- **Rigid inclusions/piles are highly effective in cases requiring deep slope stabilisation**, as they can transfer significant loads to deeper, more stable ground layers. However, installation can be challenging and costly, particularly for long or large piles. Additionally, cast-in-place piles are vulnerable while still "green" (not fully hardened) when formed in an active landslide mechanism, which can compromise their integrity before they are fully set.

6.1.5.5 Example Applications

This subsection provides examples of real-world applications where slope reinforcement techniques have been successfully implemented to mitigate slope instability.

Soil Nails

Soil nailing has been reliably applied to the stabilisation of slopes for many years. The soil nail system relies on the interaction between the relatively closely spaced soil nail inclusions and the surrounding, potentially unstable ground to effectively maintain the mass stability of the slope.

Figure 6.9. Soil nail stabilisation works at Brynderwyn Hills, SH1 Northland

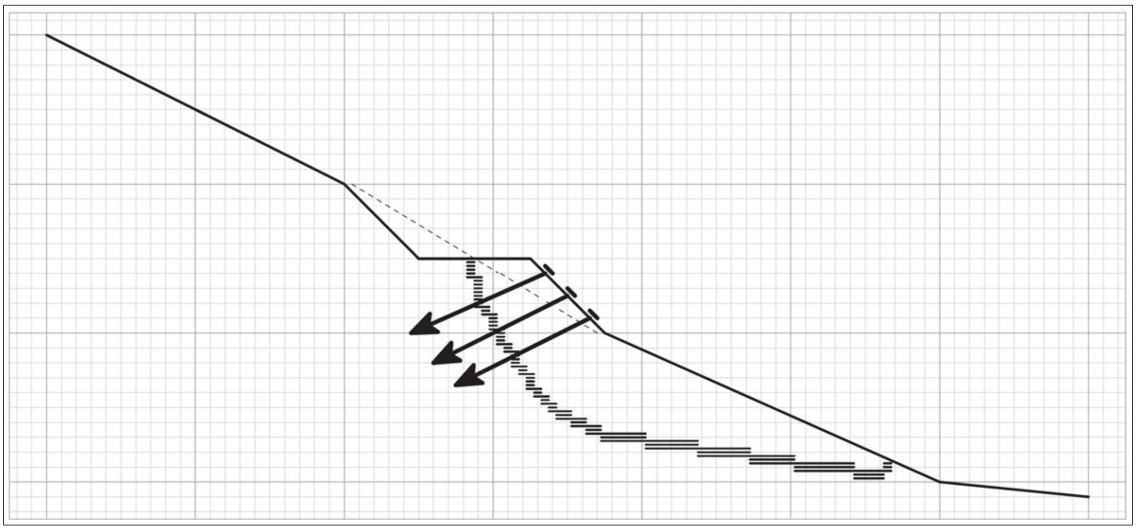


Figure 6.10. Limit equilibrium stability model incorporating soil nails

A typical schematic section of a soil nail stabilisation system is depicted in Figure 6.10.

A comprehensive summary of the design approach for soil nailing was prepared by the Transport Research Laboratory (TRL) in 2002. The TRL Report 537, *Soil Nailing for Slopes* (Johnson, Card, and Darley, 2002), remains a fundamental guideline on the principles and design assumptions that should be followed in practice.

However, it is recognised that in New Zealand a common approach for the geotechnical design of soil nail systems for the stabilisation of an active landslip, or to improve the stability of a marginal slope, will rely on proprietary limit equilibrium stability software packages that permit the incorporation of soil nail reinforcement within the stability model.

Before using such software, it is recommended that designers be familiar with the design principles set out in documents like TRL Report 537 and understand how the designer-specified input parameters will be applied in the software models and how the contribution of the nails to the stability of the slope will be determined by the software.

Typically, the characteristic properties of the soil nail specified by the designer will be:

- Horizontal and vertical spacing
- Ultimate tensile capacity of the nail
- Soil nail grout/ground design bond strength per unit length
- Shear resistance of the nail
- Plate capacity

While some software packages permit the inclusion of the nail shear capacity in the design parameter inputs for the nail, it is generally accepted that the axial resistance of the nail inclusion is the major component in maintaining the stability of a soil-nailed slope.

The contribution from bending stiffness and shear of the nail is small unless significant deformation has occurred, and the nail bond strength is fully mobilised. Any beneficial effects arising from the bending stiffness and shear capacity of the nail section are therefore considered a "post-serviceability" phenomenon and should not be relied upon in design.

Soil nail slope stabilisation design analysis using Limit Equilibrium (LE) stability modeling software provides a reliable determination of the stabilising contribution of the specified and distributed soil nails in the slope. However, it primarily addresses the soil nail failure mode associated with the extrusion of the embedded nails from the stable ground beyond a postulated instability mechanism.

The designer is also required to check that the soil nail spacing (both vertically and horizontally), the soil nail anchor plate at the surface, and any slope face treatment (geogrid, mesh, unreinforced, reinforced, or fibre-reinforced shotcrete) has the necessary system design capacity to ensure the postulated instability mechanism acts as an intact "free body" and does not simply pull away from the fixed/embedded soil nails - commonly referred to as a "stripping" failure mode.

There are proprietary software stability models that purport to consider the soil nail failure mode associated with stripping, but their reliability is fundamentally driven by the designer's appreciation of the requested input parameters for what is commonly referred to as "plate capacity".

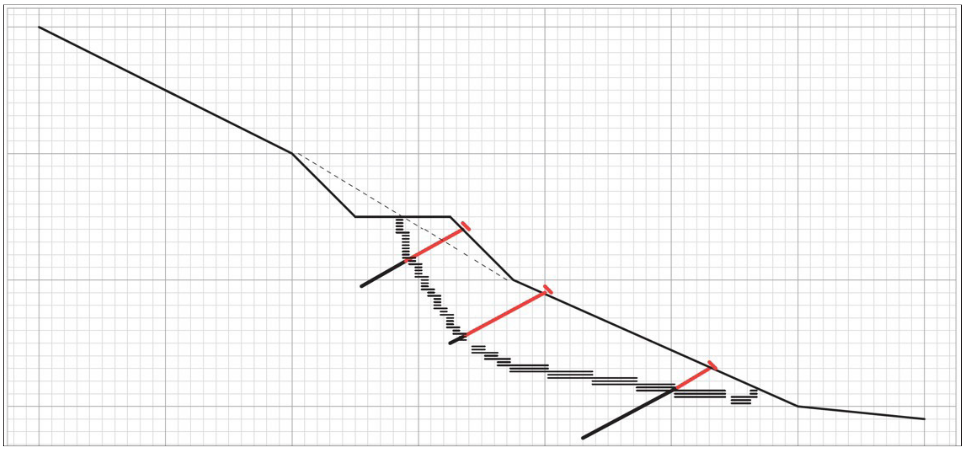


Figure 6.11. Soil nail "pull-out" capacity vs. "stripping" capacity

The designer must consider how the value for "plate capacity" will be applied, whether the specified value is representative of the proposed hardware (nail head & facing detail) to be installed, and whether the assumed value can be reliably mobilised at the proposed spacing to resist the sliding land mass from extruding (stripping) around the soil nails.

By inspection, the contribution of the lowest soil nail to the overall stability of the postulated mechanism will be governed by the near surface "stripping" capacity of the nail (shown in red) as this is likely to be significantly less than the "pull-out" capacity (shown in black). Conversely, for the middle soil nail, the contribution to overall stability will likely be limited by a small "pull-out" capacity given the relatively short length projecting beyond the postulated instability mechanism. For the topsoil nail, the contribution to overall stability may be limited by either the "pull-out" or "stripping" capacity.

It is therefore strongly recommended that where the designer has relied upon the use of proprietary software for the design of a soil nail stabilised slope, a rigorous independent review of the critical mechanisms and the assumed contribution to stability from the specified soil nails within the analysis is undertaken.

Rigid Inclusions/Piles

A typical schematic of a rigid inclusion stabilisation system is shown in Figure 6.12.

For geotechnical design of Rigid Inclusions/Piles for landslide mitigation, it is crucial to understand how stability analyses apply the "shear contribution" property where the inclusion intercepts any theoretical instability mechanism.

Limit Equilibrium (LE) stability analysis algorithms estimate the available shearing resistance on any postulated slip mechanism surface and compare it to the resolved disturbing gravity forces.

The Factor of Safety (FoS) is determined by calculating moments around the centre of rotation. Where rigid inclusions are introduced to the system, Designers face the challenge of selecting a "shear" contribution for the structural element intercepting the postulated mechanism.

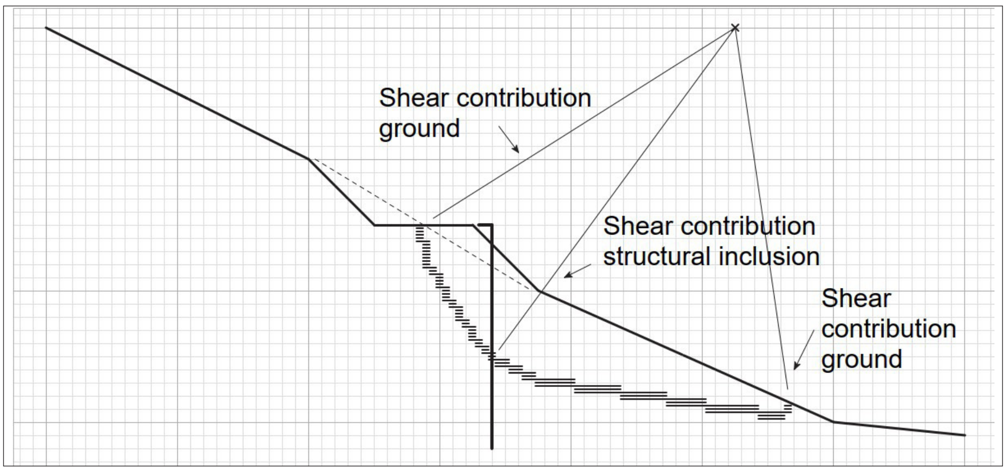


Figure 6.12. Limit equilibrium stability model with a rigid inclusion or retaining wall

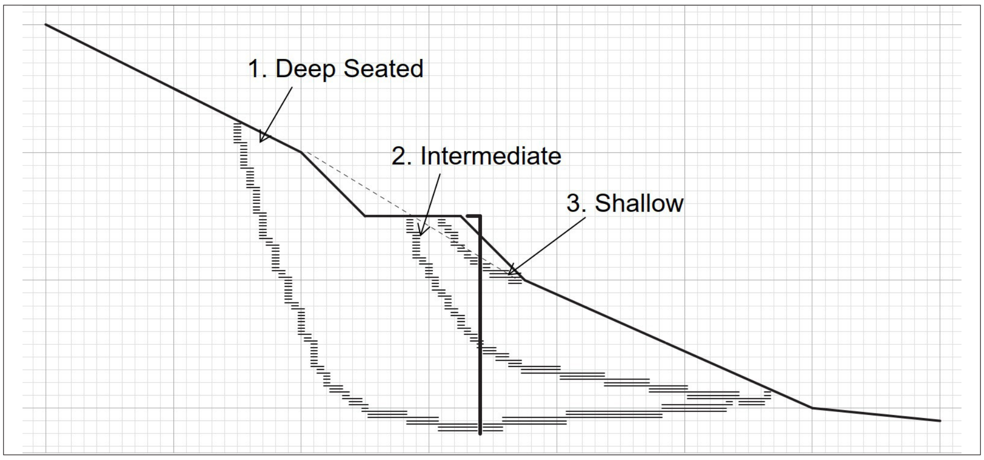


Figure 6.13. Variable "shear" stabilising contribution to critical mechanisms

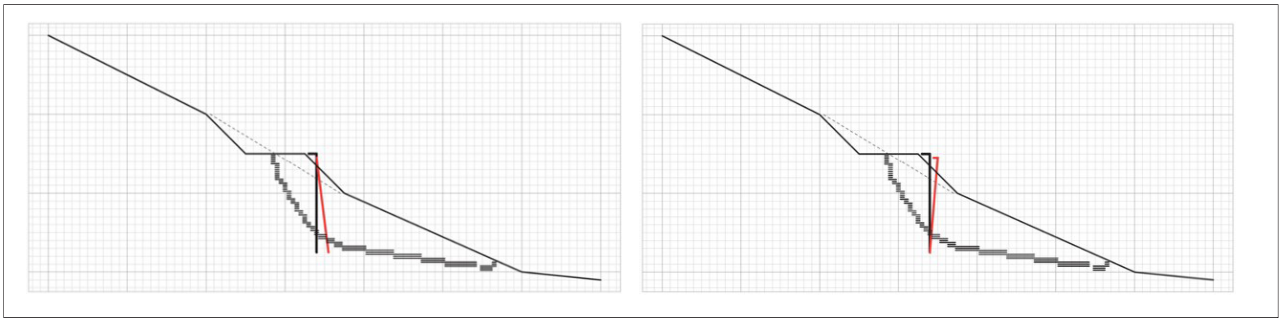


Figure 6.14. Rotation mechanism (toe failure)

Most proprietary software packages allow incorporating a shear resistance value for the structural element, but this value is applied uniformly across all postulated mechanisms.

The shear contribution of the structural element varies significantly depending on where the mechanism intercepts the inclusion.

The soil/structure interaction at the intercept location governs the mobilised shear contribution. Applying a constant shear contribution across all mechanisms is flawed.

A geotechnical design approach should consider how any postulated sliding mechanism impacts the structural element and what resistance the element can mobilise to improve stability.

For "short" stiff inclusions (embedded less than 3-5D below the shear surface intercept), the geotechnical capacity of the embedded inclusion below the postulated slip mechanism limits the shear contribution.

If the toe of the inclusion is at, or near, the intercept the minimum capacity (t) is the shear resistance between the inclusion base and the ground. For postulated slip mechanisms intercepting above the toe of the inclusion, additional passive earth pressure forces (s) resist failure.

If t < s, then "t" is the maximum shear contribution, and left figure in Figure 6.14 is the likely failure mode.

Where s > t, the right figure in Figure 6.14 is the likely failure mode, with the shear capacity being the passive resistance of the socket (s).

For "long" stiff inclusions (embedded > 5D below the shear surface intercept), failure modes are governed by the structural limits of the inclusion.

The embedded inclusion is "fully fixed" in competent ground and the passive socket capacity is significantly greater than the structural shear and/or bending moment capacity of the inclusion. In these circumstances, failure modes described in Figure 6.14 are not feasible.

Whether the failure mode represented by Figure 6.15 eventuates depends on the structural characteristics of the inclusion (timber, steel, reinforced concrete) and, as previously noted, the applied load by the ground varies with the depth of the stability mechanism and the inclusion's position on the critical section.

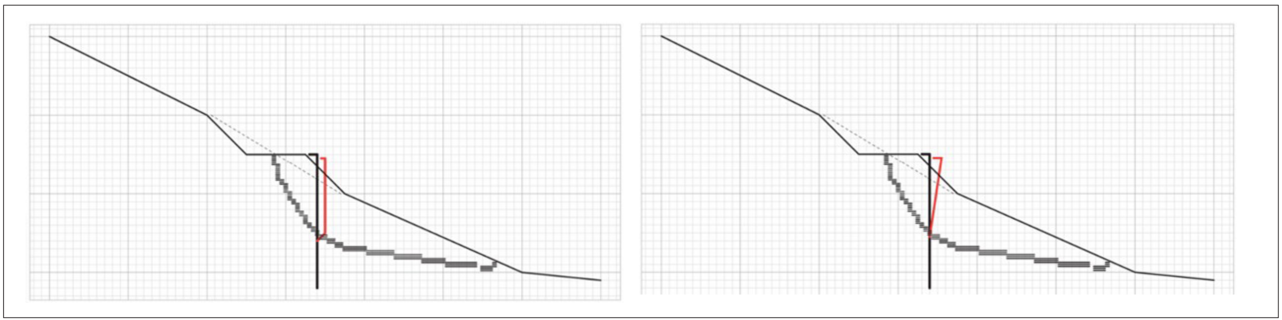


Figure 6.15. Structural shear and bending failure

Designers must identify the maximum reliable shear capacity contribution of the inclusion based on the expected failure mode for each postulated instability mechanism and apply that value in the stability model to establish the system's margin of safety.

Assessment Process:

- Establish the critical stability mechanism with the lowest margin of safety requiring stabilisation.
- Identify a desirable location on the critical stability mechanism for the stabilising inclusion.
- Determine the maximum reliable shear capacity contribution of the inclusion at the proposed location.
- Repeat the stability analysis to confirm the inclusion improves stability.
- Check the proposed inclusion location maintains acceptable safety margins for other potential instability mechanisms, recognising the shear capacity contribution varies with intercept position.

6.1.6 Ground Improvement Techniques

6.1.6.1 Description

Ground improvement techniques enhance the properties of in situ soils and are usually installed with the objective of increasing shear strength of a specific weak/vulnerable formation to prevent slope failure. Some of the ground improvement techniques are discussed in the following subsections.

- **Shear Keys:** Shear keys can be considered as a sub-set of conventional earthworks solutions as they are typically trenched excavations backfilled with compacted granular material and installed to intercept/replace a vulnerable layer perpendicular to a potential sliding/shear surface to improve stability.
- **Stone Columns:** Stone columns are discrete vertical columns of compacted gravel or crushed stone, installed to intercept a vulnerable layer or potential sliding/shear surface to improve stability and potentially drainage.
- **Deep Soil Mixing:** Deep soil mixing (DSM) involves the mechanically blending of in situ soils with cement or other stabilising agents (e.g. lime or pulverised fuel ash (PFA)) to increase strength and reduce compressibility.
- **Grouting:** Grouting involves injecting cementitious or chemical grouts into the soil to fill voids, increase density, and improve cohesion. Can be considered similar in principle to piles / rigid inclusions and deep soil mixing techniques.

6.1.6.2 Intended Use and Benefits

This subsection outlines the primary objectives and key benefits of each ground improvement technique, highlighting their contributions to enhancing slope stability.

6.1.6.3 Effective Application

This subsection summarises the typical ground and slope conditions under which each ground improvement technique is most effectively applied.

Table 6.9. Effective application of ground improvement techniques

Soil Reinforcement Technique	Effective Application
Shear Keys	Shear keys can be used for slopes with a defined and readily identifiable and accessible failure plane or weak shear zone, particularly in landslide-prone areas.
Stone Columns	Stone columns are suitable for slopes underlain by soft, compressible soils or slopes in sheared/slickensided formations with multiple, low-strength shear surfaces and elevated groundwater levels.
Deep Soil Mixing	DSM is generally used in soft clay or peat formations supporting slopes or embankments where soil improvement is necessary for enhanced stability.
Grouting	Grouting is generally considered a potentially suitable mitigation strategy for stabilising fractured rock, sandy soils, or highly permeable areas with significant water flow.

6.1.6.4 Considerations and Limitations

This subsection discusses key design considerations and known limitations associated with each ground improvement method to support appropriate selection and design.

Shear Keys

The effectiveness of a shear key depends on appropriate siting, geometry, and construction quality. Key considerations include:

- **Location and Size:** Shear keys must be founded in stable soil and of sufficient size (width and depth) to counteract sliding forces without being "by-passed".
- **Compaction:** The shear key backfill material must be thoroughly compacted to maximise capacity/resistance.
- **Shear keys are a simple and effective method for reducing slip potential**, but they may not be suitable for deep-seated failures or very soft soils with a high water table, where deep excavation and replacement are not practicable.

Stone Columns

The performance of stone columns depends on their layout, dimensions, and interaction with the surrounding soil. Key factors include:

- **Column Spacing, diameter, and depth:** These parameters should be determined based on the required load support by way of improved shearing resistance through the stone column relative to the intercepted weak/vulnerable formation.
- **Comparison with shear keys:** Similar in principle to shear keys but stone columns use discrete inclusions instead of mass excavation.
- **Drainage:** Stone columns may also function as vertical drains, helping to dissipate pore pressures within the slope.
- **Stone columns are an effective alternate to mass excavated shear keys** for both ground improvement and drainage. However, they are best suited to soils where the installation process – which often introduces additional water and significant ground vibration to an unstable/vulnerable formation - does not cause excessive disturbance and trigger ground displacements.

Deep Soil Mixing (DSM)

The effectiveness of DSM depends on the mixing quality, geometry, and interaction with the native soil. Key considerations include:

- **Mixing Depth and Pattern:** The depth and spatial arrangements of DSM columns should be designed to achieve adequate reinforcement and a sufficient replacement ratio to achieve "monolithic" improvement/strength gain.
- **Binder Type and Quantity:** Choosing an appropriate binder should be based on the soil properties and the required design strength.
- **Durability/Strain Compatibility:** Shear, bending, and the potential for crack propagation should be considered when assessing long-term performance, particularly where DSM elements are exposed to creeping or slow-moving landslide mechanisms. While DSM can be considered similar in principle to the stabilising systems described above—as stiff, vertical inclusions—it typically has lower structural capacity in shear and bending compared to other more commonly adopted inclusion methods.
- **DSM is highly effective for stabilising deep, soft soils** but requires specialised equipment and can be associated with high construction costs.

Grouting

The success of grouting depends on selecting appropriate materials and application methods. Key considerations include:

- **Grout Type:** Selection of the appropriate grout material (cement, chemical, etc.) should be based on soil type, permeability, and groundwater conditions.
- **Injection Pressure and Pattern:** The injection method and pressure should be carefully selected to avoid soil heaving or hydraulic fracturing.
- **Effective stabilising contribution:** The improvement in shear resistance provided by the grouted ground should be evaluated to determine the effective stabilising contribution (improved shearing resistance) that can be relied upon from the treated ground for any assumed or potential instability mechanism.
- **Grouting is effective for targeted stabilisation and water control**. However, the degree of improvement is often difficult to measure/quantify, and treatment success can vary. It can also be costly and requires precise application to avoid unwanted soil disturbances.

6.1.6.5 Example Applications

This subsection highlights practical examples of ground improvement techniques used in slope stabilisation to illustrate their field application and performance.

Shear Key

Shear key slope stabilisation examples are commonly found on significant subdivision earthworks projects where large volumes of earthmoving and significant modification of marginal natural slopes is required to form building platforms and sections. A typical example is described below in Figure 6.16.

The problem statement associated with the above example was likely to be a concern associated with the risk of long-term soil creep or a slow-moving, large-scale land instability on a pre-existing weak bedding layer.

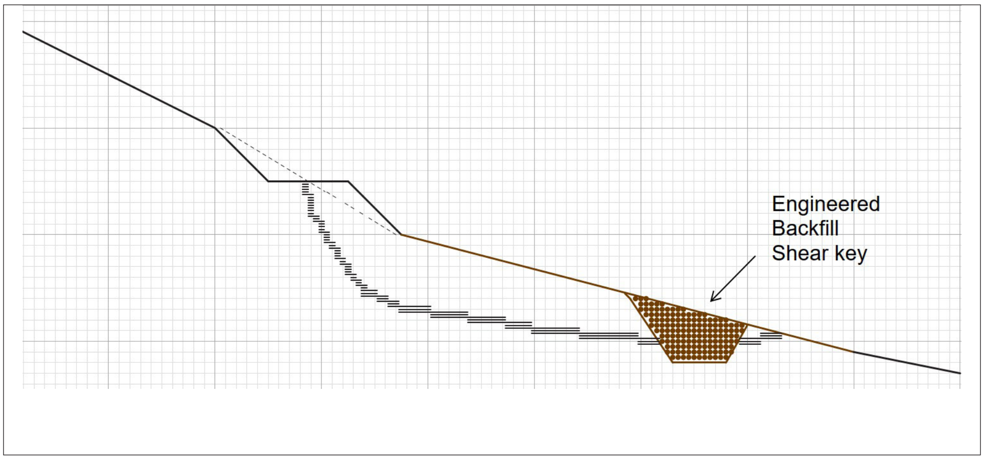


Figure 6.16. Typical shear key ground improvement for stability

The proposed solution adopted was excavation and replacement of a proportion of the weak/ vulnerable strata with an Engineered Fill of inherently higher shear strength material and, in the case of the lower shear key, the addition of a stiff vertical inclusion for addition ground reinforcement.

6.2 ROCK SLOPES

6.2.1 Introduction

This section provides engineering mitigation solutions for existing or proposed rock slopes (natural and modified), where instability is identified and assessed following surface mapping and ground investigation. The determination of instability and the engineering behaviour of the specific rock, rock mass, and the mechanisms of instability in rock slopes are covered in detail in NZGS Slope Stability Guidance Unit 3.

Rock slopes occur naturally in the landscape or are modified in construction. Natural rock slopes are formed through a series of complex geological and geomorphological processes, including ongoing weathering and erosion until rock slope stability or equilibrium is achieved (although this may change over time due to ongoing weathering and other physical processes). Modified rock slopes are formed by excavation and rely on engineering design to achieve stability.

In general, natural rock slopes tend to be steeper than soil slopes because of the higher intact rock strengths compared to soil strengths. Similarly, the excavation profile in modified rock faces is generally steeper than the excavation profiles in soil slopes. In rock slopes, however, the presence of discontinuities in the form of joints, bedding planes, and faults often dictates the final rock slope profile, and it is necessary to consider the rock mass (intact rock and the discontinuities) when assessing the most suitable engineering mitigation solution.

The slope mitigation measures provided in this section focus on the most common at-source treatments applied to rock slopes to improve stability, including;

- Removal and reprofiling
- Rock mass strengthening
- Drainage improvements

Table 6.10 outlines the above categories of rock slope mitigation along with proposed mitigation measures.

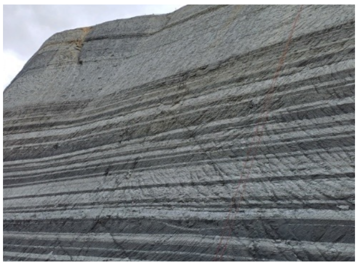
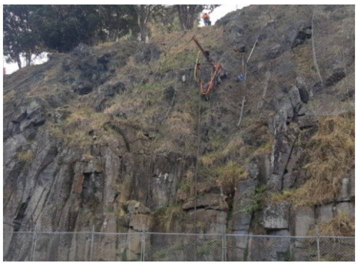
Table 6.10. Mitigation measures for rock slopes

Category of mitigation	Description / Purpose	Type of Mitigation Measures
Rock removal	Complete or partial removal of the source rock to reduce the occurrence of rockfall and instability. This may include modification of the overall slope profile to remove loose material and/or features that can exacerbate rockfall trajectories.	• Scaling (targeted removal) • Light scaling, using hand tools • Heavy scaling, using mechanical tools
		• Reprofiling (large-scale changes in slope shape) • Light reprofiling, using excavators • Heavy reprofiling, using blasting
Rock mass strengthening	Reinforcement to secure source rocks in place and reduce the occurrence of isolated rockfalls.	• Rock dowels, target individual blocks and boulders (passive support)
		• Rock bolts, retention of larger rock blocks or rock mass areas (active support)
	Structural support to secure the source rock and improve the stability of the rock mass.	• Toe buttress, gravity mass support (concrete or mass block) to provide local and global stability improvements
		• Walers and cables supported by rock bolts, to provide additional support to secure larger blocks or boulders
		• Dentition, concrete support to stabilise overhangs and zones of poor-quality rock
	Surface protection targeting the reduction in fretting of smaller rock blocks on weathered surfaces.	• Shotcrete, provides surface cover against erosion and small block dislodgment
		• Anchored mesh, provides surface stabilisation for weathered faces and loose blocks
Drainage	Removal or reduction of surface water and/or groundwater to reduce the destabilising forces. This is commonly used in conjunction with other mitigation techniques.	• Surface drainage, to reduce water overflow over the rock face
		• Subsurface drainage includes weep holes and raking drains, to reduce groundwater flow through the rock mass

The engineering mitigation solutions provided in Table 6.10 can be applied to discrete unstable rock blocks or areas of general instability to improve the overall rock slope stability.

Six examples of New Zealand rock types with natural and engineered slopes, along with possible mitigation measures, are provided in Table 6.11.

Table 6.11. Examples of different typical rock instability issues and the possible mitigation measures

Geology	Example	Description	Possible Mitigation (Depending on Risk Profile)
Miocene sedimentary rocks in North Island (East Coast Bays Formation, Pakiri Formation)		• Interbedded sandstones and siltstones. • Sub-horizontally bedded but can have a complex structure with folds and faults. Joints are closely to widely spaced. • Intact strength ranges from 1 MPa to 20 MPa, more typically, the strength is less than 10 MPa. Weathering to silt and clay.	• Cut slopes can be 60°– 85° with 5 m – 8 m batters. • Local spot bolting may be required where joints lead to the formation of wedges. • Buttresses can be used where undercutting by coastal erosion occurs. • Ongoing frittering reduced by mesh (and shotcrete) or controlled by drape netting and catch ditches.
Miocene sedimentary rocks in Central North Island (Mount Messenger Formation, Tunanui Formation)		• Interbedded sandstones and siltstones. • Sub-horizontally bedded. • Joints are widely spaced. • Intact strength ranges from 1 MPa to 10 MPa. • Weathering to silt and clay. Prone to slaking.	• Cut slopes can be 50°– 70° up to 15 m high. • Local spot bolting may be required where joints lead to the formation of wedges. • Pattern bolting and mesh can be applied to reduce slaking, but providing a catch ditch for containment is often the more cost-efficient solution.
Basalt volcanic rock (Auckland Volcanic Field)		• Basalt lava flows with rubbly basalt, scoria, and ash. • The lava flows can be tens of metres thick with columnar jointing. Intact strength 50 MPa – 150 MPa. • Rubbly basalt and scoria (and ash) can be laterally variable.	• Natural basalt lava slopes are typically 75° – 90°, and scaling of individual blocks with spot bolting is often sufficient for stability. • Rubbly basalt and scoria can be cut to 40° – 60° with mesh, shotcrete providing additional support and erosion protection.
Sedimentary units with volcanic provenance (Piha Formation, Nihotupu Formation)		• Wide range of sedimentary rock, from volcaniclastic siltstone and sandstone to conglomerates.	• Locally steep cut with low batters (less than 5 m) but typically 50° – 70°. • Ongoing frittering and dropouts are controlled by drape netting and catch ditches.
Greywacke throughout the North Island and South Island (Waipapa composite terrain)		• Arenaceous (sandstone) and argillaceous (siltstone and claystone) beds and rock fragments. Complex structure, with closely spaced joints and chaotic fracturing. • Weathering to silt and clay.	• Cut slopes can be 60° - 80° with 5m-10m batters. • Local spot bolting may be required where joints lead to the formation of wedges. • Ongoing frittering is controlled by drape netting and catch ditches.
Basement rocks and metamorphic sequences throughout South Island (Caples and Rakaia terrain)		• Schist grade metamorphic rock, volcaniclastic (Caples) and granitic (Rakaia) provenance, ranging from sandstone to mudstone	• Cut slopes can be 50° - 70° with 5m-10m batters. • Scaling and active maintenance, particularly in colder areas where freeze-thaw occurs, • Spot bolting. Ongoing frittering is controlled by drape netting and catch ditches.

6.2.2 Rock Removal

6.2.2.1 Description

Rock removal is the complete or partial removal of source rock to reduce the occurrence of rockfall and instability. Rock removal may involve the removal of discrete unstable rock blocks or the reprofiling of a rock slope. The scale of removal depends on the size of the hazard, acceptable or tolerable residual risk levels, and the specific geology and discontinuities.

A rock slope with numerous unstable rock blocks with unstable wedges, planar failure surfaces, or toppling failures may require reprofiling. Whereas a predominantly stable rock slope with localised discrete unstable rock blocks or overhangs may only require scaling. The modification of the slope geometry to improve surface water run-off or to remove specific features that may exacerbate rockfall trajectories may also be undertaken. An indication of the rock removal scale is provided in Figure 6.17.

6.2.2.2 Intended Use and Benefits

Rock removal techniques such as scaling and rock slope reprofiling are commonly applied to manage and reduce the risk associated with unstable rock masses. These methods are selected based on the type of instability present, site constraints, and the level of intervention required.

Scaling is typically employed to remove discrete unstable blocks and loose debris from natural or modified slopes. It is often used in locations where full earthworks are impractical, such as remote or urban settings, and is generally undertaken by rope access specialists. This method is suitable for smaller-scale interventions or ongoing maintenance activities. It also includes tasks such as trimming overhangs and reshaping localised rock slope features. Scaling offers several benefits:

- Removes identified hazard,
- No additional materials required,
- Cost-effective and time-efficient for targeted areas,
- Minimal environmental impact, and
- Can be used as an initial mitigation step to reduce risk quickly, and ground-truth assumptions for further engineered controls.

Rock slope reprofiling is used to improve both local and global slope stability by reshaping the slope based on detailed geological and kinematic analysis. This method is often integrated into larger infrastructure or development projects, including roads, quarries, and landfills. Key benefits of reprofiling include:

- The final slope is engineered with a pre-determined factor of safety,
- Outcomes of performance and residual risk are generally better quantified compared to scaling,
- Generally, improves the global and local stability,
- Can be combined with other stabilisation methods for cost efficiency, and
- Cut materials can be used for fill embankments.

6.2.2.3 Effective Application

The effective application of rock removal techniques requires careful assessment of the slope geometry, rock mass condition, instability type, and site-specific constraints. These considerations should be guided by the key factors outlined in Section 4, which provides a framework for selecting appropriate slope mitigation measures.

The effective applications of scaling and rock slope reprofiling are summarised in Table 6.12.

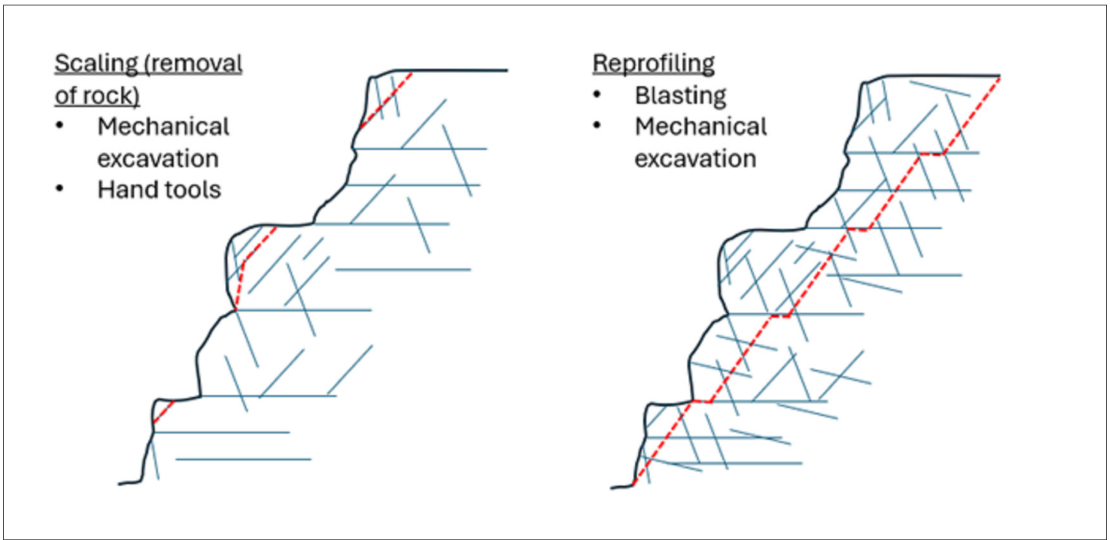


Figure 6.17. Rock removal methods

Table 6.12. Effective applications of scaling and rock slope reprofiling

Type	Application
Scaling	• Removal of discrete unstable blocks and loose materials from natural and modified slopes. • In urban or remote areas often requires rope access specialist contractors. • Tends to be smaller jobs (i.e., not large earthworks). • It may be part of an ongoing maintenance schedule. • Trimming of overhangs and localised reshaping of the rock slope. • Requires targeted mapping and a good understanding of residual risks. • Requires careful management on site by an engineering geologist to determine the appropriate level of scaling to reduce the hazard without negatively impacting the overall stability.
Rock slope reprofiling	• Uses knowledge of the mapped rock mass and kinematic analysis to provide an overall improvement in rock mass stability. • Can be used to provide space for rockfall mitigation (catch ditches). • Can be incorporated into larger civil works to improve local and global stability of the slope. • New developments, such as precincts or linear asset corridors (road, rail, and power) • Generally, included as part of the development of quarries or landfills.

6.2.2.4 Considerations for Scaling

Scaling is often considered a blend of art and science; this is generally due to the numerous uncertainties that are associated with scaling and the care and tact required during implementation. Although scaling to remove loose and unstable rock and weathered rock material (and vegetation) from the rock slope is often beneficial, there are a number of challenges and considerations needed.

Typically, there are two types of scaling as summarised in Table 6.13.

Table 6.13. Types of scaling and associated methods

Type	Methods Employed
Light scaling	• Manually using hand tools such as crowbars, hammers, and wedges. • On steep slopes with poor access, scaling is carried out by rope access specialists, working downslope, removing debris,
Heavy scaling	• Non-manual power tools and techniques including air powered jack hammers, hydraulic breakers, air drills, expanding grouts and small explosives, and hydraulic excavators. • Temporary access may be required to allow machinery and plant to reach the slope. The temporary access may also form part of the long-term design (for benches) or may act as a temporary designated area for rockfall.

HEALTH AND SAFETY DURING ROCK SCALING

Rock scaling presents significant health and safety risks, particularly due to the need for personnel to access areas with elevated geotechnical hazards. Prior to commencing any works, engineers and contractors must ensure that a thorough review of available geological and field investigation data is undertaken to accurately identify potential hazards.

Contractors shall also engage a suitably qualified geotechnical advisor to provide expert input on the identification, assessment, and management of geotechnical risks. This process must include coordination and clear communication of the identified hazards, assessed risks, and any temporary risk controls to all relevant parties involved in the scaling operations.

The key design considerations for rock scaling (light and heavy) include:

- **Clear Identification of the Rock Material to be Removed:** This can be achieved by geological mapping and marking of the rock blocks to be removed with hi-vis paint (or similar) and maintaining full-time supervision to ensure that there is no excessive removal of rock. If scaling is included as part of a drawing set, an annotated photograph is often more beneficial than aerial imagery and plan views.
- **Selecting a Suitable Scaling Methodology:** The scaling methodology will be dependent on the material type, volume of removal, and access. Conditions encountered during initial works may differ from those anticipated, requiring adaptation of the methodology during construction. There are numerous tools and methodologies available to the designer, and consulting a specialist contractor during the early stages of design is advised.

- **Removal of Rock Debris or Scaled Material from Slope:** The removal of scaled rock from the slope will be restricted by access, location, and safety requirements. Rock slope scaling will require careful control for the removal of rock from the slope in a safe manner, especially for large quantities of rock. Lowering and/or guided release down the slope requires the use of a specialist contractor and a clear and concise specification. Some options for the removal of rock from the rock slope after scaling include:
  - Scaled into wire mesh bags, which can be lowered down the slope for later removal, and
  - Allowing rocks to fall in a controlled manner using draped mesh and /or catch areas with or without additional rock protection barrier fences.

  In some areas, it may be acceptable to allow the scaled rock to be left in place downslope, although over stockpiling loose rock may lead to further instability requiring management.
- **Suitably Qualified Personnel**: Occasionally scaling is viewed as a low-cost, 'quick fix' management tool that requires low skill levels and little supervision; this assumption is flawed. Poorly executed scaling works can result in over-scaling (over-excavation), escalating costs, and increasing the risk to the construction team and downslope users. A suitably qualified Engineering Geologist who is sufficiently experienced to make decisions during construction shall be involved in the development and execution of scaling works. In addition, the use of a specialist rope access contractor qualified with the relevant safety standards, such as IRATA (Industrial Rope Access Trade Association), is imperative.

6.2.2.5 Considerations for Rock Slope Reprofiling

Reprofiling a rock slope requires large-scale removal of rock (and surficial soil) to form a new slope profile, often for larger and/or new infrastructure projects, but can be applied to existing infrastructure where significant rock fall risk requires remediation. This often includes a bench and batter profile with mid-slope access for maintenance, rock catch, and drainage. The benches can also be vegetated for aesthetic purposes.

Reprofiling can also be combined with rock stabilisation measures and rock fall catch measures to reduce the amount of excavation and limit the excavation footprint, where boundary restrictions exist.

The key design considerations for rock slope reprofiling include:

- **Final Slope Profile:** The final slope design (for civil works) should have a Factor of Safety (FoS) to meet regulatory requirements and achieve the agreed risk profile. Where there is an appetite for reducing the extent of excavation to avoid boundary conflicts, or reducing the material cut to waste, the profile may be steepened with the following criteria:
  - **Higher Risk Profile:** Remote sites with limited access or operating quarries may adopt a higher risk profile than infrastructure developments in urban areas or rock slopes along busy road networks. It is advisable to assess the risk profile by undertaking a qualitative or quantitative risk assessment before mitigation design is carried out.
  - **Rock Mass Strengthening:** The installation of dowels, mesh, rock bolts, and anchors to locally stabilise the steeper rock slope.
  - **Formation of Benches and Steeper Slopes between Benches (batters):** In certain rocks, locally steep batters with benches will improve global stability. Benching can also be used for rockfall catch areas and to improve drainage away from the faces.
  - **Improved Drainage:** This is essential to capture surface runoff and reduce infiltration to improve overall stability.
- **Intact Rock and Rock Mass Properties:** To provide the final rock slope design profile an understanding of the intact rock properties and rock mass properties is required. This information can be provided through ground investigation and mapping prior to construction and should be verified during construction. The key properties for consideration are presented in Table 6.14.

Table 6.14. Rock mass properties

Rock and Rock Mass Properties	Rock Type Examples	Analysis	Slope Design Considerations
Weak isotropic rock (UCS < 20 MPa). Highly fractured or weathered rock	Weathered greywacke, Weathered schist	Limit equilibrium Hoek-Brown	• Cut slope angle to be sufficiently shallow to achieve FoS, but not too shallow to increase surface erosion. • Benching with drainage. • Pattern rock bolts (soil nails). • Surface and sub-soil drainage.
Moderately strong isotropic rock (UCS > 20 MPa).	Basalt Andesite Greywacke	Kinematic assessment of joints.	• Cut slope surface to be combined with rock reinforcement. • Steeper batters with benches
Very weak anisotropic rock (less than 5 MPa)	Northland allochthon	Limit equilibrium. Assessment of shear strength along bedding planes.	• Cut slope less than natural terrain (1V:5H) • Sub-soil drainage. • Pattern bolting. • Buttress with shear key.
Weak anisotropic rock with dominant sedimentary bedding	Miocene sedimentary units	Limit equilibrium. Assessment of shear strength along bedding lanes. Kinematic assessment	Moderately steep slopes.

- **Excavatability of Rock:** The excavatability of the rock will determine the type of machinery required and will impact the final rock slope profile. Rock with an intact UCS strength of >20MPa and widely spaced joints can be presplit and blasted to form relatively smooth near-vertical faces. Whereas weaker rocks or rocks with closely spaced chaotic jointing is likely to have a more irregular rock face profile. The excavatability of rock in terms of UCS strength and joint spacing is presented in Table 6.17.
- **Existing Surrounding Landscape Profile:** The profile of the existing surrounding landscape may influence the final slope profile. Stabilisation of weak rock often requires the reprofiled final slopes angles to be less steep than the existing hillside profiles (assumed to be FoS = 1), this may often result in 'chasing the slope' up the hill. In these instances, it may be prudent to undertake rock mass strengthening (using dowels, bolts and buttress) and provide robust soil slope design for the upper slopes.
- **Climate and Environmental Controls:** Weak rocks are more prone to weathering and erosion (scour) as a result of excavation (stress relaxation) and exposure to the elements. The final design should include measures to reduce the impact of these weathering processes, such as steepening the slopes to reduce scour and providing catch ditches to allow localised relaxation failures.

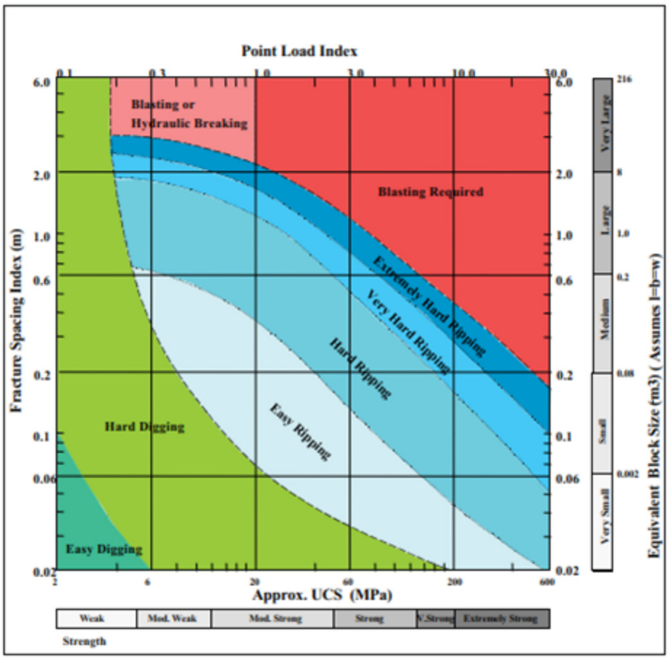


Figure 6.18. Chart showing the excavatability of rock based on UCS strength and fracture spacing (Source: Wyllie and Mah, 2004)

6.2.2.6 Limitations of Rock Removal

The limitations of rock removal are summarised in Table 6.15.

Table 6.15. Summary of rock removal limitations

Type	Limitations
Scaling	• The rock slope may require ongoing treatment for removal of rock materials (and vegetation) due to weathering and decreased stability as a result of previous scaling. • A maintenance programme with a 3 - 5-year return period is advised, especially where vegetation can re-establish and is a contributing factor for rock failure. • The removal of one rock block can destabilise other parts of the slope. The excessive removal of rock can result in undermining of the upper parts of the slope and further destabilisation. There is a risk with rock scaling that it is sometimes hard to know when to stop (removing rock). For these reasons, suitably qualified and experienced engineering geologists and contractors should be engaged early. • Working in areas of dense vegetation may require the removal of vegetation for access, consideration is needed for whether this is beneficial (reduced root jacking) or adverse (exposure to weather) for the local slope stability • Working at heights, often using heavy tooling, will require a specialist construction team. The removal of rock from the slope may require the lower slope to be temporarily closed to access. • The removal of rock from the site can be expensive, especially from urban areas where dumping of rock materials can involve long haulage to designated sites.
Reprofiling	• Involves larger mechanical excavation, including the construction of access tracks to reach the rock slope. • If blasting is required, it will be necessary to set up exclusion zones and shield nearby structures. Blasting permits and significant health and safety protocols are required. • Large-scale excavations may impact site boundaries. This can be particularly restrictive when constructing rock slopes for transport corridors where the width of the designated zone is often narrow. • Greater volumes of rock materials (cut to waste) are generated. • Reprofiling exposes fresh rock faces, potentially accelerating the weathering process. In some rock types, this can lead to significant ongoing maintenance works. • Rock slope reprofiling can be costly, due to the volumes of materials involved.

6.2.2.7 Example applications

The following examples illustrate projects where rock removal techniques have been implemented.

Maitai Valley Nelson

In 2019, a landslip occurred above a section of the Coppermine Trail, located between the Maitai Dam and Smiths Ford, following a severe weather event. After the successful reinstatement of the trail, a long-term slope scaling and monitoring program was implemented, as shown in Figure 6.19, to manage the stability of the reconstructed area. Monitoring was carried out bi-weekly and after significant rainfall events exceeding a predefined threshold. This proactive and ongoing approach to scaling and monitoring has supported the continued safety and stability of this popular section of the trail.

Figure 6.19. Rock scaling works in jointed rock in Maitai Valley, Nelson (Source: Ground Anchor Systems Limited)

Otaika Quarry

Rock slope reprofiling for commercial purposes is evident in working quarries where benches and slopes between benches (batters) are shaped to provide a safer working environment. The rock slope profile in quarries typically consists of steep batters (60° to 80° and 8 – 12 m in height) and benches (5 - 8m wide), with an effective overall slope angle of less than 50°, which provides generally acceptable levels of global stability.

Figure 6.20. Bench and batter rock slope profile in Otaika Quarry (Source: Winstone Quarries)

6.2.3 Rock Mass Strengthening

6.2.3.1 Description

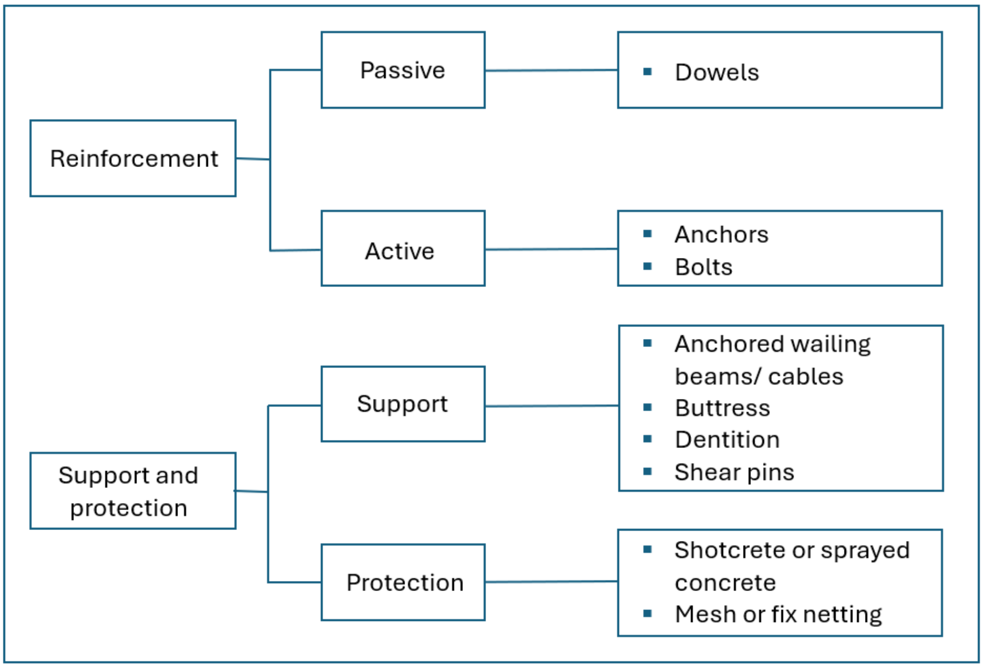


Figure 6.21. Rock mass strengthening options (Source: adapted from Koe et al., 2023)

Rock mass strengthening is the stabilisation of rock slopes through the addition of reinforcing elements or the construction of support and protection to reduce the risk of sliding failures and/or rockfall. A summary of common rock mass strengthening options is presented in Figure 6.21 and Figure 6.22.

Rock mass strengthening can be targeted to local areas of the rock slope with higher instability or may form part of a systematic mitigation for existing or new rock slopes. Stabilisation measures are less likely to be used where containment or removal is possible, due to their relatively high whole-of-life cost and the relatively localised improvements reinforcing elements have on failures.

6.2.3.2 Intended Use, Benefits, and Effective Applications

Rock mass strengthening techniques are used to improve the stability of slopes where intact rock mass is insufficient to resist deformation or where individual blocks, wedges, or weathered zones present a risk of failure. These methods provide both active and passive resistance depending on the configuration and level of reinforcement. The intended use and associated benefits of each option vary depending on rock mass conditions, block size, slope geometry, and performance requirements.

The intended uses, associated benefits, and effective applications of rock mass strengthening techniques are summarised in Table 6.16.

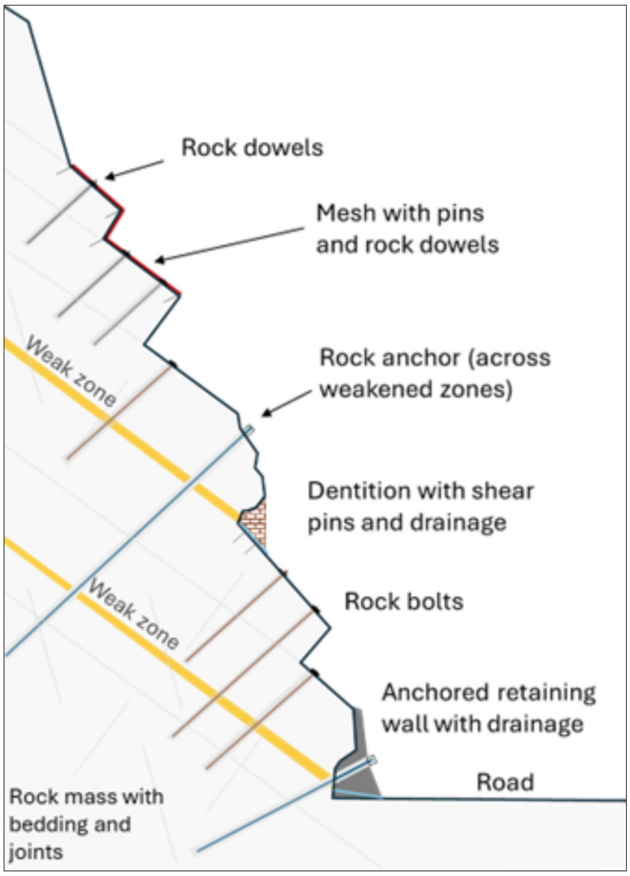


Figure 6.22. Rock mass strengthening options ((Adapted from Fookes and Sweeney 1976)

Table 6.16. Intended uses, benefits, and applications of rock mass strengthening techniques

	Option	Description	Benefits	Application
Reinforcement	Rock dowels	• Rock dowels are solid/rigid bars that are typically 3 – 5 m in length and 16 – 50 mm in diameter. • They are installed unstressed and only become stressed when deformation or movement takes place in the rock mass (McMillan et al., 2000). • Rock dowels provide passive shearing resistance to sliding.	• Less costly than tensioned anchors. • Relatively easy to install (compared to anchors that require tensioning). • Do not require rigorous testing. • Less prone to corrosion as it is well encapsulated in cement grout.	• To stabilise rock blocks less than $5m^3$. • Pattern bolting for randomly jointed rock or weak rock. • Can be used to improve global stability for near-surface slip surfaces. • Installed ahead of excavation before relaxation of jointing within the rock mass.
	Rock bolts and rock anchors	• Rock bolts are solid/rigid bars usually made from high-strength steel (>500E) and generally less than 6 m long (32 mm diameter) with a working load of 150 – 200 kN. Rock bolts can be passive or active. • Rock anchors have a higher capacity than rock bolts, with a typical working load of 0.3 – 2.0 MN. Anchors may be 10's m long and can be mono- or multi-strand. Anchors are pre-tensioned (active). • Rock bolts and anchors act in tension and are anchored using: grout, mechanical anchor, friction (including Swellex).	• Essential when movement is not tolerated. • Low visual impact compared to buttressing support. • Can tolerate high loads. • Anchoring into higher strength rock below the ground surface, which is less prone to the impact of weathering. • Long anchors are less prone to corrosion (although near-surface sleeving and corrosion protection will be necessary).	• Suited for large rock blocks > 5 m^3. • To prevent sliding of blocks and wedges on discontinuities dipping out of the face. • Installed to attach cables for supporting rock blocks and boulders. • Provide the ground connection for stabilising structures such as protection structures and mesh. • Installed though concrete buttress to increase the resisting force.

Table 6.16. Intended uses, benefits, and applications of rock mass strengthening techniques (continued)

	Option	Description	Benefits	Application
Support and Protection	Anchored waler beams and cabling	• Anchored waler beams are typically constructed of concrete or steel U-beams and extend across a section of weakened rock. The beams are anchored at points where competent rock is encountered, and the resisting force is transferred along the beam. • Cables fixed and tensioned from anchor points where competent rock is encountered.	• Spreads the retention provided by anchors over a greater length of the rock face and volume of rock. • Enables rock anchors to be optimised to share overall loads. • Can be combined with mesh to widen the area of support. • Provides an option not to drill in loose or unstable rock.	• Weaker rock masses that may break up around single reinforcement points. • Cables may span across larger boulders that cannot be pinned directly in place due to size or consisting of weak or weathered rock that is not drillable without risk of collapse.
	Gravity mass buttress (Concrete or Gabion) and Dentition	• Gravity mass buttresses are a retaining wall (Concrete or Gabions) that is built perpendicular to the main axis of the slope and serves to reinforce the slope against lateral forces, such as sliding failure. • Dentition is concrete (possibly with shear key) infill in overhangs and areas where weak rock has been removed and replaced with concrete.	• Provides vertical and horizontal restraint to the rock mass. • Prevents collapse of overhangs. • Can be designed to include drainage. • Provides a solid visual effect and generates confidence. • Dentition can be used to compensate for overscaling.	• Buttress retains and protects areas of extremely weak rock and supports overhangs. • A concrete buttress can infill overhangs. In some instances, anchors may be required to provide additional lateral resistance. • Dentition is used for infilling smaller overhangs and areas of extremely weak material, such as soft infill material between sedimentary beds or fault gouge after removal. • Design of gravity mass buttresses must consider the same forces for conventional retaining wall design as per MBIE Guidance, as well as the additional loads posed by the unstable rock mass.
	Sprayed Concrete (Shotcrete or Gunite)	• Shotcrete is a wet-sprayed concrete, whereas Gunite is sprayed dry. Both, often referred to as Shotcrete, provide support and protection for rock slopes through the binding of loose surface material. • Shotcrete can be a composite system with steel or polymer fibres or used in conjunction with fixed steel mesh reinforcement as shown in Figure 6.25.	• Protects against small rock block failure or unravelling. • Protects against weathering and degradation. • Can be used to treat large shallow failure surfaces when used in combination with steel or polymer fibres, or with steel reinforcement. • Can be coloured with various oxides to aesthetically match nearby rock. • Relatively fast application.	• Highly fractured rock slope surfaces where numerous discrete rock blocks occur. • Weathered rock slope surfaces or mixed ground where there is variable intact strength. • Can be used in combination with mesh or reinforcement fibres. • Guidance is limited within New Zealand, therefore, good practice documents such as the Shotcrete Design Guideline by Transport for New South Wales (TfNSW, 2023) and the D&C B82 Shotcrete Specification (TfNSW, 2020). • Design shall include consideration for drainage behind the shotcrete, including weep holes and toe drains.
	Mesh (and pins)	• High-capacity steel wire mesh, which is tensioned in conjunction with supporting anchors and plates. • The mesh is designed to fit tightly to the slope and can be left to allow vegetation to be established on the slope beneath.	• Arrests minor rock fall through retention as well as provides stabilisation through tensioning. • Provides some rock face support to prevent local shallow failure and erosion (using composite systems). • Vegetation can be established through the mesh. • Low aesthetic impact compared to shotcreting.	• Highly weathered or highly fractured rock slopes. • Retain small rock blocks from displacement from the rock face. • Various steel coatings allow for differing corrosion environments.

6.2.3.3 Considerations

The following section reviews the design considerations for the various rock design rock mass strengthening options, as well as details of installation methods that will be provided as part of the design.

Rock Dowels

Rock dowels are generally designed by considering the following methods:

- **Hand calculations:** The dowel capacity (and number of dowels) required to stabilise a rock block can be calculated considering the slope geometry, the size and mass of unstable rock, friction angles, cohesion along the sliding (joint) surface, and other driving forces. A reasonable knowledge of the achievable bond strength between the grout and rock is also required. Hand calculations for simple sliding and toppling failures are relatively straightforward, whereas wedge failures are more complex with multiple forces to resolve.
- **Proprietary software packages**: A number of proprietary software packages for rock slopes include the ability to consider the effect of rock dowels and provide the expected performance and requirements for installed dowels.
- **Prescriptive design:** Table 6.17 provides a prescriptive design for igneous rock (or similar, noting requirements). There are also many other prescriptive rock bolt design options available using Rock Mass Rating (RMR), Geological Strength Index (GSI), and other descriptive tools, but they should only be applied when there is a good understanding of the local geology and achievable bond strengths.
- **Typical installation**: Rock dowels are typically installed perpendicular to the potential sliding surface and increase the shearing resistance. As most sliding surface has some degree of roughness, the dowel will first act in tension because of dilation across the shear surface, and this should be considered in design.
- **Dowels** are normally installed using cement-grout mixtures to bond to the rock.
- **Quality assurance**: Proof and acceptance testing are less commonly required for rock dowels (compared to rock anchors), although it is advisable for larger projects to establish bond strengths on sacrificial dowels in similar rock materials early in the project. Bond strengths for various rock types can be readily found in the literature, although weathering grades, the presence of groundwater, and drilling methodology can have a significant impact on local conditions.
- **Corrosion protection**: The use of galvanised and/or epoxy-coated bars is advised for aggressive ground conditions such as excessive groundwater, low pH, and high sulphates in groundwater. Additional protection of head assemblies should be considered for components exposed to free air (i.e., not grouted).

Rock Bolts and Anchors

Rock bolts and anchors generally have higher load requirements than rock dowels and therefore require additional design considerations. Guidance for the design of rock bolts and anchors can be found in BS 8081 Code of Practice for Grouted Anchors (British Standards Institution, 2019), and FHWA Ground Anchors manual (Federal Highway Administration, 2003), both of which provide approaches supported by the NZTA Bridge Manual (NZ Transport Agency, 2022). In addition to this guidance are the following considerations:

- **Design Approaches**: Generally, rock bolts and rock anchors are designed based on the output requirements of proprietary software packages associated with the stabilisation of slopes. These requirements also require verification using hand calculations to undertake sensitivity checks for bond lengths and bond strength for varying rock conditions.

Table 6.17. Prescriptive measures for rock dowel design (modified after Yu et al., 2005)

Volume of Potentially Unstable Rock Block, V (m³)	$V \leq 1$	$1 < V \leq 2$	$2 < V \leq 3$	$3 < V \leq 4$	$4 < V \leq 5$
Number of Rock Dowels Required	1	2	3	4	5

Requirements:

a. The rock blocks are less than 5 m^3.
b. The rock is competent (can be drilled without breaking or degrading).
c. The angle between the slope and the potential sliding surface is greater than 10°.
d. Dowel bars are installed approximately perpendicular to the failure surface.
e. Dowel length is 3 x the thickness of the potentially unstable rock block.
f. Rock dowels should be at 0.3 m from the edge of the rock block.
g. The dowels should be evenly and effectively spaced across the unstable rock block.

- **Confirming Rock Type**: An understanding of the rock type is necessary to select the correct drill bit and tooling to ensure a consistent and regular clean drill hole. Excessive use of water flush in weak rocks, for example, may result in oversizing the drill hole and increasing the volume and cost of grout required.
- **Typical Installation**: There are several different installation methods of rock bolts and rock anchors, which are well-documented in the NZGS Ground Anchor Guideline (NZGS, 2019). A schematic sketch of a typical grouted rock bolt detail is presented in Figure 6.23. Typically, the bar should be installed in the drill hole using centralizers to ensure full encapsulation of grout. Any head assembly, including face plates, should be evenly seated on the rock face to ensure full tensioning can be achieved.

- **Selection of Anchor Type**: The decision to use a specific anchor type (cement-grout bond, mechanical, or friction) should be suited to the rock conditions and tested prior to works commencing by proof testing to failure.
- **Grouted Anchors:** Cement grout may be installed in either one or two stages. In the single-stage method, the entire drill hole is grouted at the time of installing the anchor. The free length is protected by a plastic sheath or coating to prevent bonding and to allow tensioning when the fixed length has gained sufficient strength. In the double-stage method, the anchor length is grouted in the first stage, and the free length in the second stage, after applying tension. Grouted anchors can include a solid bar or a self-drilling hollow bar. A hollow bar serves as both drill string during drilling and support tendon once grouted in place. Once the bolt is inserted to the correct depth, resin or grout is injected through the bolt to complete the installation.
- **Mechanical Anchors**: These anchors are fixed to the rock at the distal end by means of a mechanical expansion system and then are grouted after stressing (CT Bolts are an example of a mechanical rock bolt). The advantage of mechanical bolts is that the installation is rapid, and tensioning can be carried out immediately. The disadvantage of mechanical anchors is that they can only be used in medium to strong rock, in which the anchor will grip.
- **Friction Anchors:** These anchors are hollow steel tubes fixed to the rock by friction between the rock and bolt (e.g., Swellex).
- **Quality assurance**: The testing requirements for rock bolts and anchors are well outlined in BS 8081 (2019) and FHWA (2003), including the requirement for sacrificial/investigation, proof/suitability, and performance /acceptance tests to provide confidence in the installation method and assumed capacity. Requirements within BS 8081 (2019) and FHWA (2003) indicate a 100% testing requirement, whereby, in practice for rock slope applications, this is impractical, and therefore a range of total acceptance (proof and performance) testing between 10% and 20% of the total bolts and anchors is considered suitable. Noting that additional testing may be required if the results are found to be unsatisfactory.
- **Corrosion protection**: Rock anchors and bolts generally require the use of galvanised and/or epoxy-coated bars in all ground and climate conditions. The NZTA Bridge Manual (2022) and NZGS Anchor Guideline (2019) provide guidance on the protection Class requirement for different applications.

Waler Beams and Cables

Specific guidance for the design of waler beams and cables is not readily available in New Zealand or internationally, although there is useful reference for cable calculation in CIRIA C775 (Koe, Murphy, & Nicholson, 2018).

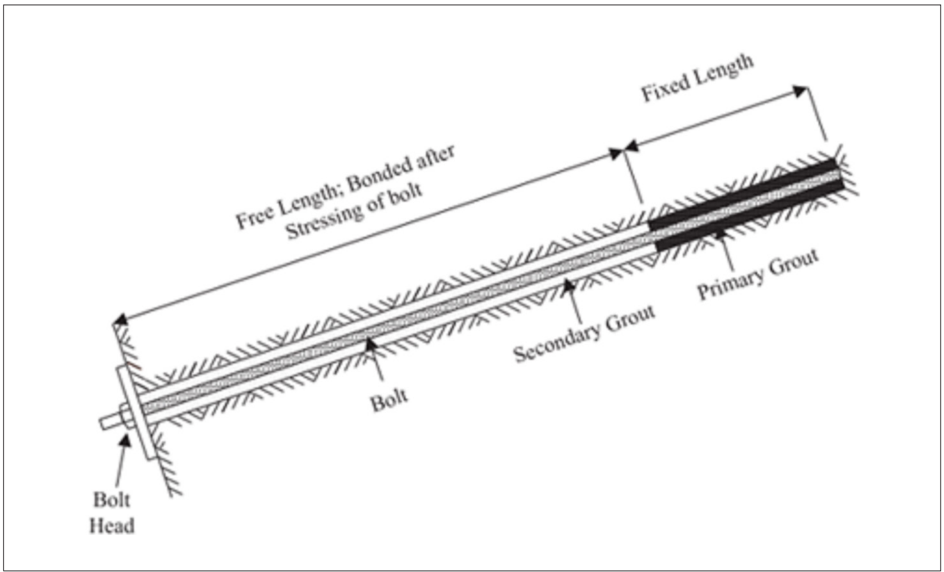


Figure 6.23. Typical rock bolt detail (Adapted from Geotechnical Engineering Office, Civil Engineering & Development Department, 2011)

The installation of waler beams and cables often requires bespoke design and should consider the following:

- Cables used as strapping across unstable boulders or wedges are loaded under tension, and a key design requirement is the minimal breaking load of the cable, details of which should be provided by the supplier.
- The cable (and waler beam) will be anchored using rock bolts or rock anchors, which will require an understanding of the rock conditions and the achievable grout-rock bond strength. Pull-out testing to confirm bond strength will likely be required.
- The cable and the rock bolt (or rock anchor) should be in line or as close to in line as possible to reduce shear on the rock bolt. This will likely require the rock bolt drilling to be angled, which can sometimes cause complications, especially in weaker materials where casing might be required. The use of wire rope anchors or Flex Head fittings on rigid rock bolts can be used as alternatives to reduce shear.
- For waler beams constructed of steel and concrete, it will be necessary to employ a structural engineer to assess the shear force and bending moment between fixed points.
- The impact of corrosion on the design life will need to be considered.

Gravity Mass Buttress, and Dentition

Toe Buttress (using gabions, or concrete blocks) for the purpose of slope support, can be designed following a standard retaining wall design as per the NZTA Bridge Manual (NZTA Transport Agency, 2022) or MBIE Module 6: Earthquake Resistant Retaining Wall Design (NZGS & MBIE, 2021) within a New Zealand setting, with the additional considerations of the ground movement load determined through slope stability analysis. For localised retention or support of loosened overhanging material within a rock slope, dentition provides a suitable option. The design of dentition will likely follow a simpler approach, considering the localised loads for the region of support. In both cases, this slope support structure should consider the following:

- **Dimensioning:** The sizing of a concrete buttress is generally governed by geometrical considerations, such that it is large enough to provide physical support to the identified unstable rock block.
- **Additional Support:** Buttressing should be founded on a level, clean, and sound rock surface. If the surface is not at right angles to the direction of the resultant force acting on the buttress, anchoring is likely to be required using dowels to prevent sliding.

Figure 6.24. Gabion-faced reinforced soil wall buttressing the road and stabilising a landslide on Milford Road, Milford Sound (Photo courtesy of Eric Ewe).

- **Dentition:** For smaller, localised dentition, support may be gained from interlocking into irregular rock surfaces. However, in some cases, dowel support at the base may be necessary to prevent sliding.
- **Drainage:** Adequate drainage should be incorporated to prevent water build-up behind the structure.

Sprayed Concrete (Shotcrete or Gunite)

There is little New Zealand-specific guidance on the design and application of shotcrete; good practice can be found in international sources such as Transport for New South Wales Shotcrete Design Guideline (TfNSW, 2023) and the D&C B82 Shotcrete Specification (TfNSW, 2020). This guidance is relevant in similar geology (competent hard sedimentary rocks). For New Zealand-specific installations, the following key considerations include:

- **Seismic Regions**: Seismic loads on the shotcrete should be considered based on the projected design working life of the structure, and the purposes of the shotcrete. Where the shotcrete forms an independent physical structure, it should be considered closer to a retaining wall in terms of design. However, for use as a surface covering to prevent fretting of a rock-face, the design may take a more practical approach to ensure suitability.
- **Reinforcement:** Steel or polymer fibres can be added to the shotcrete mix to improve shear, tensile, and post-crack strength. If steel fibres are used, an additional 50 mm covering layer of (non-fibre) shotcrete can reduce the rusting and exposure of steel fibres. Solid steel mesh can also be used to improve stability and strength across more uniform faces. If steel mesh is used, ensure it has suitable coverage to meet corrosion protection requirements.
- **Application:** Sprayed concrete may be applied using either wet (shotcrete) or dry (gunite) methods, depending on site conditions and project requirements. Typically, shotcrete provides a more consistent application. The quality of the shotcrete application is often down to the competency and experience of the nozzleman (TfNSW,2020; TfNSW, 2023).
- **Drainage:** Water build-up behind a shotcrete can lead to increased slope instability and failure of the shotcrete. Drainage is therefore essential. Weep holes should be installed to prevent the build-up of water pressure behind the shotcrete and spaced at an appropriate distance to account for the rates of flow within the groundwater and permeability of the geological unit. In smaller applications, a 300 mm clearance area at the toe of the slope can be left un-shotcrete to enable groundwater to drain freely at the base. If possible, this is easily achieved by placing a simple timber board at the toe of the slope during construction and removing it once complete.

Mesh and Pins (Active Mesh)

Active mesh through the use of steel mesh anchored to the rock is widely used throughout New Zealand, as a cost-effective approach to reduce rockfall at source, and improving stability of the identified rock mass. Guidance on the design and application of active mesh is provided in CIRIA C775 (Koe, Murphy, & Nicholson, 2018), and the learnings from the North Canterbury Transport Infrastructure Recovery (NCTIR) project are captured in the NZ Transport Agency Waka Kotahi Rockfall Protection Structures Design Guidance (2023). Additional design considerations include:

- **Anchor Capacity:** To secure the mesh to the rockface, the anchorages should be firmly fixed to the intact rock. The specific loading of the anchors can be calculated from first principles and checked within the mesh system's specific manufacturer's proprietary software. It can be beneficial to complete any performance testing of key anchors prior to installation of the mesh to prevent testing rigs from damaging or pinching the mesh.
- **Mesh Capacity:** There are a variety of different types and strengths of mesh depending on the severity of the hazard and environment. The mesh should be able to withstand the punching stress (force measured in kN measured in a direction perpendicular to the plane of the mesh) from the largest credible block.
- **Rope Capacity:** Rockfall barrier systems often include boundary ropes along the top, bottom, and sides (verticals), and sometimes additional intermediate ropes (both horizontal and vertical). The bottom rope is typically designed with a slightly lower capacity than the others. This intentional weakness helps direct the failure path in an extreme (beyond-design) event—allowing material to exit at the base of the system rather than compromising the overall structural integrity by failing at the top or sides. All boundary ropes must be securely connected to the mesh using proprietary clips and span between anchorage points. The method of terminating these ropes is critical and should be designed carefully. Common termination options include proprietary systems like Geobrugg's Flexhead, which forms a looped anchor head, or a simpler method of looping the rope directly around a bar and plate, relying on the bar's shear strength to resist load.
- **Dimensioning:** Quantifying the area of mesh and number of anchors within a mesh and pin solution can be challenging due to the undulating topography. Where the 3D effect of the rockface is complex, additional contingency may be required. In addition, the consideration will be needed for supporting perimeter and contouring anchors.

Contouring anchors are generally smaller and shorter dowels with less capacity than a full anchor, with the primary role of bringing the mesh closer to the slope within hollows and dells. Where hollows are significant, dentition may be required.

- **Corrosion protection:** Corrosion protection for the anchors shall have the same consideration as above for rock anchors/bolts and dowels. For the mesh, there are multiple levels of protection, such as zinc, galvanising, proprietary coatings and stainless. Based on the corrosion environment, design life, and cost/benefit, the correct mesh protection can be selected.
- **Installation:** Most roped access specialist contractors within New Zealand will have experience with the installation of active mesh. The key learning from NCTIR included using a crane or helicopter to lift vertically joined rolls of mesh to the top of the slope and roll out across the face. This can be done prior to the majority of anchors being installed to provide another level of protection to the drillers. The rock anchors can then be drilled through the mesh – check specific manufacturer guidance on mesh apertures and maximum drilling diameters.

6.2.3.4 Limitations

Each option for rock mass strengthening has its benefits and challenges, and depending on the specific project requirements, one option will become preferable. Table 6.18 summarises some of the limitations to consider against each option.

Table 6.18. Rock mass strengthening limitations

Type	Limitations
Rock dowels	• Typically limited to supporting rock blocks less than 5 m^3 or rock slabs with thicknesses up to 2 m. • Only effective where no prior displacement or movement has occurred.
Rock bolts and rock anchors	• Installation and tensioning can be difficult or complex compared to rock dowels. • Choosing the most effective anchor type and anchoring method often involves a degree of trial and error. Especially where rock strength and fracturing can impact drilling and grouting efficiency. • The testing schedule outlined in current standards BS 8081 (2019) and FHWA (2003) used to prove the bond strength can often be too rigorous and may lead to project delays, and/or require departure from standard.
Anchored waling beams, strapping and cabling	• Anchored waler beams are often mid-slope, requiring work at height, which can be challenging when it comes to concrete pours and formwork installation. • Installation logistics can be challenging, especially in steep or difficult terrain.
Concrete buttress	• May require extensive site preparation, including excavation, foundation cleaning, shear key installation, and anchoring. • Typically involves the use of large volumes of concrete and reinforcement. • Effective performance depends on adequate drainage design and ongoing drainage maintenance.
Dentition	• Provides only nominal support to localised rock blocks or loose surface materials. • Not suitable as a standalone measure for large-scale instability.
Shotcrete or sprayed concrete	• Can be aesthetically unappealing, particularly in natural or scenic environments, even with colouring and oxides. • Generally considered less environmentally acceptable than other options. • Offers limited structural resistance, typically effective only for shallow surface failures. • Requires proper drainage and regular drainage maintenance to avoid water pressure build-up behind the lining.
Mesh (with pins)	• Primarily effective for controlling surface ravelling or small-scale block detachment. • Can be limited in providing any global support or local support for planar or circular failure mechanisms.

6.2.3.5 Example Applications

An example of sprayed concrete reinforced with mesh at Rock Road, Nelson, is presented in Figure 6.25.

Figure 6.25. Sprayed concrete combined with steel mesh at Rock Road, Nelson (Source: Ground Anchor Systems)

An example of a mesh installation on a greywacke slope in Wellington is presented in Figure 6.26.

Figure 6.26. High-capacity steel mesh (Tecco) installed over highly fractured greywacke (Source: Geovert Limited)

6.2.4 Drainage

6.2.4.1 Description

Water is often the primary or significant contributory cause of instability in rock slopes, and this is particularly true in areas where there is high rainfall and high infiltration. The effects of water on a rock slope are primarily driven in two forms: *surface* and *sub-surface*.

Surface water, generally considered as overland flow and run-off, can have both an initial physical effect on the rock slope and a secondary effect through contribution to sub-surface water. The physical impacts are generally in the form of surface erosion and accelerated weathering of a rock slope.

Subsurface water can be a combination of the immediate surface water entering the rock slope through joints and fissures, and groundwater within the rock mass from more distal sources. An increase in subsurface water ultimately reduces the stability of a rock slope. This increased instability is often observed as:

- Increased groundwater pressure in the joints, which reduces the shearing resistance along the joint surfaces,
- Increased groundwater pressure in sub-vertical joints increases sliding forces,
- Groundwater softens weathered or clay-filled joints, lowering cohesion and friction angle,
- Groundwater may lubricate joints, enabling movement,
- Freezing of groundwater in joints and cracks can generate significant forces that induce sliding and, overtime weaken rock bridges between joint surfaces.,
- Variations in moisture content of intact rock through wetting and drying can accelerate weathering near the surface and induce slaking (particularly in fine-grained Miocene deposits), and
- Groundwater build-up behind structures with poor drainage can result in hydrostatic pressure destabilising the structure.

To mitigate the impact of both surface and subsurface water within rock slopes, it is beneficial to:

- Understand critical flow-paths contributing to the surface-run-off and sub-surface groundwater,
- Actively manage surface water run-off above the slope, and in areas that may contribute to the immediate sub-surface levels,
- Identify and reduce sources of surface water infiltration to the ground, and
- Improve drainage of sub-surface water to depressurise groundwater in joints and fissures, and reduce hydrostatic pressure behind structures such as shotcrete and buttress retaining walls.

The installation of drainage measures can be challenging around rock slopes compared to soil slopes, as slopes are generally steep and have irregular surfaces.

A selection of drainage options available to achieve these measures is presented in Figure 6.27.

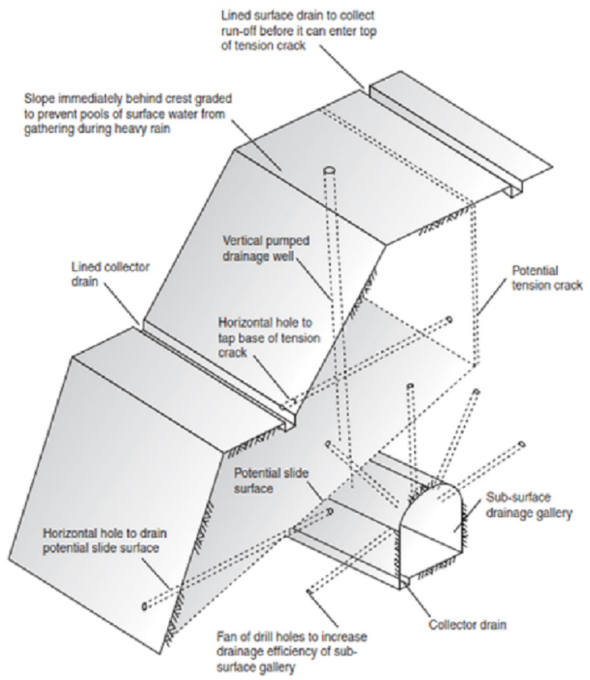


Figure 6.27. Slope drainage methods (Source: Wyllie and Mah, 2004)

6.2.4.2 Surface Drainage

Surface drainage and management are designed to collect and distribute surface runoff and reduce infiltration into the ground. Surface drainage and management may include the following:

- Crest drains (sometimes referred to as cut-off drains), installed at the top of the rock slope to prevent surface water from entering or flowing over the rock slope,
- Mid-slope drain (lined collector drain),
- Toe drain, installed at the base of the slope to collect and discharge water, and prevent ponding,
- U-channels from weep holes and benches (lined collector drain), and
- Ensuring all near horizontal surfaces have a suitable fall to prevent ponding.

The drains should be interconnected so that surface water is discharged to the stormwater drainage system of nearby water courses.

6.2.4.3 Subsurface drainage

Subsurface drainage is designed to intercept fractures, discontinuities, or more permeable layers within the rock mass. Subsurface drainage often involves drilling and installing drainage within the rock mass. Subsurface drainage and management may include the following:

- Relief drains, installed at locations where groundwater has been observed, i.e., seepage from a joint or bedding plane.
- Raking drains installed inclined at approximately 10° above the horizontal, using perforated PVD pipes (in less than 65 mm).
- In-pit sumps (more likely to be used in quarries and as temporary works)
- Counterfort drains, excavated into the surface layers of the rock mass to create preferred flow paths.
- Subsurface drainage galleries and an associated network of fan drillholes or similar for large jobs with excessive groundwater infiltration.

6.2.4.4 Intended Use and Benefits

Drainage systems are an essential component of rock slope management, aimed at controlling both surface water and subsurface groundwater to improve slope stability and reduce long-term degradation. Their primary function is to prevent the accumulation of water within or on the face of rock slopes, which can exacerbate instability through increased erosion, elevated pore pressures, and corrosion of reinforcement systems. The following table summarises the typical benefits of both surface and subsurface drainage systems in the context of rock slope management.

Table 6.19. Benefits of surface and subsurface drainage

Drainage	Benefits
Surface	• Reduces erosion and scour • Reduces surface water infiltration to the ground • Directs groundwater flow away from assets at the toe of the rock slope (e.g., roads, developments)
Subsurface	• Reduces groundwater pressure in joints • Reduces pore pressure in permeable, weak rock • Intercepts groundwater before it can reach the rock slope face • Reduces groundwater in weak zones, such as clay-filled shear zones • Reduces the likelihood of freeze-thaw damage • Increases the lifespan of rock slope reinforcement by reducing corrosion

6.2.4.5 Effective Application

The applications of surface and subsurface drainage are summarised in Table 6.20.

Table 6.20. Applications of surface and subsurface drainage

Drainage	Application
Surface	• In areas of high rainfall where surface runoff is eroding the rock slope or contributing to significant localised groundwater levels
Subsurface	• To intercept and reduce groundwater pressures in joints and other discontinuities • Intercept groundwater in permeable rock

6.2.4.6 Considerations

The design and construction considerations specific to surface and subsurface drainage are presented in the following sections.

Surface Drainage

The more common design considerations for surface drainage systems include:

- **Overland Flow Paths:** Identify and review the overland flow paths, consider the interactive properties between flow paths and the rock slope in question, ensure connection of designed drainage with existing flow paths.
- **Flow Capacity**: Ensure adequate capacity and flow containment within any designed surface drainage (drainage is often considered as an Annual Exceedance Probability (AEP) i.e., 1% or 1 in 100-year rainfall event). Different situations may require consideration of differing AEPs as well as differing impacts of climate change and increased rainfall/ flood events, depending on the design life and intent.
- **Energy Dissipation:** If surface drains are required on steeper surfaces, it may be prudent to include energy dissipation protrusions, concreted in boulders or gabion mattresses, within the channel and/or at the base to reduce flow velocities.
- **Excavation Challenges:** Surface drainage requiring excavation in rock may be difficult or unfeasible for construction, therefore, alternative options such as berms or concrete-lined structures should be considered.
- **Infiltration Reduction:** Mapping of the rock mass head scarp, tension cracking, or outcrops should be completed to ensure surface drainage is installed upslope of any notable features that may be a source of potential infiltration.

Subsurface Drainage

Subsurface drainage is used to reduce groundwater pressures within the slope to improve the overall stability. As such, the key design considerations for subsurface drainage include:

- **Horizontal Drainage:** Installed near perpendicular to the rock slope face, providing subsurface drainage, which is typically drilled at the toe of the slope or in areas where surface seepage has been observed. There is little guidance in New Zealand or internationally on the specific formula to calculate the drain hole, diameter, depth, or spacing. As a rule of thumb, drainage holes are usually spaced between 2 m and 10 m, often using a 50 – 100 mm diameter drilled hole with corresponding pipe, to a depth of at least one-third of the rock slope height. If existing borehole or ground information is available, drilling beyond the known groundwater depth or until groundwater is encountered can ensure a better reduction in pressure, with a completion depth no greater than the rock slope height.
- **Raking Drains:** Raking drains, or similar, should be inclined at approximately 10° up from the horizontal to ensure positive groundwater flow and to reduce clogging.
- **Drainage Lining:** Perforated or slotted PVC pipe is often grouted into place within the drains at the proximal end. In addition, a hinged cap and grate may be required where flows are low or ephemeral, and blockage from animal nests (mice, birds, etc.) may occur. Depending on the geology, additional approaches to avoid clogging of drains and general maintenance are needed. For example, in some fine-grained rocks, wrapping the slotted PVC pipes with geotextile can result in an algae build-up on the geotextile that will ultimately reduce its permeability and effectiveness to drain.
- **Discharge:** Consideration should also be given to the disposal of seepage water, and this should be incorporated into the surface water design to avoid erosion and degradation of rock materials at the toe of the slope. Water testing and treatment of any sub-surface water may be required in areas of hazardous or contaminating geological units.
- **Integration:** Subsurface drainage can often be used in conjunction with other rock mass strengthening approaches, such as buttresses and shotcreting. Where there is a requirement to reduce pore pressure behind rock mass strengthening options, notably in weaker sedimentary rock, a pattern of shallow (<2 m) drill holes may be effective.

6.2.4.7 Limitations

The application of differing drainage methods will likely be controlled by the specific hydrological conditions associated with the rock slope. Limitations associated with both surface and subsurface drainage are summarised in Table 6.21.

Table 6.21. Limitations of surface and subsurface drainage

Drainage	Limitations
Surface	• Requires regular inspection and maintenance to ensure drains remain clear and functional, particularly after significant rainfall events. • Prone to blockage from debris, sediment build-up, or vegetation overgrowth, which can lead to overflow and localised erosion. • It may be difficult to implement in steep, rocky, or heavily vegetated terrain without extensive site preparation. • Energy dissipation features, if not designed appropriately, can fail or become dislodged under high-flow conditions.
Subsurface	• Requires ongoing maintenance, including periodic cleaning (e.g. via air or water flushing) to remove sediment or mineral build-up that can clog the drain holes. • Susceptible to clogging from fine particles, biofouling (e.g., algae), or reduced flow due to chemical precipitation or geotextile blockage. • Access for inspection and maintenance can be limited, especially when drains are located in steep or inaccessible terrain. • Performance may degrade over time, and system effectiveness can be difficult to verify without monitoring. • Improper discharge management may lead to erosion or instability at the slope toe if not integrated into surface water drainage systems. • Ensuring the correct placement, location, and spacing of horizontal drainage can be challenging without extensive geotechnical and hydrological investigations. Due to the cost of these investigations, drainage can often be installed as a 'best-guess', which, if incorrect, may impact the effectiveness.

6.2.4.8 Example Application

An example of a subsurface drain installation on a rock slope is presented in Figure 6.28.

6.3 ROCKFALL

6.3.1 Introduction

According to the Varnes 1978 classification system and subsequent interactions, rockfall is defined as the falling, rolling, and bouncing of discrete rock fragments from a steep slope or cliff. Specifically, rockfalls are considered to be relatively small mass movements and differ from larger volume rockslides, landslides, debris, and rock avalanches.

Figure 6.28. A series of horizontal drains connected by surface pipework to a discharge point into the stormwater network on a rock slope in Wellington

However, in practice "rockfall" and the resulting "rockfall protection structures (RPS)" commonly refer to a variety of slope failures that involved rapid slope movement of individual or collective blocks (MBIE, 2016). Caution is needed when designing RPS so that the appropriate solution is developed, considering the possible failure mechanisms such as individual or small collectives of blocks compared with landslide debris and rock avalanches.

This section provides information on the design considerations for passive rockfall protection structures, which focus on the installation of a system to slow or capture rockfall debris once it has begun moving, compared to active treatments, which are specific to stabilising material at the source. Stabilisation measures are discussed in the previous section of this document.

There is good guidance provided for the design of rockfall protection structures in New Zealand, including the MBIE *Rockfall: Design Considerations for Passive Protection Structures* (2016) and NZTA Waka Kotahi *Rockfall Protection Structures Design Guidance* (2023). This section, therefore, focuses more on the applicability, design processes, and limitations of the common types of RPS available.

6.3.2 Rockfall Modelling

Estimation of rockfall behaviour and trajectory is critical to the design of passive rockfall protection structures. Modelling is typically used to estimate key parameters such as bounce height and kinetic energy, which inform the design of barriers and other mitigation systems. Proprietary software, such as RocFall 2, RocFall 3, and RAMMS, is all available and offers different means to determine the expected behaviour. The use of specific software must consider the level of information available for input. Often, 3D modelling can provide impressive results, but it is highly variable in the quality of input data, such as rock shape and density etc. For this reason, 3D modelling can provide better use to identify the most common rockfall paths down a slope, but for bounce height and impact energy, using a simplified 2D modelling approach is often more appropriate. Another key consideration for rockfall modelling is ensuring the user understands the input variables and parameters of the specific software, users should be suitably trained and experienced.

Guidance for undertaking rockfall modelling within a New Zealand setting is provided in MBIE's *Rockfall: Design Considerations for Passive Protection Structures* (2016), GNS Science Consultancy Report 2011/311 (Massey et al., 2012), and NZTA Waka Kotahi *Rockfall Protection Structures Design Guidance* (2023), all of which are aligned to the internationally accepted practices outlined in UNI 11211-4 (Ente Nazionale Italiano di Unificazione, 2018) and Austrian Standards Institute (2017).

6.3.3 Catch Ditches

6.3.3.1 Description

Catch ditches are a common form of mitigation, which can range from specifically designed catchment areas to simple longitudinal cess ditches or swales at the base of a slope. Catch ditches vary in their complexity and engineering input. The primary function of these structures is to stop and capture falling debris before it reaches the element at risk**.** The more complex catchment area structures often require detailed planning and design to ensure they can effectively manage water flow and debris capture. Whereas simple catch ditches can often be designed either to work independently or as part of a combined system. Designers must consider factors such as the area's topography, underlying geology, and associated drainage. Additionally, challenges may arise as catch ditches will often become the lowest drainage point, and therefore, consideration is needed for the materials used and the construction techniques employed to ensure long-term durability and performance.

Figure 6.29. An example of a large catch area basin for debris flows and landslides, Kaikōura, New Zealand (NCTIR, 2019)

6.3.3.2 Intended Use and Benefits

Catch ditches can be a simple solution where slope geometry and space allow, and can be adapted to suit a variety of slope failure mechanisms (i.e., small rockfalls at the toe of a steep slope to large catchment basins for the retention of landslides or debris avalanches).

The benefits of catch ditches include:

- **Cost Effectiveness:** Catch ditches provide a lower-cost approach to managing debris and slope failure risks. Their design typically involves simple earthworks, which require less financial investment compared to more complex engineering solutions.
- **Easier Consenting:** Because catch ditches primarily involve earthworks rather than intrusive structural interventions, they are generally easier to gain permits and resource consent approvals.
- **Ease of Maintenance:** These structures are designed to be straightforward to maintain over time, with minimal requirements for specialised equipment or specialist labour (such as roped access technicians). This simplicity helps keep ongoing maintenance costs low and operations manageable. Designing with good machine access for clearance improves this further.
- **Clearance Requirements:** The design and function of catch ditches often include operational guidelines for debris clearance to ensure the area maintains the design capacity. The simple shape and ease of clearance enable the catchment area to be efficiently managed and cleared.

Ideal locations for catch ditches:

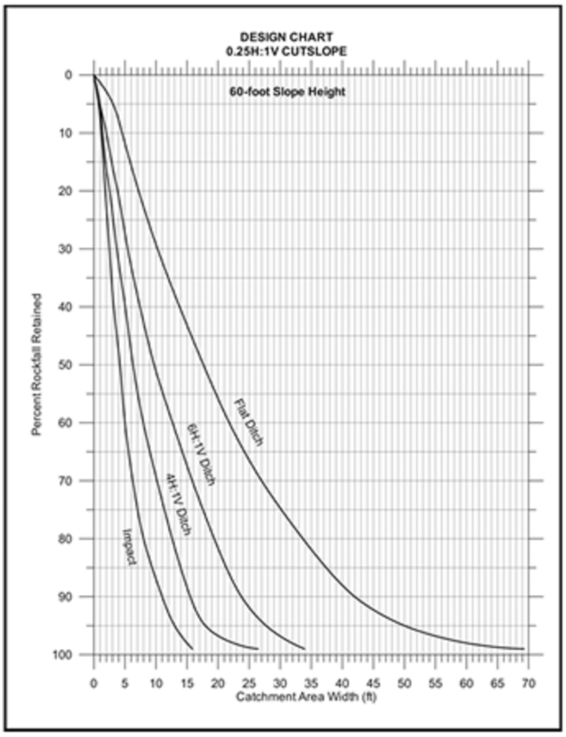
- **Transport Corridors Adjacent to Steep Cut Faces**: Catch ditches are most effective for smaller rockfalls (<0.5 m^3) but can also be adapted for larger boulders where space allows. In both cases, they perform best where the material is falling near vertically. These areas are particularly suitable because they often encounter rockfalls or slope failures due to exposed, unstable cuts. Catch ditches here can efficiently manage debris to protect roads, railways, and other infrastructure, minimising risks to users and damage to assets.
- **Available Low Gradient Upslope Space**: Where benching (natural or anthropogenic) within a slope occurs, there are lower-gradient areas that may be suitable to construct a catch ditch, either through widening and flattening or with the inclusion of a small bund. Design for these includes consideration for necessary drainage and clearance provisions, ensuring they perform as intended over time without becoming a burden to maintain.
- **At the Base of the Slope**: Installing catch ditches at the base of a slope is generally more advantageous than upper or mid-slope locations. This positioning allows easier access for construction, inspection, and clearance operations. Additionally, debris tends to accumulate naturally at the toe of the slope, enhancing the effectiveness.

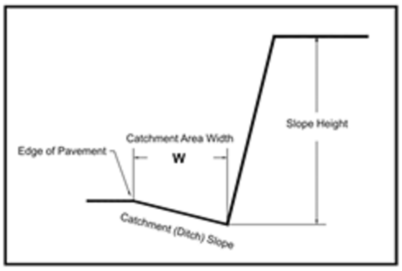
6.3.3.3 Effective Application

To effectively implement a catch ditch, a thorough understanding of the failure mode is required to determine the trajectory, boulder size, and possible velocities. Additionally, an accurate estimation of debris volumes is essential for the sizing of the catch ditch. These factors ensure the design is appropriately tailored to manage the specific risks posed by different types of slope failures.

- **Frequency-Magnitude Curves** are a critical tool for this process, as they help model the likelihood and scale of slope failures based on historical and geological data. By analysing these curves, engineers can design catch ditches that meet the necessary performance requirements for both routine and critical events, ensuring safety and efficiency.
- **Estimating Debris Volumes** involves assessing the in-situ source material and applying suitable factors to account for the entrainment and volume increase. A commonly used method is to apply a bulking factor, which accounts for the voids that form when intact rock breaks down into debris. This factor depends on the geological setting and debris' grading range, factors typically fall between 1.1 to 1.6 (CIRIA, 2018). Using these considerations ensures the catch ditch is sized correctly to accommodate the actual volume of debris likely to be encountered.
- **Historical Data** from past events can also provide valuable insights into expected debris quantities, and the material's behaviour and volume can be reliably predicted based on previous occurrences.
- **Simple Guidance Design Tables** can be found in the Oregon Department of Transportation *Rockfall Catchment Area Design Guide* (Pierson, Gullixson, and Chassie, 2001), as exemplified in Figure 6.30 below. These tables are developments of the rockfall ditch chart developed by Ritchie (1963) and later adapted in the FHWA Rock Slopes; Design, Excavation and Stabilisation (1989).

Dampening Material, such as pea gravel (AP19 or similar), can be included within catch areas with limited spaces to increase their effectiveness in attenuating rockfall. These materials work by absorbing the energy of falling rocks, significantly reducing their energy, and minimising bouncing and rolling. This attenuation effect ensures that debris remains contained within the catch area, even in constrained locations where space limits the size of the structure. However, there are several key considerations for when and when not to apply a dampening material:





Quick Reference - 60-Ft Slope Catchment Area Width - **W**				
Percent Rockfall Retained	Impact	Catchment Area Slope		
		4H:1V	6H:1V	Flat
	W (ft)	**W** (ft)	**W** (ft)	**W** (ft)
50%	4	6	10	18
75%	7	11	18	30
80%	8	13	19	34
85%	9	14	21	37
90%	11	16	24	42
95%	13	18	28	50
99%	16	26	34	69

Figure 6.30. Example Design Chart for an 18 m (60 ft) high slope (Source: Pierson, Gullixson, and Chassie, 2001)

- Catch areas incorporated to existing structures, such as on top of tunnel portal extensions or rock shelters, can greatly benefit from a dampening material to reduce the transfer of energies to the underlying structure.
- While dampening materials improve the stopping potential, they can complicate maintenance and clearance activities. The fallen debris often mixes with the dampening materials, making it more challenging to separate and remove. Over time, this contamination may necessitate replenishment of the dampening layer, adding to maintenance efforts.
- In addition, it is challenging to quantify the impact of dampening material, although applying suitable material properties in numerical modelling (such as RocFall) can provide some indication.
- Where catch ditches are within the natural ground, such as at the base of a slope, the effectiveness of dampening material is often negated by the potential for scouring of dampening materials, as catch ditches will often double-up as drainage channels and are prone to scour over long periods time or during high rainfall events. In certain instances, dampening material will not be practical due to the requirement of scour protection.
- **Debris flow** catchment areas differ from the above approaches, which are most effective for managing rockfalls and "dry" debris failures. Whereas for more complex debris flow scenarios, additional considerations are required. These events involve fluid-like movement of debris, which can significantly increase the volume and mobility of material. Detailed guidance for designing catchment areas to address debris flows can be found in the *NZGS Slope Stability Module Unit 6 (under development)*.

6.3.3.4 Considerations and Limitations

When designing and implementing rockfall catch ditches, several critical considerations and limitations must be addressed to ensure their effectiveness and long-term functionality:

- **Risk of Underestimating Volumes**: There is a significant risk of underestimating debris volumes, particularly if the assessment only accounts for source material and overlooks factors such as entrained vegetation or additional debris mobilised during failure events. Ensuring accurate volume estimation requires incorporating conservative factors of safety and understanding potential contributions from secondary materials.
- **Involvement of Experienced Professionals:** Simplified approaches, such as those shown in Figure 6.30, should involve experienced rock slope designers (e.g., engineering geologists or geotechnical engineers).

Figure 6.31. An example of a clearance marker used to indicate location and angle of structure, Kaikōura (NCTIR, Google Streetview, 2024)

Figure 6.32. A larger catch area integrated with a bund, Kaikōura (NCTIR, 2019)

Figure 6.33. A typical rail-side catch ditch to retain minor rockfalls, Stillwater to Ngakawau Line (KiwiRail, 2023)

- **Complex Hazards and Larger Landslides:** For more complex hazards, such as larger landslides or combined failure mechanisms, advanced modelling approaches should be utilised. These include rockfall trajectory analysis, fluid dynamics simulations, and deposition pattern studies. Secondary failures, such as slope instability within the captured debris, must also be considered. This includes assessing whether the debris could trigger additional failures and ensuring the catchment is robust enough to manage these scenarios.
- **Drainage:** Effective drainage pathways are critical for managing water within settled debris. Without proper drainage, water can accumulate, potentially weakening the catch ditch or leading to further failures. Special attention should be given to catch ditches, which will often double as longitudinal side drains, ensuring they remain functional under debris load.
- **Cascading Impacts:** Debris within a catch ditch may block the associated longitudinal drainage systems, leading to cascading impacts such as seepage or overflow. This can destabilise nearby slopes or infrastructure, increasing the potential for larger failures downstream. Design solutions should incorporate contingency measures to mitigate these secondary impacts, such as overflow spillways or sub-soil redundancy drainage systems.
- **Maintenance and Performance:** Rockfall catch ditches require regular maintenance to remain effective. Once partially filled, their performance diminishes significantly, leaving them unable to manage additional failures. Over-excavation during clearance is another concern, where excessive debris removal could inadvertently compromise part of an associated catchment structure. For example, in Figure 6.31 below, markers can be installed to prevent over-clearance by clearly delineating the edge and gradient of the containment structure.

6.3.3.5 Example Applications

Two examples are provided below where a catchment has been installed on varying scales to retain material.

6.3.4 Rigid Barriers

6.3.4.1 Description

Rigid barriers are classified as structures that are designed to intercept, deflect, or contain falling rocks, relying on their stiffness, strength, and mass to withstand the kinetic energy of the impact. The most common rigid barrier is a bund, but may also include interception walls or gabion/concrete block structures. Commonly rigid barriers are constructed using materials that offer minimal deformation upon impact, enabling their placement closer to the element at risk, however for larger energies the resulting bund tends to occupy a larger footprint due to the mass required. In addition, the rigidity makes this type of barrier more susceptible to damage from high-energy impacts.

Figure 6.34. An example of a non-deformable, Timber Debris Interception (TDX) Wall, Kaikōura (NCTIR, 2020)

Figure 6.35. An example of a deformable MSE bund, with deformation observed from a recent rockfall impact, Kaikōura (NCTIR, 2020)

There are two main types of rigid barriers:

- **Non-Deformable (Walls):** Constructed from low-deformation materials like concrete, timber, or steel. These barriers are suitable for relatively lower-energy impacts (< 30 kJ) and have a smaller footprint. These barriers work especially well for large volumes with low energies, such as in slower debris slides.
- **Deformable (Bunds):** Most common type of rigid barrier and built using partially compressible materials that can absorb some of the impact energy through deformation and internal compaction. They are capable of withstanding multiple impacts with very high energy, depending on their construction material and reinforcement. The most common type is Mechanically Stabilised Earth (MSE) walls or Reinforced Earth embankments, as well as earthen fill embankments and modular block systems.

The majority of the below guidance focuses on the more commonly applied bunds. Whereas only some of the information will be relevant to non-deformable rigid walls, as indicated throughout.

6.3.4.2 Intended Use and Benefits

The design and application of rigid rockfall barriers cater to a wide range of energy levels and site-specific challenges, making them a versatile solution for managing slope failures.

- **Energy Absorption:** Bunds are designed to handle a broad spectrum of impact energies. Unlike other options, such as flexible barriers, bunds are better suited for areas with very high-impact energies or scenarios involving multiple simultaneous impacts. Their durability and ability to withstand significant forces make them suitable for protecting critical infrastructure or high-risk zones.
- **Height and Footprint:** Rigid barriers must account for the bounce height of rockfalls. For bunds in particular, consideration is needed for the 'run-up' of rolling boulders, as shown in Figure 6.36. If bounce heights are underestimated, the effectiveness of the structure is compromised. For bunds, the footprint of the structure often increases exponentially with height. This relationship requires a careful balance.
- **Integration with Catchment Areas**- Both types of rigid barriers are often paired with catch area/ditch to enhance overall system performance. The catch ditch can manage smaller debris or secondary material that is captured or deflected by the rigid barrier. This combination reduces maintenance requirements for the rigid barrier itself while providing an added layer of protection.
- **Maintenance and Visibility**- For bunds, visibility behind the structure is inherently reduced, which can make regular inspections more challenging. Frequent inspections and timely debris clearance are essential to maintaining their functional performance. Accumulated debris can compromise their ability to manage subsequent impacts, reducing their effectiveness over time.

By considering these factors, rigid rockfall barriers and bunds can be effectively designed and maintained to provide long-term, robust protection tailored to site-specific conditions and energy levels.

6.3.4.3 Effective Application

Guidance for the design of bunds is well covered in MBIE *Rockfall: Design Considerations for Passive Protection* (2016), Appendix B – Earth Bund Design Calculations. The key aspects of the design and application should consider:

- **Geometry**: Determining the appropriate height, width, and slope angles of the bund embankment based on factors like design block diameter, energy, and bounce height. These factors will determine the potential penetration depth, calculated as the depth an impact may have into the deformable material of the bund. Considerations are also needed for the potential for rocks to roll up and over the structure.
  - Trajectory Analysis: The upslope face of the bund should have an angle designed to minimise the probability of boulders rolling up and over the structure. Typically, this can be performed using 2D simulation tools such as RocFall, as shown in Figure 6.36 below. Generally, an upslope face angle of 70–80° is adopted to manage boulder trajectories effectively. Additionally, trajectory analysis can estimate the expected rockfall energies, which are critical for design considerations.
  - **Penetration Depth**: The maximum depth to which an impact may penetrate into the deformable material of the bund can be estimated using curves provided in Appendix B-E3 of MBIE 2016 (redrawn from Calvetti and Di Prisco, 2007). These curves correlate penetration depth with anticipated rockfall energies. In alignment with this approach:
    - For the ULS (Ultimate Limit State) boulder at the height of impact, the bund should be at least 2 times the anticipated penetration depth.
    - For the SLS (Serviceability Limit State) boulder at the height of impact, the bund should be at least 5 times the anticipated penetration depth.

Designing a rigid barrier with suitable geometry ensures the structure can effectively absorb impacts and prevent breaches by boulders under both ultimate and serviceability limit impacts.

- **Stability:** Bunds must remain stable under static and dynamic loading conditions to ensure long-term functionality and safety, including:
  - **Internal Stability:** The structure's resistance to sliding, overturning, or internal failure under applied loads. This includes assessing the strength and compaction of materials used for construction.
  - **Global Stability:** The stability of the entire bund system, including the surrounding slope or terrain, ensuring the bund does not destabilise or cause slope failure under loading. This shall also consider the additional weight of accumulated debris (and possible saturation) captured by the bund (if this is reduced from a theoretical maximum to account for anticipated maintenance and clearance, this needs to be considered against the risk of the maintenance not being completed and the resulting impacts)
- **Dynamic Performance:** Rigid barriers (walls and bunds) should be designed to withstand both Maximum Energy Level (MEL) and Service Energy Level (SEL), considering:
  - **MEL**: The barrier must prevent piercing or structural collapse due to unravelling, excessive deformation, or material failure during extreme impact events. This may involve using high-strength materials or reinforcing the structure.
  - **SEL:** The barrier must limit deformation to a manageable level, ensuring post-impact maintenance is straightforward. This allows the structure to remain functional without extensive repair or replacement after lower-energy events.
- **Catch Area:** Rigid barriers (walls and bunds) are often combined with an upslope catch area of varying size to enhance their ability to contain rock blocks. The catch area design must consider the trajectory and bounce height of rocks, ensuring the bund and catch area work together effectively.

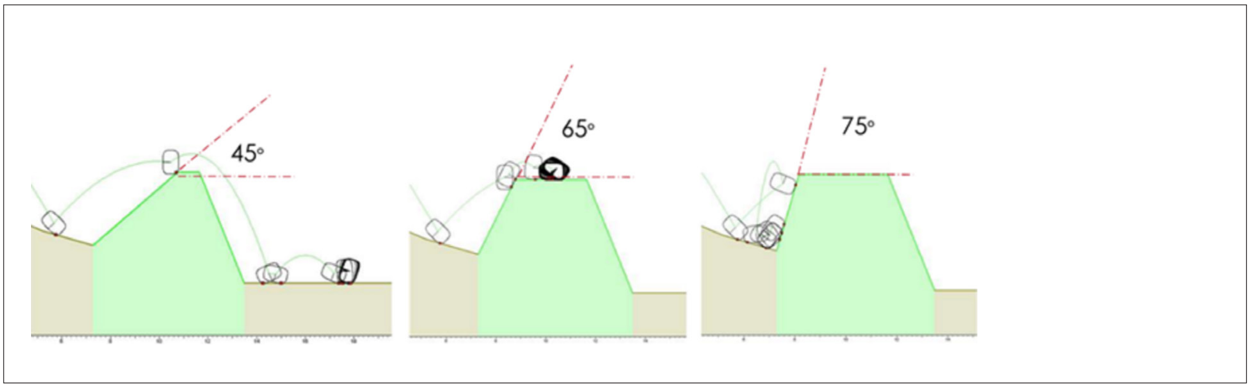


Figure 6.36. Extracted from Macaferri Rockfall Training Guidance, 2018

Figure 6.37. An example of a vegetated MSE Bund, Sumner (Google Streetview, 2024)

Figure 6.38. An example of the ease of clearance of a TDX Wall

- **Durability and Reparability:** The choice of materials for the facing and backfill significantly impacts the durability and reparability of rigid barriers. Materials should resist shattering, spalling, and weathering due to environmental exposure (e.g., freeze-thaw cycles, erosion). Materials should be easily repairable or replaceable after an impact to minimise downtime and maintenance costs. For instance, modular designs or sacrificial elements can simplify repairs.
- **Drainage:** Adequate drainage provisions are essential to maintain the barrier's structural integrity and minimise environmental impacts. This includes internal drainage systems within bunds, as well as components that allow captured debris to drain freely, reducing the risk of saturation.

By addressing these considerations during the design phase, rigid barriers can be tailored to specific site conditions and hazard scenarios, providing robust, durable, and maintainable protection against rockfall and debris impacts.

6.3.4.4 Considerations and Limitations

Rigid barriers, both walls and bunds, offer critical protection against rockfall hazards, but their effectiveness depends on carefully addressing various design considerations and limitations.

- **Site Limitations**: Often the energies involved exceed non-deformable rigid barriers (walls). In addition, the resulting size of the deformable rigid barriers (bunds) makes installation within narrow footprints challenging. Determining the rigid barrier's height, width, and length during the optioneering or feasibility to align with the site-specific limitations and expected hazard characteristics is a critical step.
- **Foundation Bearing Capacity:** The mass and forces involved with a rigid barrier requires the foundations (of either the wall or bearing capacity beneath a bund) to have sufficient strength under both static and dynamic loads. Soil investigations should assess potential issues, such as insufficient bearing capacity, possible settlement or liquefaction. As seismic events are likely to result in rockfall, liquefaction which could compromise stability is a key risk that needs to be addressed. Mitigation measures, such as soil reinforcement or alternative foundations, may be necessary for weak soils.
- **Access:** A service road should be incorporated into the design to facilitate maintenance, routine inspections and repair of walls and bunds. Easy access for machine equipment to clear accumulated debris is key.
- **Vegetation and Finishes:** This is often overlooked during design but for vegetated finishings on bunds the choice of planting must account for survival in minimal-water environments, or consider alternative finishes, such as riprap or exposed aggregate, to minimise maintenance needs.
- **Visibility of Debris:** Non-deformable rigid barriers, such as timber debris interception (TDX) walls, should incorporate measures to manage visibility behind barriers to monitor debris accumulation. This may include a slot within the timber to remove the need for accessing behind the structure in the higher risk zone to assess accumulations. In addition, the removal of timbers to access sections for clearance must be straightforward to maintain performance.
- **Whole of Life Cost:** Rigid systems, especially those requiring advanced materials or significant excavation, can be costly to construct and maintain. Factors like steep terrain or weak soils can also complicate construction, necessitating advanced techniques or additional resources, adding to the construction costs. However, the longer-term maintenance of a rigid barrier, specifically bunds, is often lower than other rockfall protection structures options due to the durability and the use of simple materials.

By integrating these considerations into the design and application of walls and bunds, their functionality and longevity can be maximised while addressing site-specific challenges effectively.

6.3.4.5 Example Applications

Two examples are provided below where a rigid barrier has been installed on varying scales to retain material.

Figure 6.39. A large earth fill bund, constructed from site won material, designed to protect the adjacent transport corridor, Kaikōura (NCTIR, 2018)

Figure 6.40. An example of on-slope diversion bunds used to redirect debris. These require careful consideration of maintenance to maintain functionality and access for constructability, and ongoing inspections and repairs

6.3.5 Flexible Barriers

6.3.5.1 Description

A flexible or dynamic barrier (also commonly referred to as a rockfall fence) is dynamic structure consisting of mesh, posts, and ropes which is designed to capture rockfall and transfer the load to anchorages. In higher energy systems, braking elements are incorporated to disperse the energy.

Of all the Rockfall Protection Structure (RPS) discussed within this document, flexible barriers are the most well covered in terms of available industry design guidance. These documents include:

- MBIE (2016) – Rockfall: Design Considerations for Passive Protection Structures
- ONR (2021) – Technical requirements for flexible protective systems against rockfall
- Grimod and Gianchetti (2012) – Italian guidelines for flexible barriers (UNI)
- NZTA (2023) – Rockfall Protection Structures Design Guide

Therefore, the intention of this document is to provide the intended use scenarios as well as some additional considerations and limitations to consider for these structures.

6.3.5.2 Intended Use and Benefits

Rockfall fences are a versatile and effective solution for managing rockfall hazards across a range of energy capacities and site conditions. Their design and application are adaptable to varying levels of risk, making them suitable for both temporary and long-term protection measures.

- **Adaptability:** Rockfall fences are designed to accommodate a wide range of energy capacities, typically between 10 and 10,000 (kJ). The height and energy absorption capacity of the fence can be tailored to the specific hazard, such as single-block events, large single blocks, or multiple smaller blocks with high cumulative energy.
- **Efficiency:** Rockfall fences generally have a narrower footprint compared to rigid barriers, especially when designed for equivalent energy capacities. However, the deflection zone of rockfall fences must be carefully considered during design and is discussed below.
- **Construction and Maintenance:** Rockfall fences are generally quicker to construct and easier to replace following an impact compared to rigid barriers, making them ideal for locations requiring rapid deployment or regular repairs. This shorter construction time often results in a lower upfront cost.
- **On-Slope Applications**: A key benefit, and where rockfall fences are most effectively applied is an on-slope solution, and where other systems are not viable. This is especially true in areas with clearance challenges or limited space for larger structures exist. Although access for installation and maintenance can be challenging, with proper planning, design and experienced contractor, these constraints can be overcome.

In addition, flexible barriers can also be viable in other applications.

- **Shallow Landslide Barriers:** Flexible barriers can also be developed for shallow, translational landslides. This requires the design to consider debris loading and subsequent overtopping (measured in kPa) rather than discrete energy impacts (kJ). This often requiring a distinct engineering approach, with good guidance outlined in Kwan and Chueng (2013). Some proprietary barriers have both a rockfall energy and debris load capacity which can be effectively used in multi-hazard environments, which is often the case in New Zealand.
- **Temporary Mitigation:** Rockfall fences can serve as temporary solutions to address short-term, high-likelihood risks. This is particularly beneficial in scenarios where long-term solutions are delayed or where immediate action is required. Temporary fences can help mitigate hazards cost-effectively, especially when considering the lower initial costs and minimal footprint compared to other systems.

6.3.5.3 Effective Application

Rockfall fences must be designed and implemented with precision to ensure effective hazard mitigation. Their performance depends on understanding key design parameters, incorporating reliable testing data, and adapting to site-specific conditions.

- **Rockfall Trajectory Analysis:** Similar to other RPS, understanding the expected energies and bounce heights of the rockfall is critical to determine the suitable barrier to apply. It is essential to assess the impact heights, and the residual height of the barrier once impacted to ensure it can contain falling rocks effectively. In addition, both kinetic and rotational energies of rockfalls should be evaluated and where possible, ground truthing (field verification) should complement modelling to refine design inputs and improve accuracy. Good guidance on rockfall modelling is provided in NZTA Waka Kotahi Rockfall Protection Design Guide Appendix A (New Zealand Transport Agency, 2023), and GNS Consultancy Report 2011/311 (Massey, et. al., 2012).
- **Deflection:** The amount the mesh and total barrier system elongate (deflect) during an impact is a critical factor, especially when the protected elements are close to the RPS. Deflection includes both a *dynamic deflection* (the greatest horizontal extent a barrier may stretch), and *residual deflection* which is the position the fence returns to with load. A general rule of thumb is a deflection ratio of 1:1 ratio of elongation to the total height of the

Figure 6.41. An example of the use of a middle transmission rope on an SL-150 Geobrugg Shallow Landslide barrier to reduce deflection into the rail corridor, Kaikōura (KiwiRail, 2023)

barrier, although specific deflection values should be obtained from manufacturers.

- Reducing deflection can be achieved if required through the installation of an intermediary middle rope horizontally between the top and bottom ropes. This can reduce deflection by up to 40% (depending on the system), however, this adjustment increases the barrier stiffness, which may decrease overall energy absorption capacity.
- In some cases, deflection can be treated as a temporary state, enabling reduced clearance requirements for shorter periods of time.

- **Energy Considerations (SEL vs. MEL):** As outlined in the MBIE (2016) guidance for RPS design, designers should select and apply only one energy level design based on site conditions and risk profiles.
  - **SEL (Service Energy Level)** represents the energy level a barrier can repeatedly absorb without significant damage and is generally used where multiple frequent impacts are expected.
  - **MEL (Maximum Energy Level)** represents the maximum energy the barrier can withstand during a single extreme event and is generally used where there is a single event being mitigated. This is often the stated "capacity" of a proprietary system.
- **Anchorage**: Flexible barriers are often proprietary systems designed and manufactured by specialist companies (such as Geobrugg, Maccafferri, Trumer and others), which have been designed to withstand a specific energy capacity and bounce height. The main purpose for the designer is to ensure suitable placement relative to the hazard, and to determine the suitable anchorage and connection with the site-specific ground conditions. Guidance on the design of anchorages is well covered in the NZGS Ground Anchor Guideline, 2023. Specific to flexible barriers some consideration is needed for the different types of supporting anchors, outlined below.
  - **Lateral Anchorage:** These anchorages connect the top and bottom ropes of the fence and provide the main energy absorption connection point, often with the greatest loads. These anchors are also installed in isolation and therefore provide a potential for a single point of failure of the system. As such these anchors are better designed with a higher Factor of Safety for both grout/ground strength (> 3) and bar/grout strength (> 2), based on the uncertainty Testing of these anchors is often critical to confirm capacity, but also provides the greatest challenge as they are often inclined making set-up of a testing rig challenging. These challenges need consideration during the application phase to manage the possibility of reduced testing and the need for higher conservatism in design.

- **Post Supports:** These anchors are often incorporated into a concrete plinth or directly fixed to the base of the post. These anchors provide the connection of the vertical posts to the ground and are often working at lower loads in both tension, and shear. Testing for these anchors is generally more straightforward, but sequencing of tests is improved if completed prior to the erection of the fence.
- **Upslope Anchorage:** These provide additional support to the top of the posts and assist in energy absorption and retention of material. Although these anchors do not create a single failure point, the head detail of these anchors is often in the firing line of debris, and therefore, consideration for some loss of surface material should be considered; the total length considered will vary for soil, rock, and depth of instability. Compressive support will also need to be considered, as often there is a requirement for reinforced concrete support, a technique developed is the use of a spiral reinforcing cage and large diameter PVC casing to the unstable depth to provide an easily applied localised concrete head detail, as shown in Figure 6.42 below.

Figure 6.42. An example of a localised concrete head detail to support the upslope anchorage (NCTIR, 2019)

- **Contouring Anchors:** In some cases, to ensure connection of the fence and mesh to a variable topography, additional short-length anchors/ pins may be needed to contour to the slope; these often are designed to a nominal load and anticipated to fail under a SEL and MEL event.

- **Barrier Testing and Verification:** The majority of flexible barriers will be proprietary systems; however, some applications may be designed as bespoke, non-proprietary systems.
  - **Proprietary Barriers:** typically tested to EAD 340059-00-0010 standards (formerly ETAG 027), however, EAD testing does not always require independent verification. Designers should review testing data and, where necessary, seek additional assurance from manufacturers to confirm the system's suitability for the specific application.
  - **Non-Proprietary Systems:** Non-proprietary barriers require independent testing or alternative verification methods to ensure their performance when used as an interception structure. Any field testing should replicate site-specific conditions as closely as possible to ensure reliability and effectiveness.
- **Maintenance:** To ensure the barrier remains operational, scheduled and post-event maintenance is required. Considering how and when the maintenance will be achieved during the design stages will result in a better overall system. Good guidance on the maintenance of rockfall systems exists in the NZTA Waka Kotahi Rockfall Protection Maintenance Guideline (2023).

By addressing these factors during design and implementation, rockfall fences can effectively mitigate rockfall hazards and protect infrastructure and assets at risk.

6.3.5.4 Considerations and Limitations

Beyond the general requirements outlined in the guidance documents suggested in Section 4, there are several considerations that need to be addressed during the design of rockfall fences. These points focus on site-specific challenges, system integrity, and long-term maintenance to ensure long-term performance of the structure.

- **Anchorages and Ground Conditions:** Anchorages form the connection of the barrier to the ground and, therefore are critical to system performance. In areas with poor ground conditions, such as talus slopes or at the toes of recent slope activity, conventional anchoring methods may not be viable. Alternative solutions include load bearing concrete blocks or multiple anchor systems for a single contact point may be required to distribute loads effectively.
- **Design Life:** The design life of a rockfall fence should align with the expected service life of the infrastructure it protects, taking into account environmental conditions, corrosion potential, and maintenance access. Consideration should be given to the long-term durability of materials such as mesh, posts, cables, and anchors, particularly in harsh environments where exposure to moisture, freeze-thaw cycles, or salt spray is likely. Where extended design life is required, protective coatings, corrosion-resistant materials, and regular maintenance schedules should be specified to make sure there is continued performance over time.

- **Installation and Benching:** Where possible, it is recommended to avoid creating benches on slopes to aid installation. Although it may make installation and maintenance slightly easier, cutting benches can lead to localised erosion and undermining of the posts, compromising the stability of the barrier. Installation should minimise any disturbance to the natural slope profile.
- **Debris Clearance:** Debris removal and maintenance access is often missed or overlooked in much of the guidance documentation; however, considering the practicalities of removing debris, including the tasks of releasing braking elements, cutting high-tensioned mesh and ropes, and similar activities should be assessed in design and accommodated to be safer where practical. Using a Safety by Design approach is a critical step and is discussed in more detail in Section 9 of this document.
- **Fence Geometry:** The layout and geometry of the flexible barrier should account for variable topography. Achieving a proper fit often requires a tailored solution with considerations for minor deviation from standard rope, post, and anchorage angles. With collaboration with proprietary providers, length, angles, and connections can be refined to best suit the site conditions.
- **Lateral Extents:** The lateral extents of barriers require careful consideration during design. Lateral anchorages often extend several meters beyond the final post and need to be accounted for in the design layout. In confined spaces, such as gullies, bespoke details or additional mesh panels may be necessary to ensure the fence ends align closely with the surrounding topography. Lateral anchors are sometimes required to extend downslope, and this can be restrictive where barriers are abutting highways. infrastructure and other structures.
- **Anchors Testing:** Lateral anchors are often installed at an angle of horizontal and vertical to best align with the top and bottom ropes. As such, they prove to be challenging to test; however, as one of the single points of failure in the system, the assurance of this anchorage is important. Designers may want to incorporate additional safety factors to compensate for the limited testing capabilities.

By integrating these considerations, rockfall fence designs can achieve greater reliability, safety, and efficiency, even in complex or constrained environments.

6.3.5.5 Example Applications

There are a number of examples where flexible barriers have been installed, namely along the Kaikōura Coast, which saw a significant number installed in response to the 2016 Kaikōura Earthquake.

Figure 6.43. An example of a non-proprietary system, Otago (Waka Kotahi Rockfall Protection Design Guideline, 2023)

Figure 6.44. An example of a newly completed proprietary (Geobrugg) rockfall and shallow landslide barrier, Kaikōura (NCTIR, 2018)

6.3.6 Drapes

6.3.6.1 Description

A drape or 'drapery mesh', comprises steel mesh placed over a source area, such as a weather rock face, to limit the 'fretting' and outward trajectory of rockfall. Drapery meshes are used in a variety of situations to mitigate rockfall hazards. They are commonly used in areas where falling rocks are a concern but where it is acceptable for failures to occur beneath the netting, such as when the rockfall frequency is high, but volumes and energies are generally low. Different from active mesh, drapes are not appropriate where the rock mass needs to be stabilised to prevent failures from occurring.

Drapes are often used in conjunction with other systems, such as a simple catch ditch or a more complex rigid or flexible barrier, in order to reduce the height and energy requirements through attenuation of falling rocks.

6.3.6.2 Intended Use and Benefits

Drapery meshes are best utilised in situations where:

- **Close Proximity Between Hazard Source and Element at Risk**: These systems are well used on near-vertical weathered rock faces that are close to the element at risk. They are well used when the frequency of small rockfall is high across a larger area, and access for maintenance at the base is suitable.
- **Small to Medium-sized Rockfalls are Expected:** This is because the mesh is typically designed to contain individual blocks or smaller blocks that form a debris pile at the base.
- **A Cost-Effective Solution is Required:** Drapery systems can be less expensive to install than other types of rockfall mitigation measures, such as stabilisation netting systems.
- **The Surface is Rough (without having large hollows or protrusion):** The surface of the slope contributes to the attenuation of the rockfall between the mesh and the slope. A uniformly rough slope increases this attenuation or disruption to the falling blocks.
- **The Slope has a Distinct Crest:** A prominent and distinct crest or change in slope is beneficial as it improves the interface friction between the mesh and slope, which reduces the load transferred to the crest anchorages.
- **There is Enough Catchment Space Available to Allow Rockfall Debris:** Drapery systems do not prevent rockfall, and can often contain high volumes of debris, so it is important to have adequate space at the base of the system to allow for this debris to accumulate. Maintenance of this catch area is an important consideration during design.

6.3.6.3 Effective Application

Guidance for the effective design and application of draped mesh systems is provided in CIRIA Report C775 (Koe, Murphy, & Nicholson, 2018). The CIRIA guidance provides the relevant design load cases to consider and elements to apply. This guidance can be supplemented by NZS 1170 for the relevant considerations applicable to New Zealand conditions, such as the specific regional snow loading (NZS 1170.5). The items below provide some additional considerations in the effective application of draped meshes.

- **Anchor Design and Placement:** Anchors are used along the top, bottom, and lateral perimeter of the draped mesh, and should adhere to the NZTA Bridge Manual (NZ Transport Agency, 2022) and NZGS Ground Anchor Guidance (2019). In cases with a high frequency of failures, perimeter anchors may be optioned to have tether attachments (0.5 – 1 m length of wire rope between the mesh and anchor connection) to allow more dynamic movement within the system. Bottom anchors are generally used for securing the system in narrow corridors or areas with limited space at the base, however, this does limit the ability for material to 'self-release' from the base of the drapery and can result in high maintenance requirements. Where load cases are higher, wire rope reinforcement along the perimeters can improve performance.
- **Point of Failure Philosophy:** Considering the point of failure of the system if overwhelmed by a larger-than-design event case is recommended for drapery meshes. In general, the bottom rope should be the 'weakest point' in the system to allow for debris to spill out at the base rather than causing failure of top-row or perimeter anchors. This approach minimises damage to the system and ensures safer maintenance and repair processes. Critical load cases such as ice, snow and debris caught within the system should be considered in design.
- **Maintenance and Material Clearance:** Regular maintenance is essential to ensure the continued performance of draped mesh systems. Considering the approach for debris clearance during the design phase is key to facilitating safe and efficient operations. The practicalities of accessing and removing material from the mesh should be addressed, particularly in areas with steep slopes or limited ground access. Design features such as strategically placed release points or access pathways can reduce operational risks and costs.

By addressing these considerations, draped meshes can be effectively applied to manage rockfall hazards while ensuring safety, durability, and ease of maintenance.

6.3.6.4 Considerations and Limitations

Draped mesh systems, while effective for managing rockfall hazards, have notable limitations that should be carefully evaluated during their design and application. A primary challenge lies in determining the extent of the drape, as it should extend beyond the immediate hazard zone to account for potential head scarp regression and lateral extension and the system's primarily non-stabilising effect. Below are the key limitations associated with draped meshes:

- **Regular Maintenance Requirements:** Draped meshes require ongoing maintenance to clear debris and repair damage caused by rockfalls or environmental factors. Maintenance activities can be costly and time-consuming, particularly in areas requiring specialised access, such as those involving traffic management or rail protection.
- **Not suitable for larger blocks:** Larger blocks (between 0.5 and 1.0 m^3) can potentially cause dynamic impact failure of the mesh.
- **Less suitable for uneven and non-uniform slope profiles:** Hollows and protrusions that draw the mesh away from the slope may require targeted treatment prior to placing the drape.

- **Visual Impact:** Draped mesh systems can be visually unappealing, especially when installed in prominent locations like urban settings or tourist areas.
- **Whole-Life Cost Considerations:** The installation, maintenance, and repair costs must be evaluated holistically to ensure the drapery system provides value over its entire lifespan. Systems requiring frequent intervention may lead to higher cumulative costs compared to other solutions over the life of the structure.

By understanding these limitations, designers can better assess the suitability of draped mesh systems for specific sites and ensure they are implemented in a way that maximises effectiveness while managing costs and visual impacts.

6.3.6.5 Example Applications

- The following examples illustrate the use of drapery mesh systems for rockfall mitigation:

Figure 6.45. A simple drapery mesh system installed adjacent to a railway line (KiwiRail, 2023)

Figure 6.47. Snow loading impacting a draped mesh system, Fjordland New Zealand (Photo courtesy of Leon Gerrard, Heads Up Access)

Figure 6.46. A drapery mesh system in Clifton Terrace, Christchurch (Photo courtesy of Eric Ewe)

6.3.7 Attenuators

6.3.7.1 Description

Attenuators are a specific type of passive rockfall protection structure (RPS) intended to slow rocks by controlling their trajectory, compared to capturing or stopping the blocks. This energy attenuation enables a reduction in the capacity of a secondary passive structure (such as catchment areas, rigid barriers, or flexible barriers) to stop and contain the blocks.

Attenuators are generally installed in a similar way to flexible rockfall barriers, consisting of posts, wire ropes, and intercepting mesh. The key difference to a flexible barrier is that the intercepting mesh is slightly longer and not fixed at the base of the fence. The length of this mesh is generally three times the height of the fence. In some situations, a 'hybrid attenuator" may be used where the tail may be much longer, forming a catchment drape on the lower slope. This often involves additional securing of the perimeter of the tail to prevent material from escaping. Design guidance on attenuators and hybrid barriers is limited, mainly down to the challenges around quantifying the energy reduction and determining the variable behaviour when the block and attenuator tail interact.

6.3.7.2 Intended Use and Benefits

Attenuators are particularly useful in the following situations:

- **High Rockfall Frequency:** Attenuators are well-suited for areas with a high frequency of rockfall events, and cleaning a standard rockfall barrier that catches and retains rocks would be costly. Attenuators and hybrid barriers can also be used where maintenance access is difficult, as they allow debris to collect at the base of the slope.
- **Limited Space:** Attenuators can be a more space-efficient solution than other RPS types like catch ditches or rock sheds (see Section 6.3.3). They are also suitable when the required protection height or energy level exceeds the capacity of existing protection structures like rockfall galleries (see Section 6.3.8). The attenuator can reduce the kinetic energy of the rockfall to match the capacity of these existing structures. For this reason, attenuators are often installed closer to the source area (or mid-slope) compared to conventional rigid or flexible barriers, which are often located closer to the element at risk or toe of the slope.
- **High Energy Impacts:** When rockfall energies increase, the capacity and resulting structure of a rigid or flexible barrier increase, which can take up excessive space and result in large anchor loads. Attenuators offer a solution for managing these higher-energy impacts. Attenuators can be constructed with lighter structures than conventional flexible barriers, making them easier to install in inaccessible zones. This lighter construction, combined with their self-cleaning nature, contributes to lower construction and maintenance costs compared to structures with larger deflections. The downslope passive structure can also be reduced in size and capacity, as the energies and bounce heights will be attenuated.

6.3.7.3 Effective Application

The choice to implement an attenuator or hybrid barrier is influenced by project-specific constraints such as rockfall frequency, space limitations, cost, construction time, and topographic restrictions. Attenuators provide a viable solution where traditional flexible barriers or drapery systems are not practical, and a combination is required.

There are no guidelines provided for the design of attenuators and hybrid barriers, and the current industry approach relies on empirical methods, engineering judgment, and collaboration with manufacturers. Some recent research and guidance from Hofmann and Shevlin (2019), and Wyllie et al. (2017) outline approaches to determine required attenuator capacity. In addition, providers of proprietary attenuator systems are developing online dimensioning tools to assist designers in checking design assumptions against specific systems.

A key aspect of the effective application of an attenuator or hybrid barrier for rockfall protection requires the consideration of both dynamic and static design cases.

Dynamic Design

The dynamic design approach is similar to that of a standard catch fence as referenced above, relying on trajectory analysis to determine the minimum energy capacity, velocity, and required height of fence posts. This is supplemented by observations of hybrid fence behaviour and documented performance. The key considerations for the dynamic design include:

- Determining the capacity from the following factors:
  - Design block mass (kg)
  - Block velocity (m/s) at the point of impact
  - Bounce height (m)
  - Location of the attenuator and relationship to the debris catch area or secondary passive structure.
- Rockfall modelling using proprietary software such as RocFall2, plays a critical role in attenuator design, guidance for rockfall trajectory analysis will be the same as for flexible barriers outlined in the above sections.
- Research from *Colorado's Full-Scale Field Testing of Rockfall Attenuator System* (Arndt et al., 2009) suggests that impact forces on hybrid fences can be reduced by up to 50% compared to standard catch fences due to impact duration attenuation.

Static Design
In addition to the dynamic design approach, the attenuator or hybrid barrier should be considered as a simple drapery application following recommendations from the *Washington DOT Research Report* "Analysis and Design of Wire Mesh/Cable Net Slope Protection" (Muhunthan et al., 2005).

More applicable to hybrid systems, with longer attenuator tails, the system in the static state should be designed to function passively, allowing rockfall debris to be controlled and directed beneath the mesh while maintaining structural integrity.

6.3.7.4 Considerations and Limitations

When designing and installing a rockfall attenuator, several considerations are needed regarding the materials, design, site location, and maintenance requirements.

- **Material Selection**: Attenuators are typically constructed using a rated flexible barrier system but are modified to incorporate a draped net tail. For hybrid fences, EAD 340059-00-0010 standards (formerly ETAG 027) fence components for similar energy capacity fences can be used in the absence of international guidelines, with the understanding that deceleration will be slower and loads lower. The designer needs to consider the material type (weight, durability) and length of the drapery, taking into account the slope over which the drape will rest, including slope angle and roughness. Consideration should also be given to potential slicing forces that could result from the rotation and bouncing of the block. Rotational velocity of the block and wire thickness of the mesh, therefore, are more important for attenuators compared to conventional flexible barriers.
- **Site-Specific Elements**: Site-specific assessments and a detailed engineering design will need to be undertaken to determine the viability of an attenuator for long-term rockfall hazard management. The location of the structure should be chosen in consideration of boulder flux, favouring frequent, low-magnitude events. In addition, the maintenance of the structure, likely within the mid-slope, will still require inspections and repairs to the intercepting mesh, presenting construction challenges similar to flexible barriers.
- **Mesh Distortion**: Ring nets distort more easily when draped as part of an attenuator tail, resulting in 'necking'. Consideration for this behaviour is crucial to prevent the drape from pinching in and not covering the potential trajectory rockfall path. To hold the mesh open across the required area, additional perimeter retention ropes may be required to connect to the sides of the attenuator net to hold 'open' the drape. These lateral permitter connections can generally be designed to have a minimum pullout load slightly greater than the ring nets' tensile strength.

Figure 6.47. Comparison of ring nets for slope protection (adopted from Washington Department of Transport [WDOT], Figure 10)

- **Attenuator Tail Behaviour**: A key consideration in the design of attenuators and the behaviour which makes the quantification of reduction and requirements for design so challenging, relates to the potential for multiple blocks travelling through the system simultaneously and 'lifting' the mesh allowing other boulders to pass un-attenuated. In addition, the free movement of the tail, can also allow 'pocketing' where a boulder will form a pocket in the tail, and load the mesh rotationally creating large, localised loading. With regards to pocketing, the rotational energy needs to be considered for tearing of mesh and is often higher than in flexible barriers. The design should therefore consider how the tail length and mesh strength are affected by these behaviours.

- **Vegetation** requires significant consideration, as larger vegetation in the tail of an attenuator can 'trap' mesh and prevent the dynamic movement required for attenuation. The maintenance of vegetation within the fence can be challenging. Consideration for the natural setting of the attenuator and appetite for ongoing vegetation management should be carefully considered. The design may also need to include revegetation with specific species to reduce larger growth species developing within the structure.

Figure 6.48. An example of the impact vegetation growth can have when developing within the dynamic section of the structure (NZ Transport Agency Rockfall Protection Design Guideline, 2023)

- **Ongoing Research and Development**: As research progresses, the design approaches and guidance for attenuators will likely be refined around the design procedures, ensuring more effective rockfall mitigation solutions tailored to varying project needs. In some design cases, undertaking or considering full-scale testing can be conducted to better understand attenuator behaviour, develop standardised design methodologies, and improve the safety and reliability of hybrid rockfall fences.

6.3.7.5 Example Applications

Two examples are provided below where an attenuator has been installed on varying scales to retain material.

Figure 6.49. Attenuator fence in the Gondola, Christchurch (Photo courtesy of Eric Ewe)

Figure 6.50. An example of an attenuator installed close to the roading corridor, with additional retention cables and mesh at the base to reduce deflection. Kaikōura (Google Streetview, 2024)

Figure 6.51. An example of a rockfall shed installed as a tunnel extension, dampening pea gravel has been placed to dissipate energies, Kaikōura (NCTIR, 2020)

6.3.8 Rockfall Canopies and Sheds

6.3.8.1 Description

Rockfall canopies and rockfall sheds are two types of rockfall protection structures (RPS) commonly used to protect linear infrastructure. This protection is provided in the form of a roofed protection above the element at risk and installed as either a rigid or flexible system.

- **Rockfall Sheds,** also known as rockfall galleries, are more common around the world, and are fully enclosed, reinforced concrete structures with a roof slab that can be covered with an energy-absorbing layer or shaped to deflect rockfall over the protected area.
- **Rockfall Canopies** are similar to rockfall sheds but are constructed from steel mesh and posts, and act dynamically to deflect rockfall over the protected area. They are essentially an extended flexible barrier with angled mesh supported by steel beams to form a protective barrier above the infrastructure below.

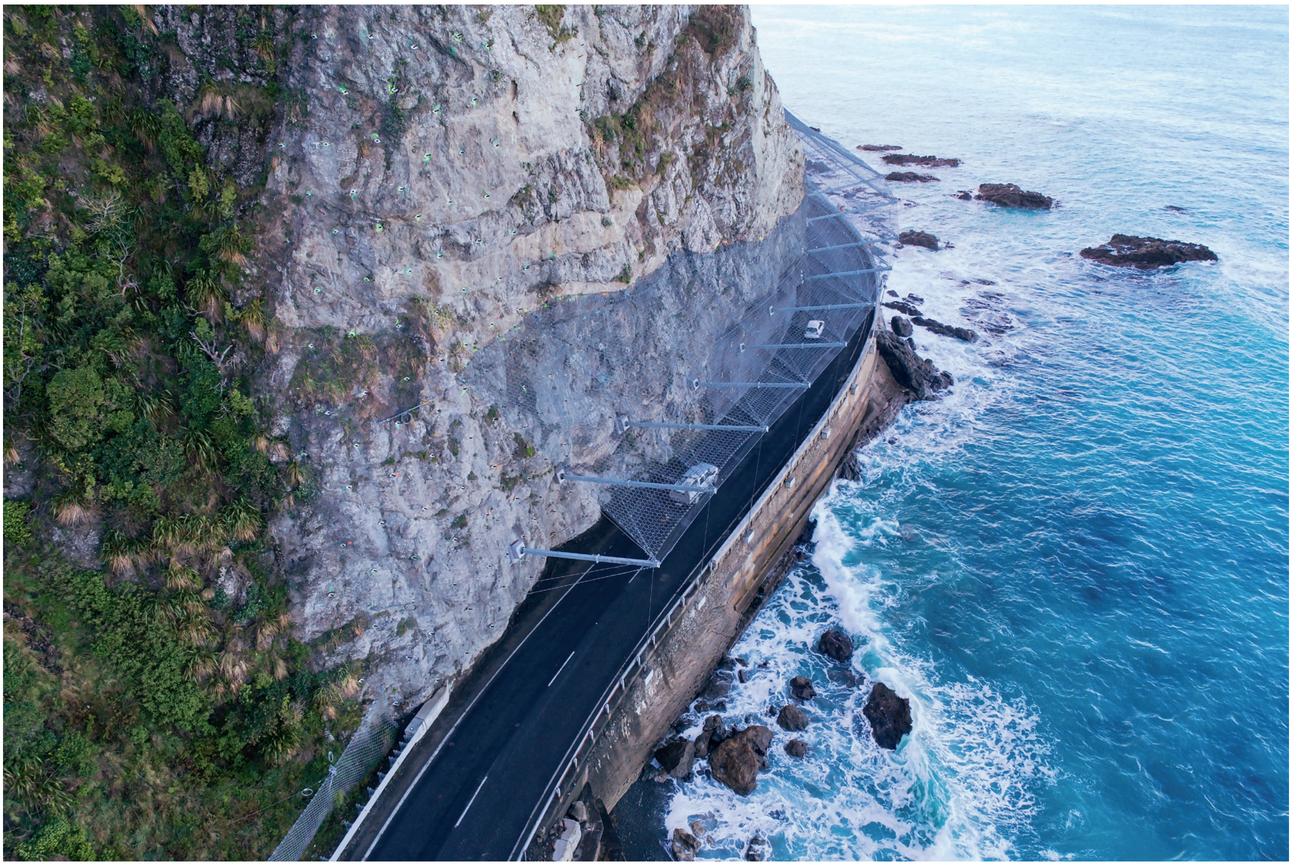


Figure 6.52. An example of a rockfall canopy installed across a State Highway to mitigate the rockfall from a near-vertical sea cliff, Kaikōura (NCTIR, 2021)

Generally, these systems are expensive and therefore are only applied in unique circumstances where the cost-benefit analysis outweighs more conventional systems. This is typically used in areas with high rockfall frequencies or severe consequences in the event of an impact, and where the rockfall occurs vertically above the protected area and the hazard areas are sufficiently large, such that it is impractical to either target at source or reduce the risk by draping or stabilising.

6.3.8.2 Intended Use and Benefits

Rockfall sheds and canopies are more practical in specific environments. There is no specific guidance for the design of rockfall canopies, however, the recent construction of the southern hemisphere's first rockfall canopy (Revell et al., 2021) provides insights into the learnings and key takeaways for similar structures. The key features when considering the use of canopies and sheds include:

- **Steep-sided Bluffs with High Rockfall Frequencies:** Rockfall sheds and canopies are commonly used in these areas to protect transportation routes from frequent rockfall. They are particularly suitable in areas where the required protection height or energy level exceeds the capacity of alternative structures.
- **Narrow Corridors**: Due to the shape and limited width of a shed or canopy, they are most effective in areas where falling debris needs to be diverted away from a narrower corridor. The shape of the shed or canopy can be designed to deflect falling rocks over the protected structure, such as a roadway or railway line. This is particularly useful in areas where other RPS types may not be feasible, such as areas with limited space or challenging terrain, or catchment on slope is impractical and raises maintenance challenges and safety concerns.
- **Protection from other Hazards:** Rockfall sheds can also provide protection from snow avalanches and debris flows, which makes them a versatile solution for mitigating multiple hazards in a single structure.
- **Tunnel Portals:** A common location for sheds and canopies is at the portals of road and rail tunnels, as this is often an area of higher rockfall hazard as the tunnel daylights beneath a steeper slope. In these cases, sheds and canopies can extend the protection of the tunnel without the same construction challenges as underground work. Tunnel portal extensions are often a form of rockfall shed and designed as such.

Figure 6.53. An example of the placement of pea-gravel (AP19 or similar) to act as a dampening material above a tunnel/rockfall shed

6.3.8.3 Effective Application

For the effective application of a rockfall shed or canopy, several elements should be considered, including maintenance requirements, durability, rockfall modelling, attenuation material, and geometry.

- **Low Maintenance:** Compared to other types of Rockfall Protection Structures (RPS) that require regular debris removal, rockfall sheds and canopies can be "self-cleaning," needing less frequent maintenance, which can make them a more cost-effective solution over the long term.
- **Durability:** Rockfall canopies and sheds can withstand multiple high-energy impacts without significant damage, providing reliable protection over their design life. The working life of passive systems is generally controlled by the frequency and magnitude of rockfall events. Concrete rockfall sheds, in particular, can be long-lasting assets requiring minimal input over their working life.
- **Rockfall Modelling.** Similar to other flexible and rigid barriers, rockfall modelling is key to ascertaining the impact energies and locations. Determining the bounce heights requires a slightly nuanced approach as the barrier angle differs from being perpendicular to the slope, therefore, greater care is needed when assessing the location of impact on the barrier. It should also be considered that the barrier capacity may vary depending on where the impact occurs, i.e., the centre of a mesh panel versus close to a top or bottom rope.
- **Attenuation Material.** For rigid rockfall sheds, an attenuating material that is either freely placed or secured in bags can be used to dissipate the impact loads on the structure. Angling the roof can help deflect or reduce impact forces, further enhancing the shed's ability to withstand rockfall events.
- **Geometry.** The design of canopies and sheds is heavily influenced by geometry, as the terrain for these systems determines their feasibility and effectiveness. For these systems to be cost-effective, the source area must be sufficiently large to justify the expense. Key considerations include the angle of slope relative to the angle of canopy/shed, and height offset from the protected asset. Accounting for deflection will provide the approximate dimensioning. This should be the first check to confirm that the canopy or shed interception area is reasonable.

6.3.8.4 Considerations and Limitations

Rockfall canopies and sheds have limitations and require some careful considerations for their successful implementation. These factors should be addressed in the early design stages, as they can be costly to remedy during construction, and encompass the following.

- **High Cost:** Rockfall sheds are one of the most expensive RPS options, and the cost will increase with the size and complexity of the structure. A detailed cost-benefit analysis should be conducted to determine if a rockfall shed is the most economically viable option, considering the whole-life costs of the structure. However, when applied appropriately, the option can be a feasible long-term option, such as the two example applications below.
- **Visual Impact:** Rockfall sheds can be large and visually unappealing, particularly in scenic areas. Designers should consider the aesthetic impact of the structure and explore options to minimise its visual impact on the surrounding environment.
- **Energy Limitations:** Due to the nature of rockfall canopies and sheds, they have a limited energy capacity range, which is generally limited to 500 kJ for canopies and 1500 kJ for rockfall sheds. However, in such cases, higher energy capacities may be achieved with additional measures such as attenuation material and secondary structures (drapes and attenuators).
- **3D Modelling and Geometry:** Rockfall sheds have relatively large footings, which need to be considered on existing infrastructure and the impact this may have on the clearance and corridor width. Rockfall canopies, on the other hand, are generally limited by a maximum beam length of 15 m, which limits their applicability to specific locations where the span is insufficient for effective coverage of the corridor. To aid in this critical verification, the use of a comprehensive digital design model cannot be overstated to identify the potential shortcomings and residual risks. Adopting a digital design and site-specific numerical modelling will further assist designers in selecting an approach tailored to the site's unique requirements, risk assessment, and structural considerations.
- **Challenging Design:** It is worth noting that the design of rockfall sheds requires specialised expertise, and much of the research and design guidance for these structures has been developed in Switzerland and Japan. When considering a rockfall shed project, it is crucial to engage with experienced professionals, including structural designers, who can provide appropriate design and construction guidance.
- **Downslope Considerations:** As both systems deflect or redirect material downslope, consideration is needed of where this redirected material will travel. Canopies and sheds are, therefore, not suitable where other infrastructure or public access areas are in the rockfall zone beneath the structure.

6.3.8.5 Example Applications

Two examples are provided below where a rockfall canopy and rockfall shed have been installed on varying scales to divert material over a linear corridor.

Figure 6.54. Arthur's Pass rockfall shed (NZTA, 2015)

Figure 6.55. An example of the Southern Hemisphere's first dynamic rockfall canopy, Kaikōura (NCTIR, 2021)

6.4 DEBRIS FLOW STRUCTURES

Debris Flow Structures should be considered alongside slope mitigation measures when considering the available options, especially in areas where the primary hazard comes from debris flows or hyper-concentrated flows.

Due to the uniqueness and complexity of debris flows, separate guidance has been developed as part of these NZGS modules, which is detailed in Unit 6 – Debris Flow Assessment and Mitigation.

This separate unit presents a comprehensive guide for assessing and mitigating debris flow hazards in New Zealand. It defines the various hydrogeomorphic processes, including debris flows, debris floods, and hyper-concentrated flows, highlighting their distinct flow behaviours and initiation mechanisms. The unit also covers the geomorphological characteristics of watersheds susceptible to debris flows, emphasising key factors such as catchment morphometry, channel gradients, and fan characteristics. Unit 6 provides a framework for conducting engineering geological assessments, encompassing catchment analysis, main channel characteristics, as well as outlines the role of numerical debris flow modelling. The key design guidance is also provided, focusing on debris flow mitigation strategies, detailing both active and passive measures to minimise damage and providing guidance on designing debris flow protection measures.

7 DESIGN COMPLIANCE

As outlined in the above sections, there are a variety of mitigation measures used to reduce the impact of geotechnical hazards across New Zealand.

In the majority of situations, compliance with all applicable clauses of the Building Code is required[2] irrespective of whether building consent is required for the mitigation. Building Code compliance will normally be achieved via alternative solutions, with guidance found in Appendix A of MBIE Rockfall: Design Considerations for Passive Protection Structure (2016).

Building Consent requirements will vary depending on the type and nature of the mitigation system. It is recommended that the designer liaises with the appropriate Territorial Authority (TA) to confirm the consenting and compliance requirements. The below is not intended as a determination but provides some indicative guidance to aid these discussions.

In the simplest definition, under Section 8 of the Building Act (BA8), all the hazard mitigation systems that are *immovable structures* that have *mechanical systems*, are considered buildings and require consent. If consent is required, then Section 7 (BA7) indicates that the *associated siteworks* may need to be consented too, including *earthworks*.

However, based on a review of the consenting requirements outlined in the NZTA Highway Structures Guide (2016), MBIE Rockfall Design Guide (2016), and CCC Technical Guidance for RPS (2013), there are different consenting requirements based on the type of mitigation systems installed, fundamentally between a "passive" structure design for impact, and an "active" treatment stabilising the slope or source treatment. A summary of the interpreted consenting requirements for rockfall protection structures is provided in Table 7.1. This highlights potential uncertainty in the consenting requirements for source treatment or slope stabilisation works to reduce rockfall potential.

2 Section 5.10.3 – Building Code Compliance – NZTA Highway Structures Design Guide.

Based on this table the following guidance is recommended.

Building Consent is required for:

- **Passive Structures:** including but not limited to: gabion bunds, MSE bunds, unreinforced and reinforced fill bund, concrete block walls, gabion, and reinforced fill, modular block walls, debris interception walls, and soldier pile fences, proprietary rockfall fences, other rockfall fences, shallow landslide barriers, debris flow barriers, attenuators, canopies, rock sheds and hybrid fences. These barriers have been designed for impact and debris retention and are characterised by MBIE as wall-type structures and should be consented.

Building Consent is NOT required for:

- **Active Treatment:** including but not limited to: at-source stabilisation and/or rockfall prevention measures (anchored mesh, rock bolting, slope soil nailing, slope stabilisation works, and at-source pinned stabilising mesh (draped mesh).

However, under Section 9 (BA9) some network provider works, such as NZTA, KiwiRail, and Transpower, may be exempt as the Building Act allows exemption of simple structures for Network and Utility Operators (NUO). Passive structures not covered by this NUO status, require a building consent, except where the structure is not more than 1.5 m in height (exemption 20), or where a retaining wall is in a rural zone and is not more than 3.0 m in height, and is more than its own height from the boundary or building and is designed or reviewed by a chartered professional engineer (exemption 41). A building code exemption from the Building Consent Authority should be applied for prior to starting works.

Producer Statements are generally required for all mitigation structures that have been designed. Where building consent is not required, an "A series" Producer Statement can be used.

As a minimum, the Producer Statement shall cover Clause B1. For some passive structures, the designer may choose not to include Clause B2 (Durability)

Table 7.1. Rockfall protection systems – interpreted building consent requirements

RPS types	Building Act	NZTA HGS (2016)	MBIE Rockfall Design (2016)	CCC Technical Guideline (2013)
Passive Structure (design for impact)	Yes	Yes	Yes	Yes
Active Treatment (stabilisation, earthworks, anchored mesh or similar)	Not Specified	Not Specified	No	Not Specified

depending on the accepted design life. In this case, as outlined by Engineering New Zealand, a letter accompanying the Producer Statements to provide a means of compliance with Clause B2 (Durability) shall be provided. This letter shall generally include:

- A table outlining the specifically designed structural elements with the standards and construction verification methods used, and
- A table outlining the monitoring and maintenance requirements, and a summary of the inspection requirements to achieve the intended design life.

In all cases, where slope mitigation is designed, it is recommended that the designer engage with the Local Authorities to obtain their agreement on the requirements for Building Consents.

8 NON-ENGINEERED MITIGATION OPTIONS

8.1 INTRODUCTION

Non-engineered slope remediation measures leverage natural processes and materials to stabilise slopes and prevent erosion. These methods are often favoured in environmentally sensitive areas as they minimise landscape disturbance and promote ecological balance. By working with the natural terrain and existing vegetation, these approaches enhance the slope's resilience against erosion and landslides. They are especially useful in locations where traditional engineering solutions may be impractical or too expensive.

A significant benefit of non-engineered measures is their ability to blend seamlessly into the natural environment. They typically involve using locally sourced materials and plants that are well-suited to the local climate and soil conditions. This not only aids in slope stabilisation but also supports local biodiversity. Over time, these measures can foster the development of a more stable and self-sustaining ecosystem, reducing the need for ongoing maintenance and intervention.

In this section we will be dividing non-engineered mitigation methods into three logical units:

- **Quick Risk Reduction** options for slope instability mitigation are essential for addressing immediate threats and preventing further deterioration of the slope. They focus on minimising the immediate risk of slope failure by addressing the most critical factors contributing to instability, such as water infiltration and loose materials. By quickly reducing these risks, these measures help protect infrastructure, property, and lives, buying valuable time for detailed assessments and planning permanent remediation efforts.
- **Non-Intervention** measures for slope instability mitigation involve allowing natural processes to stabilise the slope without direct human interference. This approach relies on the inherent resilience of the landscape and the gradual establishment of natural vegetation and natural slopes while human involvement in this space is oriented towards land use planning, monitoring and education.
- **Bioengineering** in slope instability mitigation involves using living plants and natural materials to stabilise slopes and prevent erosion. This approach leverages the mechanical and hydrological properties of vegetation to reinforce and protect the soil structure. These methods are environmentally friendly, enhance biodiversity, and can be more cost-effective and aesthetically pleasing compared to traditional engineering solutions. By integrating natural processes with engineering principles, bioengineering provides a sustainable and resilient approach to managing slope stability.

These units will be discussed in more detail in the following sections.

8.2 QUICK RISK REDUCTION OPTIONS

8.2.1 Description

Quick risk reduction options are used to immediately address slopes that are imminently susceptible to slope movement. These measures are intended to reduce the likelihood of slope instability and can include removing the source material, providing immediate stability improvements, and allowing for movement and clearance.

- **Removing the Source Material** includes the partial or complete removal of any material that is at immediate risk of movement. Methods include 1) scaling or sluicing to remove loose rock from rock slopes, and 2) using excavation or controlled failures to remove soil lobes and debris from unstable slopes.
- **Providing Immediate Stability Improvements** comprises undertaking actions to immediately reduce the risk of failure by providing support to the unstable slope or removing the factors that are contributing to the instability. Such methods would include 1) diverting stormwater away from the unstable slope, 2) placing a temporary bund or rock bags to support the unstable slope, 3) covering the slope with an impermeable membrane to prevent water ingress into the slope.
- **Allowing for Movement and Clearance** involves allowing the unstable ground to fail on its own accord and being immediately ready to clear the resulting debris. This option is only feasible where there is no/low risk to life or assets from failure.

8.22 Intended Use and Benefits

Quick risk reduction options are often required to respond to an immediate increase in the risk of slope instability. The increase in risk may be caused by a large amount of rainfall, an earthquake event, or even immediately following a landslide or rockfall. These measures are required where slope instability movement is likely to harm people, damage assets, or cut off access, and prevention of further movement is essential.

Quick risk reduction options are useful where there is limited amount of source material, or the source material is contained to a small area.

Figure 8.1. Scaling using an excavator to reduce rockfall risk at the Kauriki/Korere Terrace development in Stonefields

Figure 8.2. Rock bags used to reduce risk of further land movement and undermining of road (Bluemont, 2025)

Figure 8.3. Plastic membrane sheeting used to prevent immediate ingress of stormwater into an active slip site in a vicinity of a transmission tower (Source: Northpower, 2024)

These measures contain a number of benefits, including:

- Partial or complete removal of source material in small areas is generally inexpensive. However, this depends on ease of access.
- Placing bunds can also be inexpensive depending on the availability of bund material and ease of access. This can be tied with the partial removal option, where destabilising mass can be removed and placed at the toe to enhance stability.

- These measures are quick to implement across small areas.
- These measures are also quick to remove or decommission when constructing the permanent stability solution.

8.2.3 Effective Application

The following process should be undertaken to determine the applicability and use of quick risk reduction options.

Table 8.1. Effective application of quick risk reduction options

Step	Action	Description
1	Identify an area where quick risk reduction options may be required.	This may be following a natural hazard event such as an earthquake or storm event.
2	Assess the existing condition of the area.	Assessment will determine whether there is likely to be any imminent movement of the slope.
3	Assess risk to people or assets.	Assessment will determine whether there is any risk to people's lives or a risk of damage to assets as a results of debris flow/rockfall/ material movement.
4	Determine which risk reduction options are suitable to the area.	This will take into account: • Access restrictions • Availability of material to be used • Extent of solution required • Time that risk reduction option will be required to be in place
5	Choose the appropriate solution.	

8.2.4 Considerations and Limitations

The considerations and limitations for the quick risk reduction options are as follows:

- These measures are unlikely to provide long term solutions to slope instability as the measures do not improve global stability but more focus on short term local stability.
- Larger areas, or larger amounts of material, would significantly increase the time and cost required to implement these options. It also may not be possible to reduce the risk of a large area to an acceptable level.
- Difficult access may require machinery to be lifted in using helicopters or result in helicopter access for sluicing which can significantly increase costs.
- A suitable water supply is required if using sluicing.
- Consideration for where any removed source material is discarded.
- Removal works may require rope access which will require careful consideration of health and safety requirements.
- A suitable location must be identified for diverting stormwater.

8.2.5 Example Applications

Non-engineered scaling was implemented at Cathedral Cove in response to a rockfall hazard identification undertaken in 2011. The scaling was completed by rope access and ladders and removed the potentially unstable ignimbrite blocks.

Potentially unstable rocks were hit with a sledgehammer with the sound of the strike used to determine whether the block was likely to be loose enough to pry off. Slabs of up to 3m long and 300mm thick were then levered off using a pry bar.

This solution was used to help reduce the potential of rockfall using non-engineered, but effective, scaling methods. Scaling of the arch was preferred to active stabilisation measures like rock bolts for aesthetic reasons and also because the arch is in a dynamic and active coastal environment where the hazards are constantly evolving.

Figure 8.4. Scaling undertaken by rope to remove the rockfall risk at Cathedral Cove

8.3 NON-INTERVENTION MEASURES

8.3.1 Avoidance or Retreat

8.3.1.1 Description

Avoidance or retreat mitigations protect an asset's users from potential harm caused by slope instability. If the slope becomes unstable and fails, any debris flow/fall will not impact the asset or asset users.

Avoidance or retreat mitigations can include:

- **Relocating users** to an alternative route (usually pre-existing). This is often a temporary measure while alternative mitigations are undertaken.
- **Relocating the Asset** to an alternative location away from the slope instability. Examples include: (a) a coastal road adjacent to a steep slope being moved inland, where the land is flatter and has a lower risk of slope instability, and (b) residents evacuated from an area prone to a landslide during heavy storm events.

Where the Asset cannot be relocated, and/or engineered mitigation measures cannot be used to stabilise the land instability, the following avoidance or retreat mitigations may be used:

- **Bridging** the area of slope instability by leaving the existing asset in its same location and spanning a section of the asset across the unstable area using a bridge or viaduct.
- **Tunnelling** a portion of the asset beneath the slope instability so that the asset is unaffected by any slope failure that occurs above the tunnel. The tunnel would have to extend below any basal shear surfaces to prevent any movement of the tunnel.

8.3.1.2 Intended Use and Benefits

If a slope adjacent to an asset were to fail immediately, the risk would be not only damage to the asset but also potential harm to the asset users. Removing the users and/or assets from the slope instability removes these risks. These measures would generally only be used for critical assets such as large roads, key rail lines, or even entire towns.

- **Relocating users** is used where there is a suitable alternative route. The is beneficial as it can be implemented immediately and is low-cost due to using pre-existing infrastructure.

Figure 8.5. SH4 between Whanganui to Raetihi involved retreating into a hill following a 2015 landslide (NZTA, 2023)

- **Relocating the Asset** can be used when there is a suitable location for relocation. This mitigation can be beneficial when a planned upgrade to an asset will already incur a cost to upgrade the existing location, in which case, the costs can be used for relocation instead.
- **Bridging** is typically used for sidehill linear infrastructure, such as a road or rail line, where the terrain is undulating, steep, and allows for appropriate bridging. Bridging is beneficial where the area of instability is relatively small, and it is not feasible to relocate an entire asset. The bridging allows for a small portion of the asset to be supported away from the instability so that it is unaffected if the instability were to occur.
- **Tunnelling** is likely only used where the asset is critical and must remain in operation, and if other mitigation options, both engineered and non-engineered, are inadequate or not feasible. Tunnelling can be beneficial as a long-term option as the tunnel will likely be founded within competent rock that is below the level of any instability.

8.3.1.3 Effective Application

The following process should be undertaken to determine the applicability and use of the avoidance or retreat mitigations.

Table 8.2. Effective application of avoidance and retreat mitigations

Step	Action	Description
1	Assess the risk of a landslide impacting the asset.	Ideally, this is done at an early stage before there is an imminent risk of the landslide occurring.
2	Determine whether avoidance or retreat measures are required.	This will likely involve determining the risk of loss of life and/or economic impact of damage to the asset versus the cost of mitigation.
3	Implement temporary avoidance measures.	Where the threat of a landslide is imminent, asset users may be re-routed to a temporary alternative, pre-existing route to avoid the land instability.
4	Undertake a feasibility assessment of alternative options.	This will involve determining any suitable alternative locations and determining the potential for bridging or tunnelling. Planning input will be required at this stage.
5	Choose the appropriate solution.	

8.3.1.4 Considerations and Limitations

The considerations and limitations for avoidance and retreat mitigation measures are as follows:

- Avoidance and retreat need to be considered and undertaken early, before any slope instability occurs. This will allow the new asset to remain operational and will reduce the risk of harm to the asset users and/or isolation of communities due to being cut off by the landslide debris flow.
- When relocating the asset, the alternative solution will need to be assessed for other hazards as well, such as soft ground or being in a flood-prone area. Also, alternative locations may not be possible for some assets due to topography, distance, lack of capacity, and/or connectivity to the existing asset or network.
- Careful consideration of any social impacts will be required if relocation contributes to any rehousing.
- When bridging, the bridging structure and accompanying foundations would need to be designed to withstand the movement, impact, and/or loading from any slope instability.
- A tunnelled option may increase the maintenance requirements of the asset, including adding new hazards related to confined spaces.

8.3.1.5 Example Applications

Bridging to avoid potential instability was implemented through the Otira Viaduct in Arthurs Pass, Canterbury. The original road was a notoriously rough road featuring many hairpin corners, was prone to avalanches and landslides, and was constantly needing repair.

An early report on the original road indicated that there was a 90% chance that the zig-zag road would fail entirely by 1999 (Harvie, 2019). This report justified the need to bridge the area of instability and maintain the West Coast – Canterbury link.

Figure 8.6. The Otira Viaduct, which bypasses the original, zig-zag road, in Arthurs Pass, Canterbury (Bell, 1999)

8.3.2 Land Use Planning Measures

8.3.2.1 Description

Land use planning measures include plans and policy statements that can be used to avoid areas of slope instability by providing constraints and limits for new developments. Regulators and developers use these tools, including: 1) Regional policy statements and plans, 2) District plans, and 3) Resource and building consents. Further information can be found within the MBIE Landslide Planning Guidance (de Vilder et al., 2024).

- **Regional Policy Statements and Plans**: These set the basic regional integrated environmental management direction. Regional plans contain guidance and rules for managing our natural and physical resources. Generally, two matters that can be addressed at the regional level are:
  1) the mapping of landslide susceptibility, hazard, and risk, and
  2) the policy framework for managing these.
- **District Plans**: District plans contain guidance and rules about land use and development. As territorial authorities manage subdivision and most land uses, a district plan is generally the best-placed document for landslide risk management.

Resource and Building Consents: Resource consent processes enable the detailed consideration of hazards and risks affecting a site, and decisions can include targeted conditions to avoid or reduce these identified risks. Building consents are usually at the end of the process, so should not be used as the primary method for addressing landslide risks. However, building consents should not overlook landslide hazards in the event that a resource consent is not required for development.

8.3.2.2 Intended Use and Benefits

Land use planning measures are intended for regulators and developers to use when planning and designing new developments. When considering new areas for development, landslide risk assessments can be made early, and land-use planning practices and approaches can be implemented to reduce landslide risk.

These measures are intended to provide:

- Zoning and land use restrictions in high-risk areas to limit development.
- Recommendations for suitable housing types.
- Recommendations for any requirements for fixed floor levels to reduce flooding/debris flow vulnerability.
- Measures to reduce vegetation removal.

The benefits of land use planning measures include:

- Minimising the economic impact caused by a landslide, such as the cost of recovery, debris removal, reconstruction efforts, and loss of production for the affected community.
- Minimising the social impact caused by a landslide, such as loss of life or injury, displaced family environment, and loss of community.
- Allows for long-term sustainable development and resilient infrastructure.

8.3.2.3 Effective Application

For any new areas of development, it is recommended that landslide specialists are consulted early to identify the potential landslide risks. The MBIE Landslide Planning Guidance recommends a minimum level of analysis for strategies/plans, resource consents, and building consents. The decision tree process for plan development is shown in Figure 8.7.

The following process should be undertaken to enable the effective land use planning measures to be implemented in relation to new development areas.

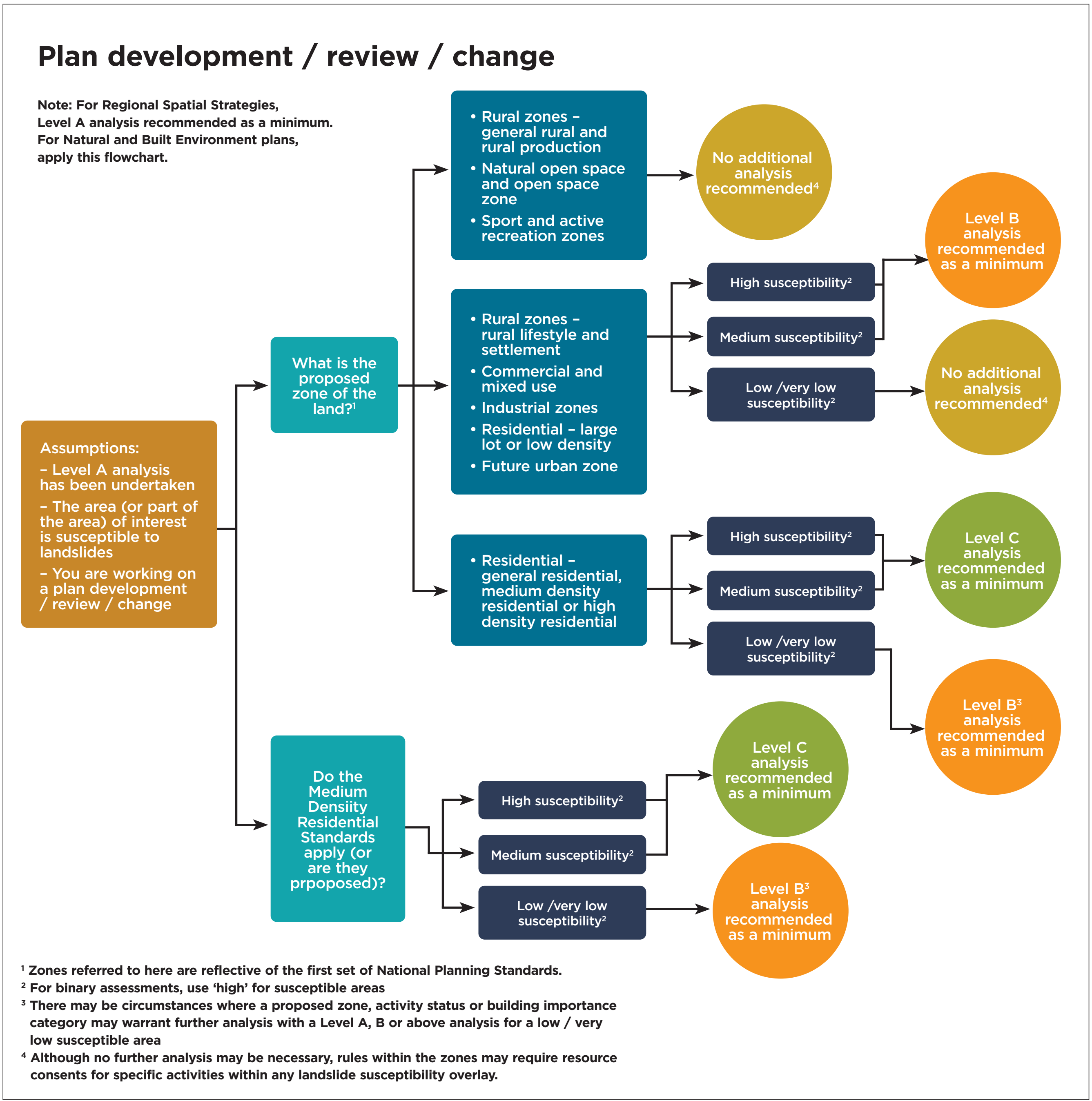


Figure 8.7. Decision tree process for plan development (reproduced from de Vilder et al., 2024)

Table 8.3. Effective application of land use planning measures

Step	Action	Description
1	Undertake a landslide susceptibility (Level A) analysis for the new development.	This is undertaken in accordance with the MBIE Landslide Planning Guidance (de Vilder et al., 2024) and involves mapping existing landslides and areas of potential landslides.
2	Undertake the required further landslide analysis.	Further analysis undertaken in accordance with the MBIE Landslide Planning Guidance decision trees (e.g., as shown for plan development/ review/change in Figure 8.7).
3	Prepare plans, policies, and rules for development.	These are based on the assessed level of slope instability risk, with risk expressed in terms of thresholds: acceptable, tolerable, and intolerable.
4	Undertake development.	In accordance with the plans, policies, and rules.
5	If required, prepare an appropriate geotechnical report.	Required as part of the resource consent application where a land-use change, or new development is proposed for an area identified as having a potential landslide hazard.
6	If appropriate, consider other risk mitigation measures.	Where it is determined that the risk is intolerable, a policy of avoidance or managed retreat should be considered, along with prohibiting activities.

8.3.2.4 Considerations and Limitations

The considerations and limitations for land use planning measures are as follows:

- Planning professionals should be consulted for all matters relating to the land use planning measures.
- Landslide specialists who are consulted should have the regional- and district-scale expertise when helping to assess the risk.
- Plans need to be appropriate to the community's circumstances due to variability in geology, topography, and rainfall across regions.
- Tolerable and intolerable risks may differ between communities depending on community size, remoteness, and ability to respond to instability.
- There may be limitations with authority over new developments, and the governing authority may not have the necessary means to put sufficient plans into place.

8.3.2.5 Example Applications

In 2016, the Kaikōura District experienced an earthquake, which raised the community's awareness of natural hazards, including landslides. This resulted in a new assessment of potential natural hazards for the district. In 2018, Kaikōura District Council set out to review its District Plan, which started with the Natural Hazards Plan Change 3. The Plan Change sought to incorporate the natural hazards assessments and their potential to impact the Kaikōura District, including landslide debris inundation (Kaikōura District Council, 2021).

The purpose of the Natural Hazards Plan Change 3 included (list not exhaustive):

- Improve community resilience.
- Introduce new policies and rules regarding natural hazards in the Kaikōura District.

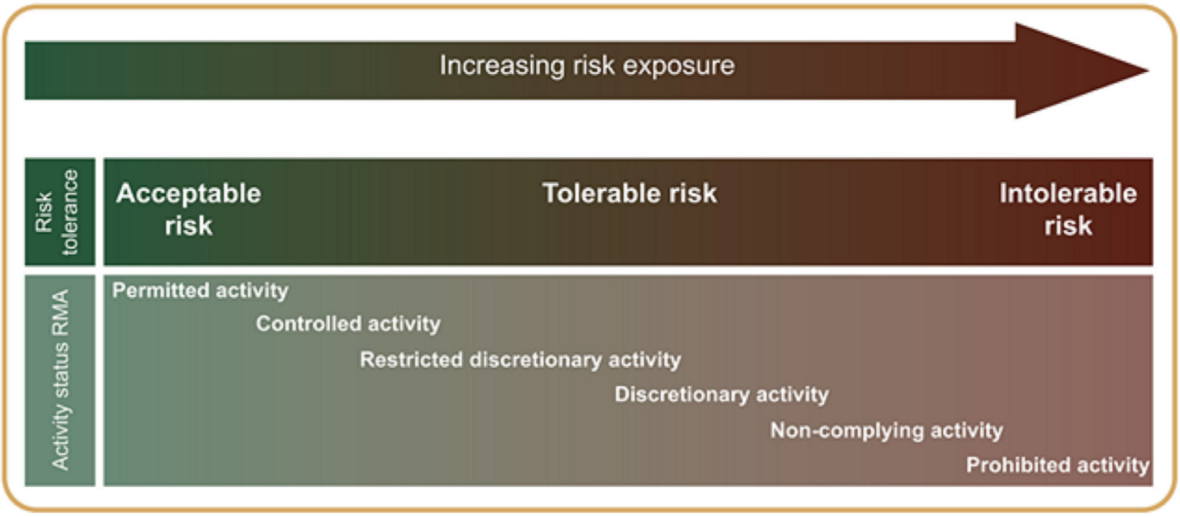


Figure 8.8. Risk tolerability and activity status for plan rules (reproduced from de Vilder et al., 2024)

- Provide certainty as to how natural hazards will be managed in the future.
- Clearly indicate where land use activities are and are not appropriate in regard to natural hazards.
- Using a risk-based approach to provide for and manage land use planning in areas that may be subject to natural hazards.

8.3.3 Monitoring and Early Warning Systems

8.3.3.1 Description

Monitoring and early warning systems gather information and data from various sources to provide indicators of when the risk of a landslide is imminent. This can be monitoring an existing landslide at risk of further movement or a marginally stable piece of land at risk of a landslide. An effective system also includes communication and appropriate response processes that enable stakeholders to take the required actions to reduce the risk of disaster.

Table 8.4. Measurable factors for monitoring and early warning

Factor	Description
Visual inspections	Undertaken in person or using a drone or other high-resolution satellite data to determine whether there has been any cracking in the slope, indicating some movement.
Surveys	To monitor any movement of the slope (can be manual measurements or using survey equipment such as a total station).
Groundwater measurements	Undertaken, preferably using telemetry, to allow sharp changes in levels to be observed early.
Rainfall and snowmelt measurements	Rainfall and snowmelt can often contribute to increases in groundwater levels and corresponding instability.
Geotechnical monitoring instruments	Other movement indicators such as inclinometers, crack meters, tilt meters, and extensometers - preferably using telemetry.
Water levels	Measuring water features close to the slope (rivers, lakes) as the water level rises may correspond to a groundwater level rise.
Seismic monitoring	Using earthquake-induced ground shaking measurements to indicate susceptibility to movement.
Fibre optics	Using fibre optic sensors embedded in shallow trenches in the ground to monitor the strain field induced in the sensing fibre (Schenato et al., 2017).

Early warning systems can be broadly classified into two categories (Kwan et al., 2013):

- **Regional Systems** cover a large area and are normally used to provide general warnings to raise public awareness of landslide hazards and trigger stand-by emergency services. Regional systems often use a rainfall threshold for triggering a landslide, as other factors are difficult and costly to monitor over a large area.
- **Site-specific Systems** are established to monitor a particular slope or hillside and give early warning to stakeholders (such as nearby residents or emergency services) of a potential landslide. A multitude of factors can indicate the trigger of a landslide. Table 8.4 presents measurable factors for monitoring and early warning.

8.3.3.2 Intended Use and Benefits

Monitoring and early warning systems should only be applicable for use on existing developments or assets only. New developments should not be located where monitoring and early warning systems would be needed. The systems are ultimately intended to allow stakeholders (such as residents, asset users, Council's emergency responders) to be informed of the potential landslide risk, to be given sufficient warning for a potential landslide, and to be provided with appropriate preparedness and response plans.

These measures are intended to prevent harm to people, generally by removing them from the landslide's damage path. However, these measures will not prevent a landslide from occurring and, therefore, will not eliminate the risk of damage to assets.

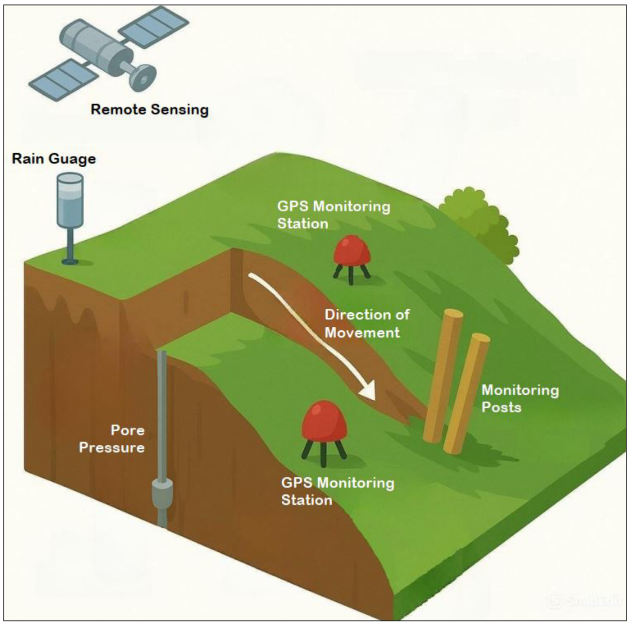


Figure 8.9. Example slope movement monitoring system (Adapted from SHEAR, 2021)

Figure 8.10. Example of a community that might utilise monitoring and early warning systems to protect its residents (Photo from Highland & Bobrowsky, 2008)

The benefits of monitoring and early warning systems include:

- Useful in remote areas or for smaller communities where the cost of engineered stabilisation measures cannot be justified.
- Allows the cost of mitigation to be deferred until it is absolutely needed. For example, implementing an evacuation plan immediately prior to a landslide occurring.
- Forecast information can be easily interpreted, and automatic warnings can be set up and provided to the community.
- Reduced disruption to asset users but reducing the need for frequent manual inspections.
- Engages with the community and can increase interest and awareness in landslide risk reduction.
- These systems work well with low-moving landslides, enabling a more relaxed response time.

8.3.3.3 Effective Application

The following seven activities (adopted from Harrison et al., 2023) can be used to develop and apply a site-specific early warning system.

Table 8.5. Effective application of monitoring and early warning systems

Step	Action	Description
1	Risk assessment	This is undertaken to determine a landslide's hazard, exposure, vulnerability, and capacity. This will allow the corresponding risk of the landslide to be determined and the potential impacts on communities.
2	Dissemination of knowledge	This will pre-identify a communication system to ensure that as many affected people as possible are warned of any threat. Consideration of the types of communication must be undertaken with a balance of detail versus speed of information transfer.
3	Establishment of a disaster preparedness team	Allocating and training an appropriate team that can respond quickly once monitoring alerts are triggered.
4	Development of an evacuation route and map	Develop evacuation plans to identify the most appropriate routes and shelters, addressing any shortfalls early. Engage stakeholders to ensure all aspects are considered and to secure community buy-in.
5	Development of a standard operating procedure	The key to this strategy is to identify which specific monitoring parameters can indicate or predict the time of failure of the impending landslide for the chosen area. These parameters must be measurable and have a credible 'alert limit' assigned to them. The responsiveness to changes in these parameters must also be considered, as must whether a certain response time is acceptable or not.
6	Monitoring, early warning, and evacuation drill	Undertake real-time monitoring of the landslide. If any of the measured factors exceed the 'alert levels', then the corresponding reactive plans are actioned.
7	Commitment of the local Government and community.	Continuous engagement with the community is required.

8.3.3.4 Considerations and Limitations

The considerations and limitations for the monitoring and early warning systems are as follows:

- If the geological conditions present a risk of brittle landslide failure, it is likely that warning systems will not provide enough time to implement emergency plans such as evacuation.
- Need to be able to match a monitoring parameter to the cause of the landslide and then be able to measure it. This may be difficult if the mechanism of the potential landslide is not well understood.
- Response time and frequency of the monitoring instruments used are critical to the success of any emergency plans. Instruments must be sensitive to changes in the parameters being monitored, or they will not be able to provide a timely alert of the landslide.
- Different monitoring measures will be required across the country as different areas have varying 1) geological conditions, 2) rainfall and snowfall conditions, and 3) groundwater responsiveness.
- Monitoring alert levels have to be credible. A threshold that is too low may result in false alarms, which may cause stakeholders to become complacent or sceptical. Alternatively, a threshold that is too high may mean response times following warnings are too short.
- Monitoring results are likely only to provide a warning to a small area and may not be suitable for indicating the risk of failure of a wider area.
- Require a high level of community engagement to ensure quick responses to warnings. This will require the community to actively pass on information to others within their community to ensure no one has missed the warnings.
- It can be hard to tell when hazard levels have reduced to a safe level for people to return to their homes/roads to be used.
- Some people may not evacuate until they are certain the event is happening. By then, it may be too late.
- Monitoring equipment may be damaged by extreme weather, wildlife, or vandalism.
- Rapidly evolving technology might make the monitoring equipment obsolete or incompatible with new software/hardware.
- With electronic data, there are risks related to cybersecurity and data breaches.
- Consider other secondary and tertiary hazards that arise from a landslide, i.e., landslide debris causing a dam and causing flooding upstream.
- Consider how to deliver alert warnings to stakeholders. Each method will have different speeds/effectiveness, which must be weighed.

Harrison et al. (2023) provide further information regarding considerations for landslide early warning systems

8.3.3.5 Example Applications

Monitoring and early warning systems have been used at the Mount Ruapehu Crater Lake (Kwan et al., 2013). Eruptions in 1995-1996 created a 7 m high dam of tephra around the rim of the Crater Lake. Failure of the tephra could lead to debris flows and threaten the residents below. Figure 8.11 below presents a cross-section of the Crater Lake and potential landslide risk.

An early warning system was established in which the risk of the tephra moving was linked to the water level within Crater Lake. Alert levels were chosen based on the lake's water levels during previous failure events. Table 8.6 below outlines the various warning levels and the corresponding response actions.

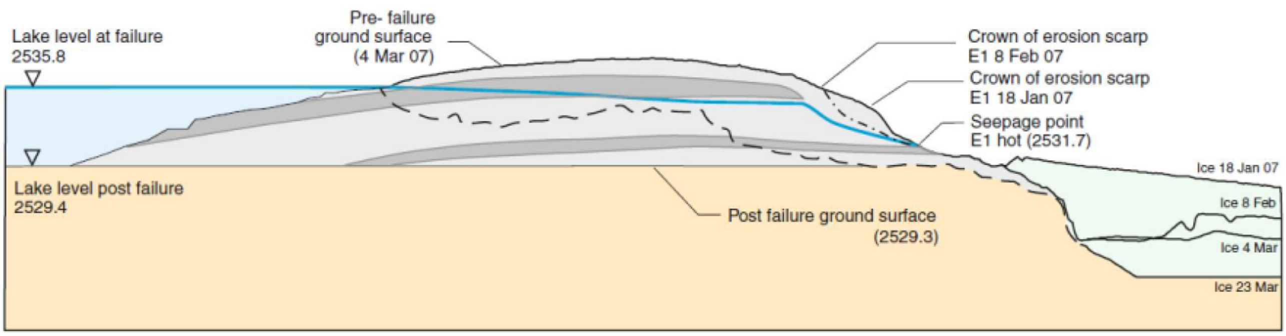


Figure 8.11. Cross-section of the Tephra Dam (Kwan et al., 2013)

Table 8.6. Alert levels for Mount Ruapehu Crater Lake (adapted from Kwan et al., 2013)

Level of readiness (warning level)	Lake level (msl)	Simplified explanation (conditional probability of dam failure based on Gillon et al., 2000)	Actions (mostly agency response time)	Anticipated time for lake to rise to next level (in summer, based on fill rates 2000–2005)
Normal	Below 2,527 m	Base level of readiness as per normal civil defence planning	Planning, preparation, and training	—
Level 1	2,526.5 m	Critical trigger point, 3 m below the new rock overflow level. (Waves caused by small eruptions or landslides could overtop tephra barrier, but the resulting lahar would be small).	Planning is largely completed. Response capability available. Response within 30 min	1 to 6 months to fill from Alert Level 1 to 1b
Level 1b	2,529.5 m (Lake 100% full)	Lake reaches the boulder rock rim outlet level at the base of the tephra dam. The probability of dam failure at this level is still very low.	Planning is completed. Full response capability is available and ready.	1 to 6 months to fill from Alert Level 1b to 2
Level 2	2,533 m	Sudden collapse could produce a lahar equivalent to the 1975 event (the largest historic eruption lahar), which passed under downstream road and rail bridges without significant damage. The conditional probability of dam failure at this level is 1–2%.	Response within 20 minutes (for example, this required one local police sergeant to always be within 20 minutes of base from this time on).	0.7 to 1.9 months to fill from Level 2 to 3, or 7.8 months to drop to Level 2 from Level 3 (depending on infill rates)
Level 3a	2,535 m	Equivalent to a large, moderately fast lahar. The conditional probability of dam failure at this level is 5–10%.	Response within 10 minutes	0.4 to 0.6 months to fill from Level 3 to 3b, or 3.2 months to drop to Level 3 from 3b
Level 3b	2,536 m	The conditional probability is 50–60%	Response within 5 minutes	0.2 to 0.3 months to fill to Level 4, or 1.1 months to drop to Level 3b from 4
Level 4	2,536.5 m	Equivalent to a large, fast lahar. The conditional probability is 90%.	Response within 5 minutes	0.2 to 0.3 months to fill to Level 5, or 0.7 months to drop to Level 4 from 5
Level 5	2,536.9 m	Lake at the top of the tephra dam. The conditional probability is 100%.	—	—

Response actions included providing warning signals to road users, using automatic road barriers to prevent traffic, and notification to the local police.

8.3.4 Education

8.3.4.1 Description

Education measures aim to provide awareness and knowledge to the relevant stakeholders who may be impacted by slope instability. The awareness and knowledge can be provided in several forms, including:

- Community engagement nights
- Practical demonstrations
- Social media posting
- Information drops into letter boxes
- Signage and warnings

8.3.4.2 Intended Use and Benefits

Education is intended to be used to raise public awareness, increase the public's knowledge of landslides, equip the public with the tools to help prevent landslides across their properties, and encourage safer land use decisions/property purchasing, and development. Education should be used in conjunction with any of the other non-intervention measures discussed above, or any of the engineered measures discussed within Section 6.

Education also plays an important role in the monitoring and early warning systems discussed in Section 8.3.3. The impacted community must be aware of the monitoring alerts and ready to react once they are reached.

The main benefits of education are as follows:
- This measure is cost-effective when compared to other engineered solutions.
- Education empowers the community to take an important role in protecting themselves and their properties.

8.3.4.3 Effective Application

To be effective, awareness and knowledge must be disseminated to the public in a simple and understandable way. The material should be presented in layman's terms without being weighed down with technical jargon.

The information should be relayed in a staged process, with each stage intending to engage with more and more of the public. This might be as follows.

Table 8.7. Effective application of education measures

Step	Description
1	Information drops into letterboxes with details of future information stages
2	Initial community meeting to discuss information from Stage 1 drop with Q&A
3	Spread of information over social media pages
4	Subsequent community meeting with practical demonstrations
5	Frequent refreshers and ongoing support to the public

8.3.4.4 Considerations and Limitations

The considerations and limitations for the monitoring and early warning systems are as follows:
- Public enthusiasm may start very high as the threats of landslides are presented, but public interest may drop over time if landslides do not occur and the threat does not appear to be immediate.
- People may only be concerned with their own properties or the properties of those they know. It may be hard to get interest when personal factors are not in play, and this will prevent the unity of the whole community.
- Education measures traditionally tend to target life risk. However, the information must be presented to also equip the pubic with tools and knowledge to reduce the risk to their properties.
- The information will have to be carefully curated, as information can be dangerous in the wrong hands.

8.3.4.5 Example Applications

An example of how education can be implemented is a hypothetical education for the residents of Muriwai following the 2023 Storm events. Steps would include:
1. Prepare a basic information package covering the basics of landslides (cause, signs, prevention measures). This information will be provided in letter drop form and on social media pages.
2. Alert the public of areas of high landslide risk within Muriwai.
3. Hold a meeting within the Muriwai community to discuss the information provided, answer any questions, and advise on what residents can do to:
   a. Look out for telltale signs and indicators of landslides,
   b. Reduce the risk of landslides on their properties, and
   c. Put evacuation plans in place.
4. Provide ongoing information and warnings during forecast heavy rain events.

8.4 BIOENGINEERING

8.4.1 Description

Bioengineering refers to the use of live plants and plant parts planted directly into the ground or used in conjunction with engineered mechanical measures to provide additional mechanical support to the soil. In addition to the mechanical advantages, bioengineering measures can also significantly affect the hydrology of the system.

These mechanical and hydrological effects may be beneficial or detrimental, depending on the vegetation type, soil conditions, slope conditions, and others. Figure 8.12 below illustrates the potential impacts of bioengineering on a slope.

Bioengineering measures are broadly separated into four techniques (Phillips and Marden, 2006):
- **Soil Protection Techniques** protect the soil from surface erosion by providing cover from rainfall and reducing the velocity of surface runoff-related stormwater flows.
- **Ground Stabilising Techniques** are designed to stabilise and secure slopes by using root penetration and decreasing porewater pressure.

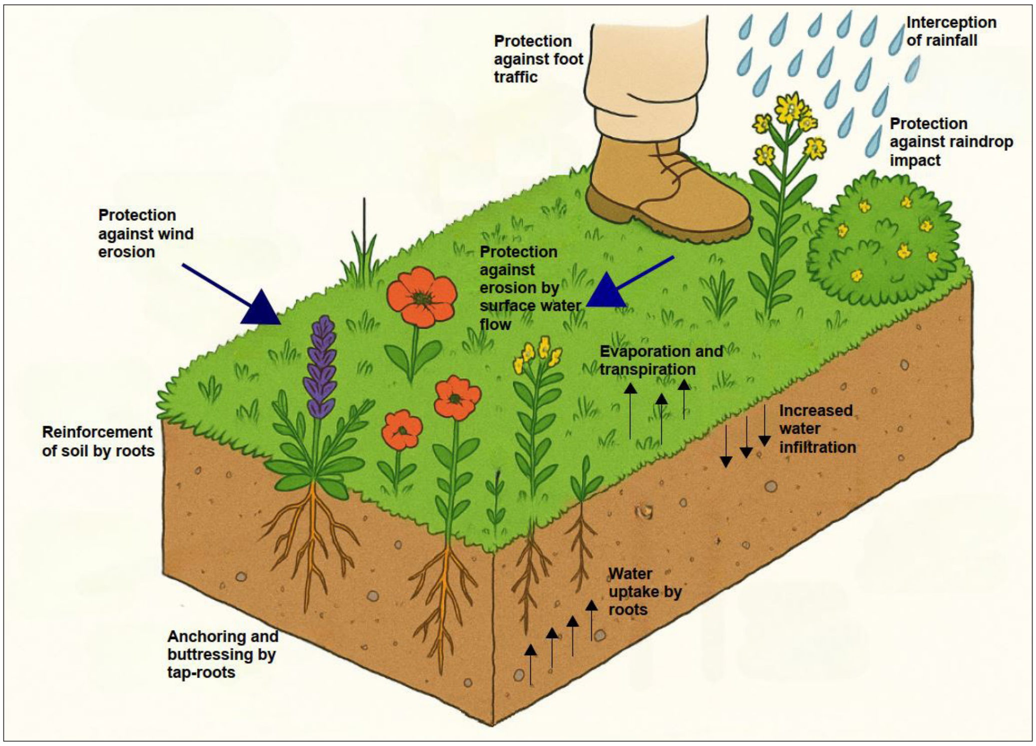


Figure 8.12. Influences of vegetation on the soil (Adapted from Coppin and Richards, 2007)

- **Combined Construction Techniques** combine live planting with structural materials such as timber, concrete, and steel to support slope instability.
- **Supplementary Construction Techniques** comprise planting and seeding following construction to provide long-term support.

It is important to note that designing to consider the positive effects of bioengineering is particularly complex. We therefore currently consider that the addition of bioengineering to slopes in New Zealand should generally be considered as a layer of resilience and to promote the additional benefits described in Section 8.4.2.

8.4.2 Intended Use and Benefits

Bioengineering measures are intended for use where the consequences of failure (such as loss of life and/or asset damage) are low. This is due to the difficulty in designing for and providing an accurate Factor of Safety for these measures. They are also intended for use where the cost of standard engineered mitigations is prohibitive.

Bioengineering measures can be used in the following instances:

- Improving the stability of shallow, unstable slopes by increasing the shear resistance of the soil or reducing the porewater pressure;
- Addressing areas susceptible to erosion or scour from wind, rain, or stormwater;
- Complimenting other engineered measures where a natural aesthetic is desired;
- Supporting projects aimed at achieving sustainable certification;
- Providing a natural aesthetic and positive social and cultural impacts; and
- When other measures are not economically viable.

Bioengineering cannot significantly affect deep-seated instability as the failures extend beyond the limits to which the roots of most trees and shrubs normally penetrate (Coppin and Richards, 2007). Some trees may provide slightly deeper stability; however, studies show that the rooting depth of New Zealand native trees rarely exceeds 2 m (Phillips and Marden, 2006).

A number of different bioengineering options can be used for slope stability improvements, each with its own benefits. Table 8.8 outlines these options.

Table 8.8.Common bioengineering measures (modified from Campbell et al., 2006; and the Norwegian Geotechnical Institute, 2023)

Bioengineering measure	Description	Intended Use	Illustration
Grassing	The application of grass by sprigging and turfing, hydroseeding, and/or broadcast seeding is used to provide grass coverage across a slope. Grasses, such as vetiver grass, generally have quick establishment and dense ground cover; however, the protection is not immediate, as seeds need to germinate.	• Used for erosion protection, but not very effective for shallow surface stability. • Not ideal for steep slopes. Note that the resistance of grassed slopes to erosion can be enhanced by the use of permanent geosynthetic mats that reinforce the root mat (Hewlett et al., 1987).	 Grassing on slope (Photo from Puhoi to Warkworth Motorway)
Planting	The planting of shrubs, herbs, and trees across a slope is used to develop a root system within the slope. The time for establishment, extent, and depth of the root system is dependent on the plant type and species used. Commonly used species in New Zealand include harakeke flax and muehlenbeckia.	• Used for erosion protection, shallow soil stabilisation, and stream and river edge protection. • Planting is not immediately effective in controlling erosion. • Not suitable for steep slopes.	 Planting on cut slope (Photo from Puhoi to Warkworth Motorway)

Table 8.8.Common bioengineering measures (modified from Campbell et al., 2006; and the Norwegian Geotechnical Institute, 2023) continued.

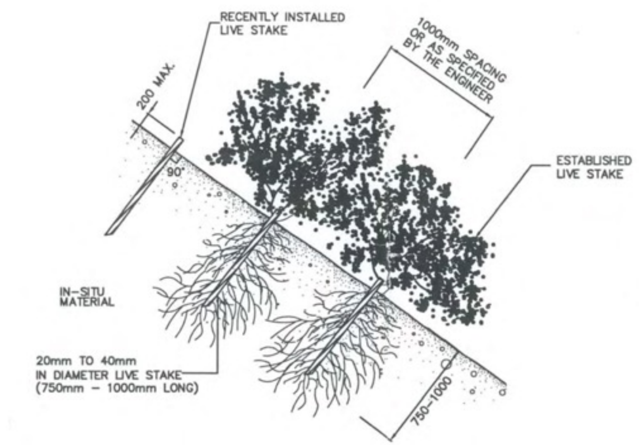
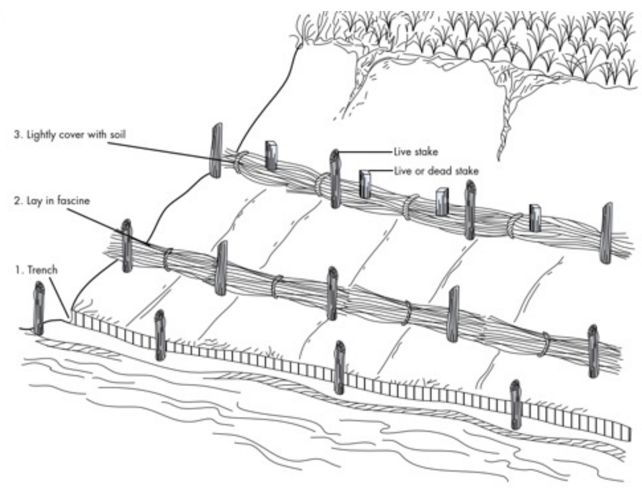
Bioengineering measure	Description	Intended Use	Illustration
Live stakes	Live stakes are live branch cuttings and tree stems that are inserted into holes in the soil to grow into new shrubs and trees. Live staking is quick to install but takes some time before the new plants are established. New Zealand species include ponga tree ferns.	• To protect from surface erosion and to provide shallow reinforcement to the soil. • Simple to install.	 Live staking illustration (Source: Campbell et al., 2006)
Live facines	Live facines are tubular bundles of live branch cuttings that are installed into shallow trenches along a slope. Live facines provide immediate stabilisation to the top 150 to 500 mm of a slope, depending on the diameter of the live facine. Additional roots will develop in time.	• Used for improving surface erosion and shallow mass movement within a slope. • Often used to restore shallow mass movement.	 Live facines illustration (Source: Shrestha et al., 2012)

Table 8.8.Common bioengineering measures (modified from Campbell et al., 2006; and the Norwegian Geotechnical Institute, 2023) continued.

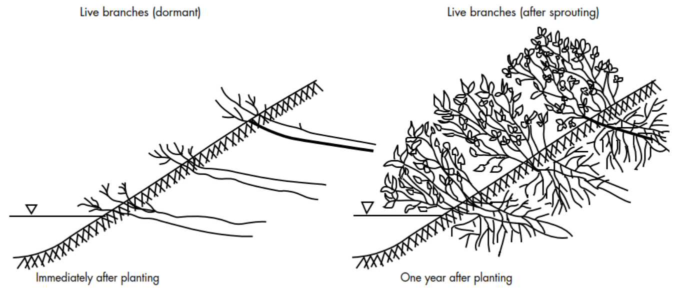
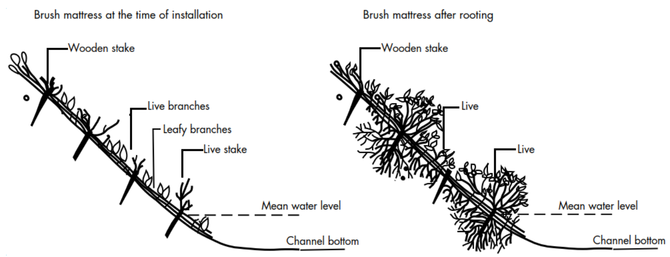
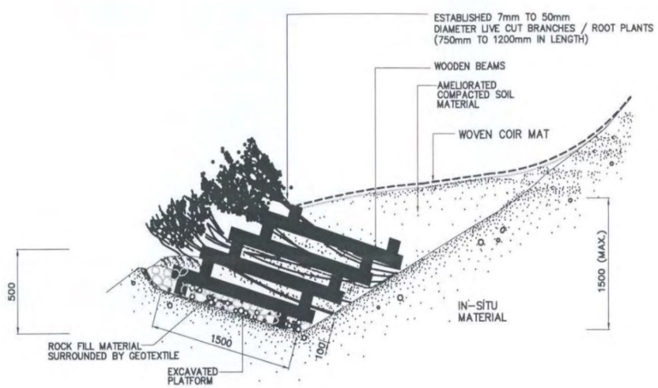
Bioengineering measure	Description	Intended Use	Illustration
Brush layers/ hedge layers	Consists of live cut branches and plants (brush layering) or rooted plants (hedge layering) that are placed in layers onto benches that are excavated into the slope, generally 700mm to 100mm wide. This vegetation is installed approximately perpendicular to the slope which provides immediate shallow support.	• Used for improving shallow mass movement within a slope. • Requires trenching to install. • Suitable for very steep slopes.	 Brush layering illustration (Shrestha et al., 2012)
Brush mattress	Brush mattresses are living branches placed close together in a crisscross pattern across a slope face to form a mattress. The entire slope face becomes covered and provides immediate protection.	• Provides erosion protection and shallow stability, particularly along stream banks, as well as acting as a sediment trap. • Not suitable for steep slopes.	 Brush mattress illustration (Shrestha et al., 2012)
Live retaining walls	Consists of introducing live branch cuttings within retaining walls such as crib walls and gabions. The cutting will be rooted into the soil portion of the retaining walls, and once established, will take over the structural function of the original retaining wall. These options provide immediate stability, which will improve as the vegetation becomes established.	Used where retaining structures are required, such as in steep banks.	 Live retaining wall illustration (Campbell et al., 2006)

Table 8.9. Bioengineering effects on slopes (modified from Punetha et al., 2019; Campbell et al., 2006)

Mechanism	Description	Influence
Mechanical	Rooting systems can reinforce the soil and increase the shear strength of a slope.	Beneficial
	Vegetation cover can provide erosion protection from surface water flow and wind by binding the soil particles at the ground surface.	Beneficial
	The weight of the vegetation can surcharge the slope and either 1) increase the driving force or 2) increase the resisting force when placed at the top or bottom of a slope.	Beneficial/ Adverse
	The vegetation might attract wind loading, which will transmit forces into the slope.	Adverse
	Tap roots may anchor into underlying firm strata, supporting the surface soils through buttressing and arching.	Beneficial
	Vegetation may filter and trap sediment from runoff down the slope.	Beneficial
	Vegetation can help prevent the severity of repetitive shrink-swell processes by protecting from direct exposure to sunlight and rainfall.	Beneficial
	Indirectly improves the shear strength of the soil by increasing the matric suction in the unsaturated root zone.	Beneficial
	Vegetation on rock slopes may result in root jacking, where roots grow into the cracks of rocks and expand to cause rock failure.	Adverse
Hydrological	Vegetation intercepts and absorbs rainfall, which reduces surface infiltration into the soils.	Beneficial
	The rooting systems absorb water from the soil, which reduces porewater pressures.	Beneficial
	Absorbing water from the soil may lead to increased desiccation cracking and a subsequent increase in infiltration capacity.	Adverse
	Roots and stems can increase the roughness of the ground surface, leading to higher soil permeability and increased infiltration.	Adverse
	Vegetation intercepts rainfall and prevents the surface soils from rain impact erosion.	Beneficial

Bioengineering can have beneficial and adverse impacts on a slope, relating to both the mechanical and hydrological mechanisms. The following table summarises the different mechanisms of the soil-plant interaction along with the beneficial and adverse effects on the stability of the slope.

In addition to the mechanical and hydrological impacts, bioengineering provides a number of non-geotechnical benefits for both people and the environment, such as:

- Cost-effective compared to engineered stabilisation measures;
- Provides environmental benefits by providing carbon sequestration and transpiration (water returned by vegetation back to the atmosphere);
- Improves air, soil, water, and groundwater quality;
- Can enhance green spaces and biodiversity for the area;
- Protection of important cultural, historical, and natural resources;
- Reduced long-term maintenance costs;
- Provides a natural aesthetic to slopes, concealing structures to blend them in with the natural landscape; and
- Reduces the heat island effect in urban areas.

8.4.3 Technical Design of Bioengineering

While in New Zealand, it is generally recommended that bioengineering is added as a layer of resilience and to promote the other benefits as discussed in Section 8.4.2. Eurocode EC7 design Clause 11.4 (10) identifies vegetation as one potential way to stabilise potentially unstable slopes.

Coppin and Richards (2007) present methods for assessing slope stability when using the addition of vegetation. The stability analysis can incorporate five major effects of vegetation (as shown in Figure 8.13 below:

1. Increased effective soil cohesion due to root matrix reinforcement, c'_R;
2. Increased effective soil cohesion due to soil suction, c'_s, or a decrease in pore-water pressure, u;
3. Increased surcharge due to the weight of vegetation, W_V;
4. Increased disturbing force due to wind, D; and
5. Increased restoring force, T, due to large roots acting like tensile elements.

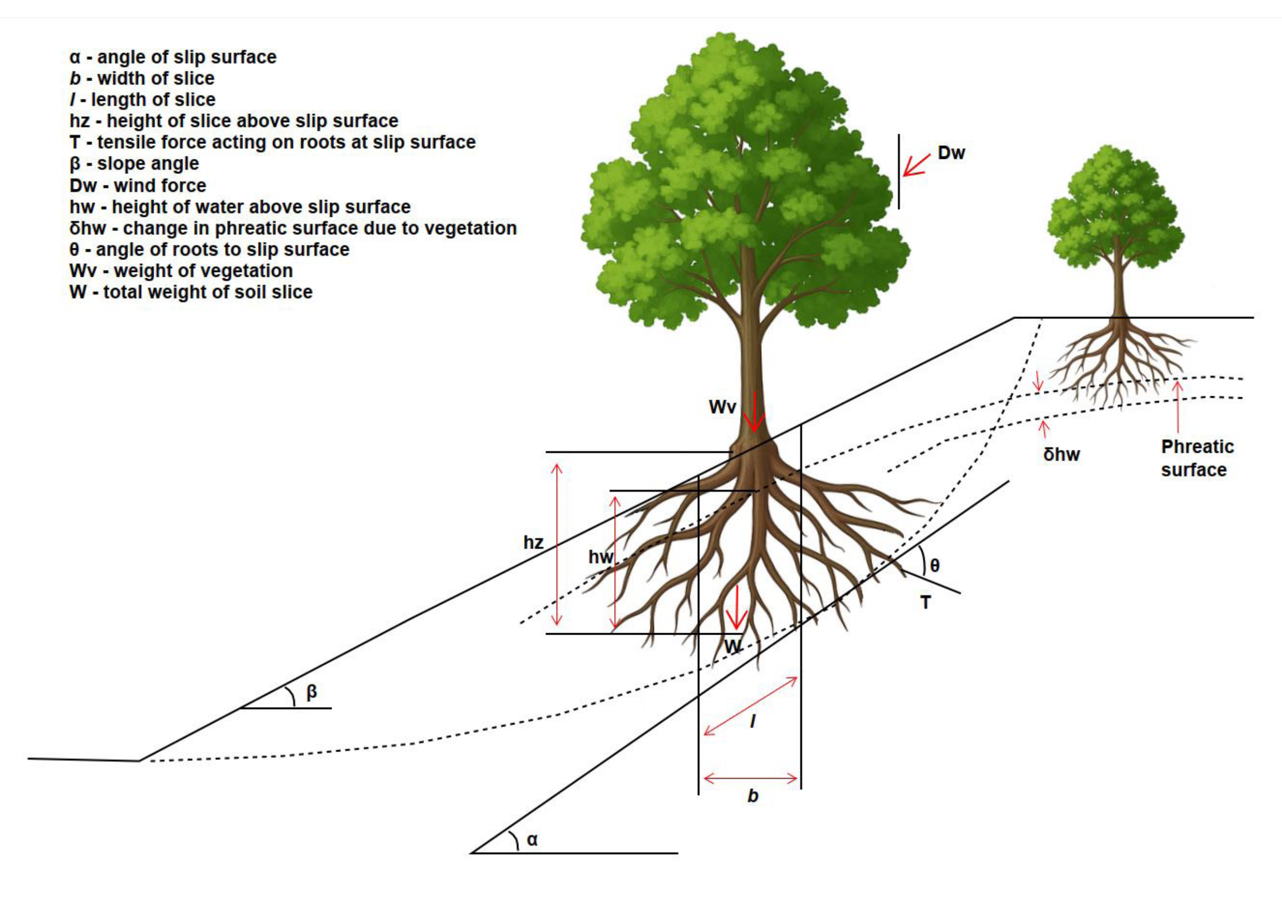


Figure 8.13. Typical slice in a slope, showing the five main influences of vegetation (Adapted from Coppin and Richards, 2007)

Studies such as Coppin and Richards (2007), Loftalian et al. (2019), and Greenway et al. (1984) have suggested a relationship between additional root cohesion, C_R, and average root tensile strength, T_R, ranging from:

$$C_R = (1.15 \text{ to } 1.25)\ T_R\ (A_R/A) \qquad \text{Equation 8.1}$$

where A_R/A is the ratio of root area to total area.

The reliable benefit of an enhanced c' value is limited to shallow depths, as root distribution is concentrated mainly within the top 1 m of the ground surface (Chen et al., 2024).

Greenwood et al. (2015) present how case studies in the UK, Greece, and Italy demonstrate how results from in-situ root pull-out tests may be used to estimate the potential reinforcement forces available from the roots. These case studies showed that the safety factor was increased by more than 10% with the addition of vegetation. Greenwood et al. (2015) also suggest that a partial safety factor of 8 or more is recommended, given the variability and uncertainties surrounding improvements due to bioengineering.

Generally, this is a more common research area overseas, but less so in New Zealand. Phillips et al. (2023) present a retrospective view of tree root research in New Zealand and present evaluations of the mean tensile strength of tree species across New Zealand, while Simon et al. (2023) collected data on 11 native species used for bank stabilisation. However, Phillips et al. (2023) recommend that further work is required to address the challenges in dealing with spatial and temporal variability in the species-specific characteristics of tree roots and in factors such as soil and soil hydrology, and how this affects root reinforcement. Without such additional data, it is unlikely that the positive stabilisation due to vegetation will be able to be credibly calculated.

8.4.4 Effective application

The following process should be undertaken to determine the applicability and use of bioengineering and which bioengineering option to use.

Table 8.10. Effective application of bioengineering measures

Step	Action	Description
1	Assess the slope	Identify the existing or potential failure mechanisms to determine the required depth of stabilisation or erosion protection.
2	Assess any geographical and climate conditions	Consider weather patterns, growing conditions, and susceptibility to pests and diseases to inform suitable bioengineering options.
3	Determine the need for additional structural elements in conjunction with the bioengineering measure	Planting alone may not provide sufficient stability. Additional structures (e.g. live crib walls) may be required to meet stabilisation needs.
4	Determine whether native or exotic species will be used	Choose species based on expected root depth and growth rate to meet the project's stabilisation requirements.
5	Identify any aesthetic requirements	Consider visual outcomes and landscape integration of the proposed solution.
6	Consult with stakeholders	Engage stakeholders to understand their needs, preferences, and any concerns regarding potential solutions.
7	Undertake a technical assessment	Where sufficient input information is available, it may be possible to undertake a calculated slope stability assessment using guidance within such publications as described in Section 8.4.3. These designs should be undertaken with caution, as gathering the required input information to accurately model the bioengineering/soil interaction is very complex.
8	Select the appropriate bioengineering measure	Choose a solution that meets the stabilisation and erosion protection needs of the slope.
9	Determine an appropriate installation timeframe	Consider standard planting seasons, though off-season planting may be possible with an appropriate maintenance plan.
10	Monitor and document performance	Collect data over time on performance, cost, and maintenance to inform future projects and improve best practices.

8.4.5 Considerations and Limitations

The following table outlines important considerations when choosing whether bioengineering is appropriate and what type of bioengineering to use for slope stability.

Table 8.11. Common bioengineering measures

What to consider	Description
What measures to use	• Protection for surface erosion versus slope stability requirements, including depth of reinforcement required. • Time for sufficient establishment. May require temporary measures such as using coconut matting to assist, or geosynthetic for longer support. • Access for planting and maintenance. • The resistance of any measures to pests and diseases.
Native versus exotic plant species	• Impact/interaction with the existing environment. • End of plant life – time to reach this stage, loss of strength/reinforcement, maintenance, pollination, etc. • Ability to create biodiversity and green corridors. • Consider the growth rates and growth habits of the proposed species. • Phillips and Marden (2006) studies found that New Zealand native species have higher tensile root strengths than exotic species, tend to be slower growing, and have shallower root systems. However, data from Hawke's Bay following Cyclone Gabrielle indicated native forests had less damage than exotic plantations. • Philips et al. (2023) generally found that exotic tree species outperform native tree species in terms of their contribution to soil reinforcement and for most empirical metrics other than root tensile strength. • Wilding pines are now a pest in New Zealand and needing to be poisoned in conservation areas. Selection of native tree species with appropriate fast-growing native nursery species, such as manuka and kanuka, would be preferable for biodiversity and long-term environmental benefits. • Willows have been found to provide erosion control on river and stream banks (Bay of Plenty Regional Council, 1998).
Installation	• Time for sufficient establishment. May require temporary measures such as using coconut matting to assist. • Planting density required. • Access for planting and maintenance. • Unable to be used in areas where there is no soil – i.e. rock slopes. • Planting season restrictions to allow plants the best success of taking root. It is important to plant when soils are moist, materials are "green" and not susceptible to drying out.
Existing environment	• Different areas of the country will require different measures due to varying geological conditions, rainfall, exposures, and temperatures. • Soil moisture – moisture retention and drainage. • Ground slope angle – run-off and topsoil application/retention. • Proximity to existing/proposed infrastructure and buildings. • The increase and uncertainty of natural disaster events due to climate change. • Competition with other plants.
Root system type	• Long and deep or shallow and wide root systems. • Using any known root tensile strengths or root pullout forces. • The groundwater regime strongly influences root development. Shallow groundwater may cause roots to grow laterally rather than downwards, reducing their effectiveness in providing stability. • Rooting along is unlikely to be useful in preventing deep landslides.
Water uptake	• Effects on the local groundwater table. Will it lower the groundwater locally and cause any issues further down the line (e.g., settlement)? • Will there be sufficient water available for vegetation growth?
Maintenance	• What maintenance will be required? • Will there be access in the long term? • Who will be responsible for maintenance, and what will happen if it gets forgotten about?
Design limitations	• Planting can be supplemented with other techniques and engineered solutions such as geofabrics, geogrids, rock armouring, and drainage. • Is there sufficient information to design for soil strength improvements due to the addition of bioengineering? • Determination of appropriate factors of safety to use when designing with bioengineering.

8.4.6 Example Applications

The effectiveness of vegetation on slopes was evident following the February 2023 Cyclone Gabrielle storm event, which triggered widespread landslides along the eastern front of the North Island. Following the cyclone, Manaaki Whenua - Landcare Research undertook rapid assessments of the damage to hill country (McMillan et al., 2023).

The intense rainfall led to increases in porewater pressure in the soils, which often caused failure on steep hill slopes at the soil/rock contact. Where vegetation was present, the roots growing through the soil/rock contact increased the shear strength and reduced the probability of failure.

The rapid assessments identified that, in the southern Hawke's Bay – northern Wairarapa hill country, there was a 90% landslide reduction where native forest was present, and an 80% reduction for exotic forest. The reductions in northern Hawke's Bay were 90% for native forest and 60% for exotic. On the Gisborne coastal hill country, exotic forests demonstrated little efficacy in reducing landslides, whereas native forests managed to achieve a 50% reduction.

These findings clearly show a significant reduction in landslides where vegetation is present, with native trees showing to be superior to exotic species.

However, improvements to slope stability from vegetation can also be limited, depending on the situation. In parts of the Waitakere Ranges, tree roots are unable to penetrate into the rock, and failures are seen along the soil/rock contact where there is no beneficial increase in shear strength.

9 SAFETY BY DESIGN

Landslides pose a significant safety risk that must be addressed at every stage of a mitigation project, from site assessment and design to construction and operation. While much of this guidance focuses on reducing hazard risks to communities and infrastructure, this section shifts focus to managing health and safety risks to people directly involved in delivering the project. Under the Health and Safety at Work Act 2015 (HSWA), all stakeholders, including owners, designers, and contractors, are responsible for managing risks and working together to enhance safety.

Incorporating safety considerations into the design process is essential to meet HSWA requirements. The primary goal of Safety by Design (SbD) is to integrate risk identification and assessment methods early in the design phase. This approach aims to eliminate or minimise potential health and safety risks associated with the construction, operation, maintenance, and decommissioning of the mitigation strategy throughout its lifespan.

This section aims to clarify certain confusions and avoid common mistakes specific to slope stability mitigation projects, rather than reiterating all well-known principles of Safety by Design.

9.1 NEW ZEALAND HEALTH AND SAFETY AT WORK ACT REQUIREMENTS

The New Zealand Health and Safety at Work Act 2015 (HSW Act) requires all organisations to:

- Identify hazards
- Assess risks if necessary
- Control risks
- Regularly review control measures

Proactively managing hazards and risks is key to preventing incidents and injuries. SbD is a procedure that incorporates hazard identification and risk assessment early in the design process. It aims to eliminate, isolate, or minimise risks of death, injury, and ill health for those involved in constructing, operating, maintaining, decommissioning, or demolishing an asset.

SbD begins in the conceptual and planning phases, focusing on making safe design choices early on. These choices can include construction methods, maintenance provisions, or materials used.

Most construction safety risk mitigation involves isolating, informing about, or controlling hazards. Considering the project's life cycle and involving decision-makers early in the design stages to eliminate hazards is invaluable. Starting this process early makes it easier to implement beneficial changes. The design stage offers the best opportunity to incorporate improvements that can save time and costs over the asset's life.

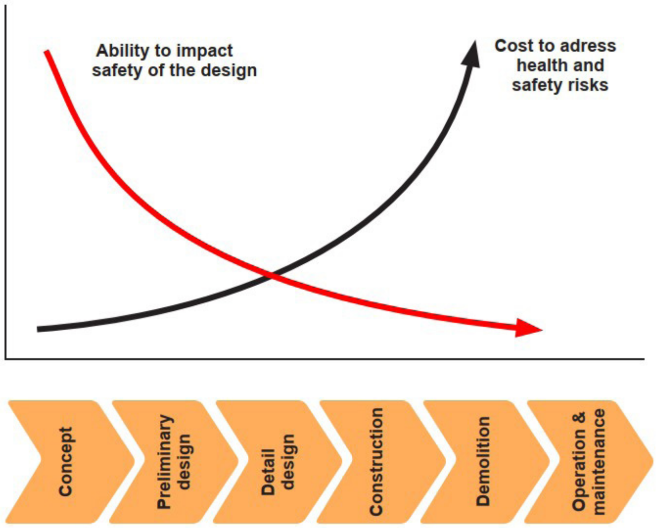


Figure 9.1. Symberski chart of influence for construction safety planning (Adapted from Engineering New Zealand (2023)

The hierarchy of hazard control for SbD is shown below.

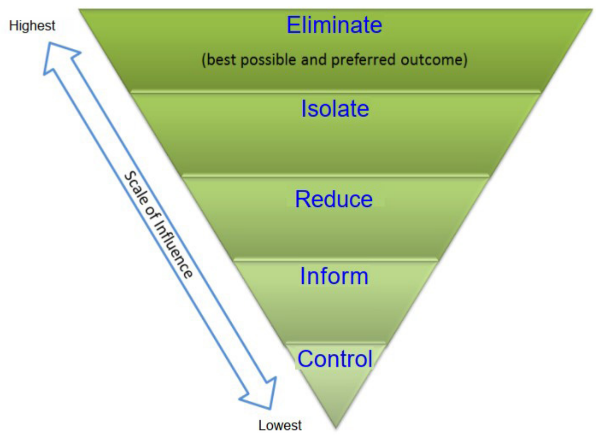


Figure 9.2. Hierarchy of hazard control (Adapted from Auckland Transport, 2016)

9.2 SMALL SCALE PROJECTS AND SBD

Managing SbD on small-scale projects can be both straightforward and effective with a few key steps:

- **Early Planning**: Safety considerations should be integrated from the very beginning of the project. Potential hazards should be identified early to facilitate elimination or minimisation during the design phase.
- **Simplified Risk Assessment**: A basic risk assessment can help identify and evaluate risks. This process does not have to be complex—the focus should be on understanding the main hazards and how they can impact the project.

- **Stakeholders Involvement**: Engaging everyone involved in the project, including workers, contractors, and clients, in safety is essential. Their input can help identify risks that might not have been considered.
- **Checklists**: Simple checklists can help ensure all safety aspects are covered. This can include checking for safe materials, ensuring proper ventilation, and planning for safe access and egress.
- **Training and Communication**: Everyone on the project should understand the safety plan and their specific role within it. Regular communication and training sessions can help keep safety top of mind.
- **Regular Reviews**: Safety measures should be continuously reviewed and updated as the project progresses. This helps to address any new hazards that may arise.
- **Documentation**: Keeping records of safety assessments and measures is valuable for maintaining safety standards and provides a reference for future projects.

By integrating these steps, designers can effectively manage Safety by Design on small-scale projects, creating a safer working environment for everyone involved.

9.3 "IF THE DESIGN DOESN'T CHANGE, YOU HAVEN'T DONE SBD"

The phrase "If the design doesn't change, you haven't done Safety by Design" means that the process of Safety by Design should lead to tangible changes in the design to address safety concerns. This is further explained in the bullet points listed below:

- **Hazard Identification**: SbD involves identifying potential hazards associated with the design. If no changes are made, it suggests that these hazards were either not identified or not addressed.
- **Risk Mitigation**: SbD involves assessing risks and implementing measures to eliminate or reduce them. This often requires modifying the design to incorporate safer materials, methods, or features.
- **Continuous Improvement**: The goal of SbD is to improve safety continuously. If the design remains unchanged, it indicates that no improvements were made to enhance safety, which contradicts the purpose of SbD.
- **Proactive Approach**: SbD is about being proactive in preventing accidents and injuries. Making changes to the design is a proactive step to ensure safety is integrated into the project from the start.

In essence, if the design remains unchanged after the SbD process, it implies that safety considerations were not effectively integrated, and potential hazards may still exist. Therefore, successful SbD should result in design modifications that enhance safety.

A pre-design phase, as described in the figure below, will set the scene for project success down the line.

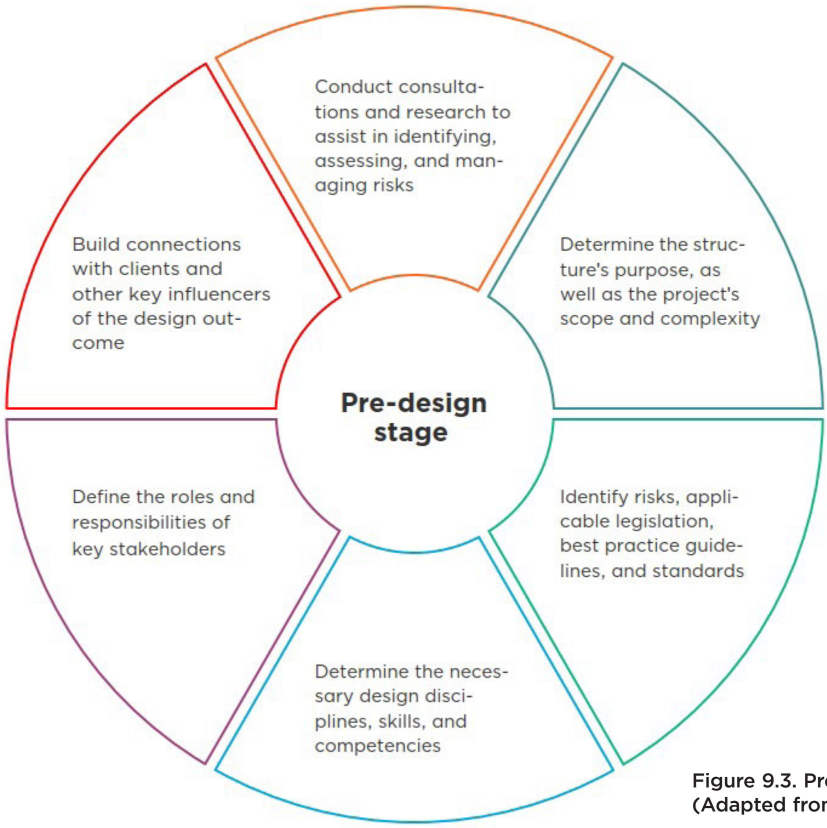


Figure 9.3. Pre-design phase SbD framework (Adapted from Worksafe New Zealand, 2018)

9.3.1 Safety in Design (SbD) Registers

Safety by Design (SbD) Registers are tools used to document and manage safety considerations throughout the design process of a project. They help ensure that potential hazards are identified and mitigated early. Key elements include:

- **Hazard Identification:** Listing potential hazards associated with the design.
- **Risk Assessment:** Evaluating the likelihood and impact of each hazard.
- **Control Measures:** Documenting strategies to eliminate or reduce risks.
- **Review and Updates:** Regularly updating the register as the design evolves and new information becomes available.

9.3.2 Project Risk Registers

A project risk register is a document used to identify, assess, and manage risks throughout the lifecycle of a project. It typically includes:

- **Risk Description:** Detailed description of each identified risk.
- **Likelihood and Impact:** Assessment of the probability and potential impact of each risk.
- **Mitigation Strategies:** Actions to reduce the likelihood or impact of risks.
- **Risk Owner:** Person responsible for managing each risk.
- **Status:** Current status of the risk and mitigation efforts.

9.3.3 Safe Work Method Statements (SWMS)

A Safe Work Method Statement (SWMS) is a document that outlines high-risk construction work activities, the hazards involved, and the measures to control the risks. It includes:

- **Description of Work:** Detailed steps of the high-risk activity.
- **Hazards and Risks:** Identification of potential hazards and associated risks.
- **Control Measures:** Specific measures to control the risks, such as PPE, safety equipment, and procedures.
- **Implementation and Monitoring:** How the control measures will be implemented and monitored.

9.3.4 Job Safety Analysis (JSA)

A Job Safety Analysis (JSA) is a process used to identify and control hazards associated with specific job tasks. It involves:

- **Task Breakdown:** Breaking down a job into individual steps.
- **Hazard Identification:** Identifying potential hazards for each step.
- **Preventive Measures:** Developing measures to eliminate or reduce hazards.
- **Documentation and Review:** Documenting the analysis and regularly reviewing it to ensure it remains effective.

These tools are essential for managing safety risks in various stages of a project, from design to execution and maintenance.

9.4 THE USE OF SBD REGISTER

The Safety by Design (SbD) register is a crucial tool for ensuring safety throughout the lifecycle of a slope instability remediation project. Its effective use during each phase of the project is outlined below:

9.4.1 Design Phase

- **Risk Identification and Assessment:** Potential slope instability risks and their impacts are documented including site-specific risks identified during site inspections and /or historical site-related information.
- **Mitigation Strategies:** Engineering solutions, such as retention systems, drainage systems, and vegetation plans are outlined along with design specifications and safety factors.
- **Stakeholder Engagement:** Inputs from geotechnical engineers, environmental scientists, and local authorities are recorded to ensure all safety concerns are addressed.

9.4.2 Construction Phase

- **Implementation Monitoring:** The installation of safety measures is tracked, ensuring alignment with design specifications. Inspections and any deviations from the plan are logged in the register.
- **Safety Protocols:** Safety procedures for construction workers are documented, including training records and emergency response plans.
- **Quality Assurance:** Test results and certifications for construction materials are recorded, verifying compliance with safety standards.

9.4.3 Maintenance Phase

- **Regular Inspections:** Scheduled regular inspections of the slope and its safety features are logged along with details of any maintenance activities performed.
- **Monitoring Systems:** The installation and operation of monitoring equipment, such as inclinometers and drainage sensors are documented with data collected and any actions taken in response to detected issues.
- **Vegetation Management:** The register tracks the growth and health of vegetation used for slope stabilisation, noting any replanting or erosion control measures needed.

9.4.4 Decommissioning/Replacement Phase

- **Risk Assessment:** A reassessment of the slope is conducted to identify any new or residual risks that need to be managed during decommissioning.

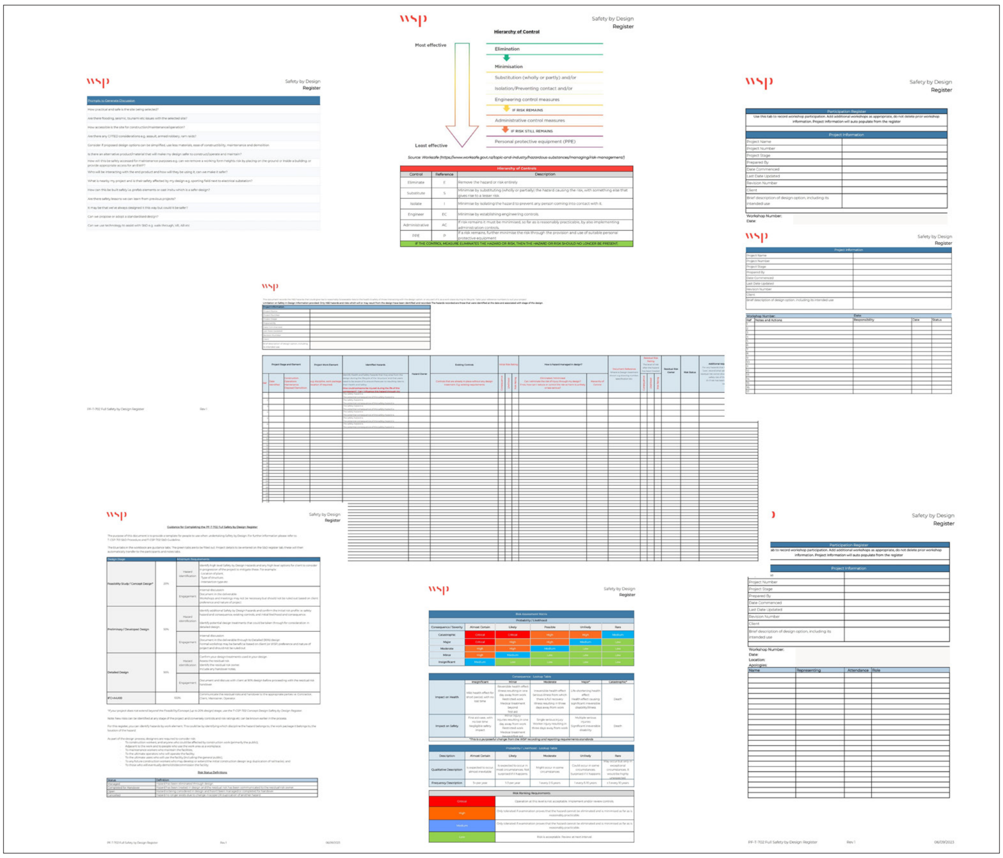


Figure 9.4. SbD register documents example set (courtesy of WSP SbD team)

- **Decommissioning Plan:** Steps for safely removing or repurposing outdated slope stabilisation measures are documented, including plans for site restoration and environmental protection.
- **Final Inspections:** Results of final inspections are recorded to confirm that all safety measures have been appropriately decommissioned and that the site is stable.

9.5 BENEFITS OF USING THE SbD REGISTER

Key benefits of using the SBD Register include:

- **Traceability**: Provides a comprehensive record of all safety-related activities and decisions, which is essential for accountability and future reference.
- **Consistency**: Ensures that safety protocols are consistently applied and maintained throughout the project lifecycle.
- **Communication**: Facilitates clear communication among all stakeholders, ensuring that everyone is aware of their responsibilities and the current status of safety measures.

Maintaining a detailed SbD register integrates safety considerations into every stage of a slope instability remediation project, reducing risks and enhancing overall project success.

Designers must prioritise health and safety when designing remediations. While they also consider practicality, functionality, cost, and aesthetics, these goals should not compromise safety. It is easier and cheaper to address hazards during the design phase than to fix them later. Focusing on safety from the start benefits everyone in the long run.

Figure 9.5. Duties of a designer in SbD space (Source: Health and Safety Authority website www.hsa.ie, accessed on March 2025)

10 SUSTAINABILITY BY DESIGN

Sustainability is "the development that meets the needs of the present without compromising the ability of future generations to meet their needs" (Brundtland 1987).

Sustainable design involves considering environmental, social, and economic impacts from the initial phase through to the end-of-life of an asset. It is an integrated, holistic approach that positively influences all phases of an asset's life cycle and enables compromises and trade-offs to be understood and agreed upon. When applied effectively, sustainable design supports the delivery of mitigation measures that meet project and client requirements while also aligning with broader societal needs.

This section provides guidance on how to integrate sustainable principles into the selection and design of mitigation measures for slope instability. It outlines approaches for identifying options that meet safety and performance requirements while minimising environmental impact, enhancing long-term resilience, and aligning with overarching sustainability goals.

10.1 OBLIGATIONS OF GEOPROFESSIONALS

Engineering New Zealand's Code of Ethical Conduct requires engineers to consider reasonably foreseeable environmental effects, maintain up-to-date knowledge and skills, and inform others of the consequences of not following advice. Work should be carried out in a manner that prioritises the safety and well-being of society and the environment (Engineering New Zealand, 2024).

Sustainability considerations should be integrated throughout the entire project life cycle, beginning at the earliest stages. PAS 2080:2023 *Carbon Management in Buildings and Infrastructure* illustrates that the ability to influence whole-of-life carbon impacts diminishes as a project advances through design and delivery phases. While early-stage decisions are often made with limited information, they offer the greatest opportunity to influence the project's carbon performance. Accordingly, the merits of adopting more resilient stabilisation solutions, extending asset life, and using low-carbon or no-material options should be evaluated at this stage.

10.2 BENEFITS OF SUSTAINABLE DESIGN APPROACHES

While incorporating sustainability into design may introduce additional cost, this is typically outweighed by the direct benefits to the client, before broader environmental and societal advantages are even considered. Sustainable design provides long-term financial, environmental, and social benefits.
These include:

- Optimised design reduces operational costs (e.g. maintenance, electricity, and water) and may also lower construction costs.
- Use of sustainable materials and designs strategies extends the lifespan of assets, reducing costs associated with renewals, repairs and decommissioning.
- Demonstrating corporate responsibility through sustainable infrastructure can enhance an organisation's reputation, attracting customers and investors.

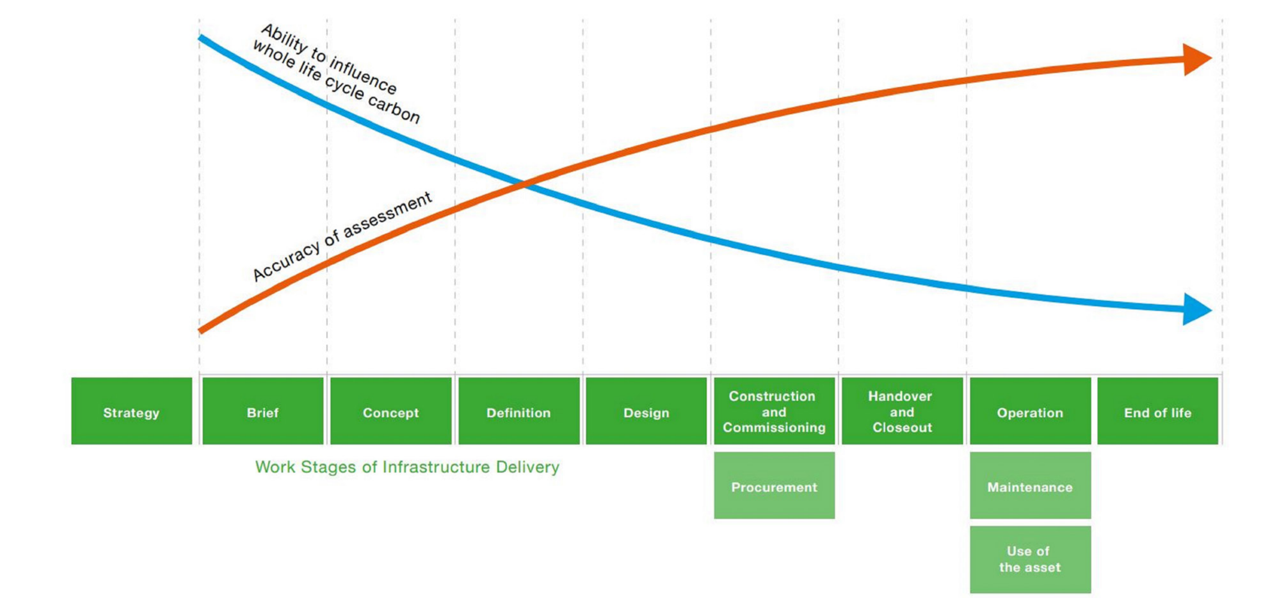


Figure 10.1. Ability to influence carbon reduction across project lifecycle stages (adapted from PAS 2080:2016, Carbon Management in Infrastructure)

- Designing for climate resilience helps minimise damage from climate-related events, supports business continuity, and reduces potential liabilities.
- Improved regulatory alignment. Sustainable design often aligns with evolving environmental regulations and planning policies, potentially streamlining approvals and reducing compliance risks.

10.3 DRIVERS FOR SUSTAINABILITY DESIGN

10.3.1 Sustainable Development Goals

The United Nations has established 17 Sustainable Development Goals (SGDs), supported by 169 specific targets, to be achieved by 2030 (Un, 2015). These goals address global environmental, social, and economic challenges in a holistic manner, aiming for improvement across all areas of sustainability while ensuring that improvements in one area do not negatively impact another.

Table 10.1. SDGs relevant to sustainable construction and infrastructure design

SGDs	Description
Goal 9	*Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.* This can be supported through the development of smart, durable, and eco-friendly infrastructure.
Goal 11	*Make cities and human settlements inclusive, safe, resilient and sustainable.* This includes creating sustainable urban spaces by reducing the environmental impact of cities and designing infrastructure that supports low-carbon living.
Goal 12	*Ensure sustainable consumption and production patterns.* Materials and design strategies should aim to minimise environmental impact, reduce reliance on natural or manufactured resources, and enable reuse or recycling at the end-of-life.
Goal 13	*Take urgent action to combat climate change and its impacts.* The construction industry has the potential to reduce greenhouse gas emissions through decarbonisation and the adoption of energy-efficient practices.
Goal 15	*Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.* This includes managing sustainable changes in land use through better earthworks design.

SDGs are widely used and communicated by governments, businesses, and investors, making them a relevant consideration in project planning and design. The New Zealand Government has endorsed these goals, stating:

> **"New Zealand will contribute to achievement of the goals through a combination of domestic action, international leadership on global policy issues, and supporting countries through the New Zealand Aid Programme."**

Accordingly, projects undertaken in New Zealand, whether directly funded by the government or undertaken within its regulatory framework, should consider the relevance of SDGs. While not legally binding, countries are expected to report voluntarily on implementation.

New Zealand has emphasised the importance of measuring and tracking its implementation without adding additional layers of bureaucracy. Understanding these goals and aligning design decisions with them, where possible, helps support this national and international direction.

10.3.2 Adaptation to Climate Change

Climate change is forecast to change the conditions that many geotechnical structures will have to withstand. In New Zealand, key impacts relevant to geotechnical practice include drought affecting expansive and settlement-prone soils, coastal erosion impacting cliff stability, and increased rainfall intensity influencing land stability.

These issues pose not only engineering challenges but also financial risks. Properties located in hazard zones may struggle to get insurance, exposing owners to significant potential losses. Even if the building platform can be protected, the loss of adjacent land may significantly reduce property value.

In 2022, the National Adaptation Plan was published and considers the impacts of climate change now and into the future and sets out how we will adapt as a nation (NZ Government, 2022). It outlines adaptation objectives that infrastructure owners and other client organisations are expected to consider. Understanding these objectives is essential to support informed and resilient design decisions.

10.3.3 Mitigation of Climate Change

New Zealand has made international and domestic commitments to address climate change by setting targets to lower our greenhouse gas emissions and transition to a low-carbon economy. Aotearoa New Zealand has committed to reducing its emissions, as a signatory of the Paris Climate Agreement. The Paris Agreement is a legally binding international treaty on climate change. The overarching goal is to hold "the increase in the global average temperature to well below 2°C above pre-industrial levels" and pursue efforts "to limit the temperature increase to 1.5°C above pre-industrial levels." In 2019, the Climate Change Response (Zero Carbon) Amendment Act was passed by Government to set a target for Aotearoa New Zealand to achieve net zero greenhouse gas emissions by 2050. Through this Act, the Climate Change Commission was established to advise on meeting this goal. The Zero Carbon Act also mandates emissions budgets to be set every five years with emission reduction plans outlining government actions to meet each budget period.

The building and construction sector is a large contributor to greenhouse gas emissions from producing materials, constructing buildings and infrastructure, and the energy used in buildings. In New Zealand the built environment has been shown to be responsible for 20% of greenhouse gas emissions (Vickers et al, 2018).

10.3.4 Climate Reporting

Climate reporting requirements apply to a range of public and private sector organisations to ensure action is being taken on climate change.

The Carbon Neutral Government Programme (CNGP), announced in December 2020, focuses on measuring and reducing emissions from core government departments and crown agents (including district health boards) to accelerate public sector emissions reductions.

The Climate-related Disclosure (CRD) regime legislated in 2021 ensures the effects of climate change are routinely considered in business and investment decisions. It covers large banks, insurers, managers of investment schemes, and publicly listed entities.

Reporting requirements are being developed by the External Reporting Board (XRB, 2023). Organisations captured under this regime will likely be required to disclose:

- Greenhouse gas emissions, including those embodied in geotechnical works that are procured or financed
- Climate-related risks, including potential resilience deficits in geotechnical structures

Understanding these requirements is essential when supporting clients who may be subject to these obligations, including large corporations, government agencies, or private entities.

10.3.5 Client Requirements

In addition to regulatory and climate-related obligations, design outcomes must balance cost, risk and quality. While priorities may vary, clients will expect optimised designs that deliver the best outcome.

10.4 PRINCIPLES OF SUSTAINABILITY BY DESIGN

Sustainable civil engineering design integrates environmental, social, and economic considerations to create infrastructure that meets present needs without compromising future generations. While there are many definitions of sustainable engineering principles (e.g. Glavič, 2022), these often confuse principles with elements. Underlying most of these are two core principles:

- **Assess multiple options and choose the most sustainable**
- **Optimise the preferred option to minimise negative impacts and maximise positive outcomes**

These principles are not sequential; iteration is expected as designs evolve, and as new information becomes available.

When assessing or optimising design options, the following elements of sustainable design should be considered:

- Social and community benefits
- Resource efficiency
- Environmental protection
- Energy efficiency
- Resilience and adaptability

The hierarchy for reducing carbon in projects is illustrated in Figure 10.2 and includes the following:
Avoid: Explore alternative means to satisfy performance requirements without constructing new asset/network such as reusing/retrofitting/repurposing existing ones.
Switch: Assess and adopt alternative scopes, design approaches, materials, or technologies that reduce whole-of-life emissions while still meeting performance needs.
Improve: Apply solutions and techniques that improve resource efficiency and asset longevity, including the use of circular economy principles to enable reuse or recycling at end-of-life.

10.5 PRACTICAL APPLICATION

The following framework, adapted from Engineering New Zealand (2024) and Roberts (2020) provides a starting point for applying sustainability principles when mitigating slope instability.

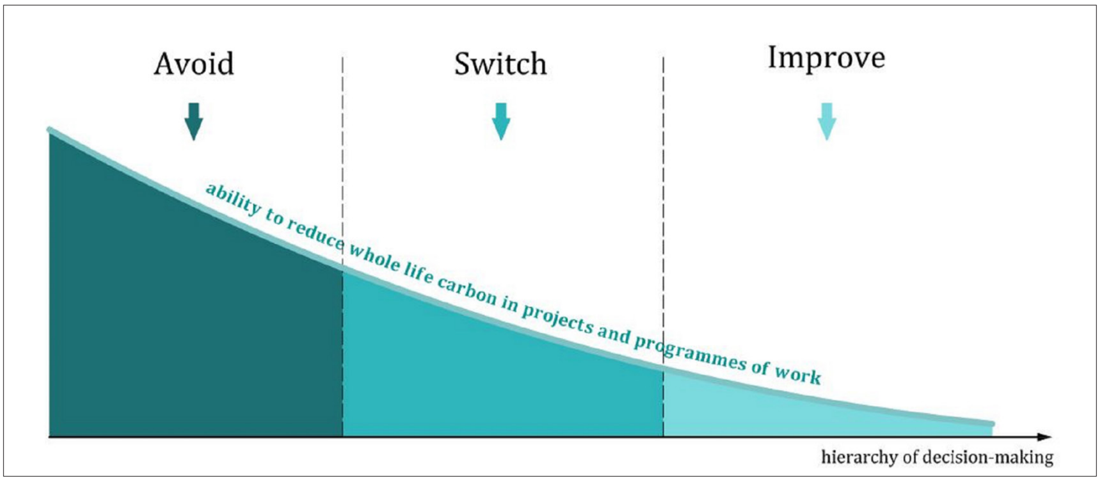


Figure 10.2. Carbon reduction hierarchy (reproduced from PAS 2080:2023, Carbon Management in Buildings and Infrastructure)

10.5.1 Reconfirm the Project Scope and Influence

Projects are often scoped, at least conceptually, before geotechnical input is sought. In such cases, the geotechnical role may be limited to delivering within a pre-defined brief. However, geotechnical professionals bring an understanding of natural hazards and climate change that may not have been fully considered in earlier decisions.

It is imperative that the entire project team shares an understanding of the client's drivers and that the project scope is regularly re-visited to reconfirm that it remains the most appropriate solution to the underlying problem. Consider the following questions:

- Is there sufficient information to understand the issues and conflicts?
- Is the environmental / climate impact of the current proposal/solution acceptable, and why?
- What is my role within the project, and how much influence do I have to support sustainable outcomes? Do I have access to the people who can influence the project?
- What is the project stage, and how much change is still possible to improve sustainability and climate action?
- Does the current proposal/solution address the underlying problem, or is there another solution that avoids the need for new construction?

10.5.2 Assess Multiple Options

The most common approach to compare options will be a multicriteria decision analysis. This involves:

- Identifying relevant criteria
- Assigning weights to each criterion
- Evaluating each alternative against the criteria
- Calculating scores based on the weights
- Ranking the alternatives based on their overall scores

Where weighting sustainability criteria proves challenging, a qualitative assessment may be appropriate.

Project-specific criteria may be project specific and will typically use the list of sustainability elements above as a starting point. Table 10.2 presents some of the sustainability considerations in slope design, aligned with key elements such as social and community outcomes, resource and energy efficiency, environmental protection, and resilience. These considerations aim to support more informed and responsible geotechnical decision-making throughout the project lifecycle.

10.6 MERITS AND SUSTAINABILITY IMPACTS OF COMMON SLOPE STABILISATION TECHNIQUES

Slope stabilisation plays a critical role in ensuring the long-term performance and resilience of infrastructure, particularly in geotechnically challenging terrain. While the primary objective is to achieve stability and safety, increasing emphasis is being placed on understanding the broader sustainability impacts of various techniques. This includes assessing embodied carbon, construction emissions, use of local or recycled materials, biodiversity outcomes, and cultural considerations. Table 10.3 summarises a range of commonly used slope stabilisation methods, outlining their technical benefits. The aim is to support informed decision-making by balancing engineering performance with environmental, social, and cultural outcomes. Sustainable design choices can often be achieved through early planning, optimisation of locally available resources, and collaboration with multidisciplinary teams.

Table 10.2. Sustainability considerations in slope design

Element	Sub-element	Considerations
Social and community benefits and intergenerational equity	Equitable access to infrastructure and public spaces	Identify all potential users and verify that the design meets their needs.
	Community engagement	Identify affected groups relevant to the geotechnical design and support appropriate engagement. Consider Te Ao Māori/mātauranga Māori/tikanga Māori. Engage with local communities, local iwi, and hapū to ensure their perspectives and concerns are addressed.
	Public health, safety, and overall quality of life	Apply engineering practices that support community and environmental health, safety, and well-being.
	Economic and social impacts between generations and demographic groups	Ensure maintenance, decommissioning, and renewal are affordable and safe for future generations, and Develop a design that balances the current and future needs.
	Assess long-term decisions that may be locked in beyond the asset's design life.	Avoid encouraging development or intensification in hazard zones, and Design to prevent the need for perpetual renewal to maintain service levels.
Resource efficiency	Minimise material use through optimised design	Reduce earthworks volumes where possible
	Use sustainable, recycled, or locally sourced materials	Use site-won or recycled material where possible to replace imported raw materials.
	Reduce construction and demolition waste	Use low-quality site-won material in low-risk applications where appropriate.
	Promote reuse and recycling of construction materials	Reuse demolition materials in the slope where suitable, and Minimise waste and promote environmentally responsible re-use, recycling, and disposal.
	Reduce water consumption in construction and operation	Program compaction to minimise the use of additional water where feasible.
	Consider repurposing, deconstruction and material recovery at the end of life	Consider NZTA's Project Emissions Estimation Tool.
	Evaluate greenhouse gas emissions over the lifecycle of the project	Consider construction emissions (e.g., plant), embodied carbon in retaining structures, and carbon emissions to decommission or renew at the end of life.
Environmental protection	Reduce land disturbance and habitat destruction	Modify the layout to reduce environmental impacts.
	Implement erosion and sediment control measures	Design out or minimise soil-disturbing activities.
	Minimise emissions, waste, and pollution during all project phases	Optimise energy requirements for construction. Identify and minimise emissions or contaminants from maintenance. Use lower embodied carbon materials where possible.
	Use benign materials (during use and at end-of-life)	Ensure components can be economically removed at end-of-life.
	Evaluate environmental impacts over the entire project lifecycle	Assess environmental impacts associated with operation, maintenance, renewal, or decommissioning. Discuss potential ecosystem and biodiversity impacts with iwi, hapū, and other stakeholders.
Energy efficiency	Reduce energy consumption in construction and operation	Generally, not relevant to slopes, unless active dewatering or monitoring is required.
	Use designs and methods compatible with renewable energy.	
	Prioritise projects that reduce non-renewable energy use	
Resilience and adaptability	Design structures to withstand climate change impacts	Account for changes in groundwater, drought, rainfall intensity, sea level, and temperature on slope stability and material durability.
	Use flexible designs to allow future modifications or repurposing.	Design efficiently for current conditions while allowing flexibility for future adaptation.
	Optimise maintenance and durability to extend the lifespan of structures	Use durable retaining structures to reduce lifecycle impacts and balance longevity with adaptability.

Table 10.3. Common slope stabilisation techniques with associated benefits

Mitigation Measures	Benefits
Bioengineering solutions	• Early adoption of bioengineering using local materials supports sustainable design. As stability demands increase, less sustainable solutions (e.g., soil nails) may be needed. • Enables cultural integration and community involvement—mana whenua may contribute local knowledge and species selection, especially near waterways. • Vegetation offers top sustainability benefits: erosion control, biodiversity, habitat creation, and a positive carbon footprint. Native species outperform exotics in long-term slope stability and ecological value; the use of fast-growing natives like kanuka can accelerate benefits. • Reusing stripped vegetation (e.g., ponga logs, forest duff) supports sustainability and biodiversity. Ecologist/landscape architect input enhances outcomes. • Reinforced grass with matting may outperform rock riprap in water flow resistance with lower emissions.
Earthworks	• Slope flattening and drainage improve stability; sustainability improves with reduced truck movements and optimised earthworks (e.g., ICOM method). • Extra site investigations can reduce material volumes. Consider CO^2 emissions from transport, waste, and machinery. • Use of marginal soils and recycled fill (e.g., concrete with high friction angles) can reduce the carbon footprint. • Electric or hydrogen-powered equipment lowers emissions and noise. • Prefabricated drains may be more sustainable than crushed aggregate unless local sources are viable.
Reinforced soil slopes and walls	• Use of on-site fill minimises carbon footprint and cost; vegetated facings offer biodiversity gains. • Imported granular fill allows smaller structures but has higher embodied carbon. • Geogrid reinforcement has a relatively low environmental impact; carbon data are available from suppliers. • Sustainability tools (e.g., IGS calculators) support design assessment.
Soil nailed slopes	• Steel or GRP nails have a moderate carbon impact due to the low volume used. • Soft facings with vegetation are more environmentally friendly than hard concrete surfaces.
Retaining walls	• Carbon calculators assess wall types and material sources. • Gabions with local/recycled rock and timber walls are more sustainable than concrete/steel. • Refer to SESOC resources (2024a, 2024b) for low-carbon design guidance and tools.

11 SELECTION AND APPLICATION OF MITIGATION MEASURES - WORKED EXAMPLES

11.1 ROCK SLOPE STABILISATION WORKED EXAMPLE

The following worked example demonstrates the application of the later stages of the rockfall mitigation design process, specifically from method selection through to detailed design and implementation. Earlier phases of the process, including hazard identification and characterisation, performance criteria development, options assessment, and sustainability considerations, were completed as part of the broader project but are not detailed here.

This example is drawn from the rock face stabilisation and rockfall mitigation design undertaken for a proposed residential development at Korere Terrace and Kauriki Terrace in Stonefields, Mount Wellington, Auckland. Acknowledgment is extended to Fletcher Living Residential for permitting the publication of this summary.

11.1.1 Site Description

The site is located in a former basalt quarry at the south end of the Stonefields subdivision, Mt Wellington in Auckland.

The former quarry highwall rock slopes, shown in Figure 11.1, are approximately 20 m high and consist of two batters separated by a single sub-horizontal to gently sloping bench. The lower batters consist of highly fractured and intact columns of basalt rock that vary from 5 to 9 m high and slope at 66° to 81° from horizontal. The upper batters consist of welded scoriaceous material and are taller and vary from 10 to 13 m with slopes ranging from 58° to 74° from horizontal.

11.1.2 Design Objective

The design objective is to provide rockfall mitigation and stabilisation design for the exposed rock face, to allow for the development of housing lots directly at the base of the slope.

Where there was an absence of residential lots near the toe of the slope, or where there was a sufficiently wide mid-slope bench to act as a rockfall catch (separately analysed), it was considered appropriate to reduce rockfall protection.

11.1.3 Design Preference

The preferred stabilisation option is a combination of rock bolts and flexible mesh.

The design length and spacing of rock bolts and the flexible mesh for the rockfall mitigation and stabilisation design are based on measured basalt rock block sizes and fracture spacing.

11.1.4 Rock Slope Investigations

Detailed face mapping of exposed sections of basalt and scoriaceous materials within the project area was undertaken to inform the design. A summary of the findings is provided in the following sections.

Figure 11.1. Basalt quarry rock slopes before mitigation

11.1.4.1 Geology

The rock slope geology at the location of residential lots is summarised in Table 11.1.

Table 11.1. Rock slope geology at the location of residential lots

Type	Description
Basalt	• Slightly weathered to unweathered • Variably fractured but is typically formed of columnar basalt to highly fractured basalt. • The rock face was disturbed by quarry operations in the past.
Scoriaceous material	• Scoriaceous mix consisting primarily of welded, subangular boulder size scoria blocks (typically 200 to 400 mm). • Large basalt blocks (up to 600mm wide).

Note: Weathered and sandy mixes of scoriaceous materials, along with tephra and ash, were also reported in the slope, but these more soil materials are not addressed in this summary.

11.1.4.2 Geological Strength Index (GSI)

The GSI was assessed to provide Hoek-Brown rock mass strength parameters for global stability assessment.

11.1.4.3 Block size and geometry

The basalt block geometry and block size were measured to inform design.

11.1.4.4 Groundwater

Groundwater was observed to be minimal or not present.

11.1.4.5 Stability Analysis

The global stability of the basalt and welded scoriaceous material was assessed using RocScience Slide 2 (RocScience), and the potential for rock topple was assessed using RocTopple (RocScience). The summary findings are presented in the table below.

11.1.6 Design

11.1.6.1 Flexible Mesh

Flexible mesh is a type of steel grid mesh that is appropriate for restraining smaller rock blocks to mitigate rockfall.

Design assumptions:

- The tensile capacity of the selected Steelgrid HR50 mesh = 76 kN/m (Strength Reduction Factor [S.R.F] = 0.85 for steel)
- The punching resistance of Steelgrid HR50 mesh = 84 kN
- Therefore, face pressure (block acting on mesh) was limited by the punching resistance of the mesh (84 kN).
- Where the load of the block exceeds 76 kN/m (tensile capacity of the grid) or 84 kN (punching capacity of the mesh), additional spot bolting will be required to reduce the block/column size, effectively reducing bolt spacing. The above scenario for the largest potential column size requires spot bolts as part of the Stabilisation Toolbox.

Table 11.2. Analysis results

Analysis	Rock type	Analysis inputs	Findings
Global stability (using Slide 2 - Rocscience)	Basalt	• Hoek-Brown parameters • GSI 35 (to account for localised thin scoriaceous layer) • 0.7 disturbance factor (to account for blasting)	• Required FoS achieved for all cases (i.e. long term static, seismic and elevated groundwater) • No additional support required (for global stability)
	Scoriaceous material (welded	• Mohr Column parameters • Parameters based on engineering judgment from working in similar materials and back-analysis of existing slope • Lose surface materials (2.5m thick) were modelled to account for disturbance	• Lower bound parameters mostly achieved FoS except where seismic load is applied to lose surface materials • To achieve minimum FoS for seismic a load of 14.2 kN/m was applied* • This applied load is achieved with 4 m long rock bolts at 2mH x 2mV spacing
Rock toppling (using RocTopple - Rocscience)	Basalt	• Slope and block geometry (a range of column widths and heights were modelled) • Barton-Bandis strength model (based on engineering judgement and experience in similar materials) • Joint Roughness Coefficient (JRC) • Joint wall compressive strength (JCS) and Phi (°)	• All static scenarios have an FoS>1.5 • For seismic cases 3m long rock bolts at 3 mH x 3mV achieve the required FoS and this is within the bolting requirements for most credible large block • 4m and 6m long spot rock bolts in toolbox if larger blocks are encountered during construction

Note: * the applied load was calculated using a simple Wedge analysis, see below

Design loads:

- The actual design loads were calculated based on the maximum observable block sizes,
- which were:
- For fractured basalt: 36 kN (assuming maximum block volume 1.33 m^3 and unit weight 27 kN/m^3)
- For basalt columns: 75.6 kN (assuming maximum block volume 2.80m^3 and unit weight 27 kN/m^3)
- For scoriaceous material, a simple wedge analysis was undertaken to assess the stabilisation requirements for scoriaceous material observed in the face. Mohr-Coulomb parameters were adopted. Results showed that using a Steelgrid HR50 (PVC) mesh and a 2 mh x 2 mV bolt spacing, a FoS of >1.5 was achieved for both the Static and Seismic cases. The required pullout capacity of the bolt for a 2 mH x 2 mV spacing is 49 kN.

11.1.6.2 Pullout capacity of bolts

Rock bolts were required to satisfy the requirements for reinforcing bars to AS/NZS 4671.

Design considerations:

- The rock bolts were designed to pin the mesh to the surface and are not there for stabilisation of global stability.
- The rock bolt design is a passive stabilisation detail as the bolts will only take on load when a block or fragment becomes dislodged and applies a force to the mesh (and bolt).
- For bolts installed in basalt, a minimum ultimate pullout capacity of 76 kN is required.
- For bolts installed in scoriaceous material, a 4 m bolt (with a minimum 1.5 m bond length beyond the theoretical failure surface) and a minimum Pullout Capacity of 49 kN is required.
- Assumed bond length between the grout and the rock is the length of the bond beyond the block.
- The ultimate bond strengths were based on previous work in similar materials. NZGS Ground Anchor Guideline and BS8081.
- In competent basalt, a 1 m grouted bond length has a pullout capacity of 267 kN.
- A 1.5 m grouted length in scoriaceous material has a pullout capacity of 49 kN.

The final bolted and meshed rock slope is shown in Figure 11.2.

11.2 BIOENGINEERING WORKED EXAMPLE

11.2.1 Site Description

For this worked example, we will look at a hypothetical site within the Hawke's Bay region. The site consists of a steep slope, with a gradient of approximately 22°, some extending over 200m in height. The site is located in a remote area with a river at the base of the slope where machinery access is difficult. There is limited vegetation cover/modified land cover due to deforestation. There is no development within the immediate surroundings.

Figure 11.2. Final rock slopes with rock bolts and mesh

However, there are floodplains at the base of the slope along the riverbanks.

The underlying geology in the area is soft sedimentary rocks of alternating mudstones, sandstones, and siltstones. The soils are known to be susceptible to saturation during periods of high rainfall. A walkover of the site has indicated that the sedimentary rock has a shallow weathering profile, with a residually weathered thickness of no more than 1m before becoming highly to moderately weathered. Shallow colluvium is also expected to be present across the area as a result of historical shallow landslides.

Regionally, slips within similar material across the area indicate that shallow landslides are common following heavy rain and storm events where there is no forest coverage.

11.2.2 Hazard Identification

Considering the expected geology and topography of the subject site, the key geotechnical hazards identified onsite include shallow landslides within the residually weathered sedimentary rocks and the shallow colluvium, as well as sediment flows and inundation within the flood plains.

Based on a review of the historic failures, there have been occasional landslides following heavy rainfall, and in some cases, the landslide debris has washed down and inundated the flood plains.

Landslide Hazard

Future failure scenarios consider that heavy rainfall, or potentially seismic shaking, could produce widespread shallow landslides within the residual soils and colluvium. The landslides are estimated to contain up to 250 m^3 in debris flow. These volumes are based on the estimated volumes of the historic landslides across the area.

Sediment Inundation Hazard

In addition to the primary landslide hazard, there are historical instances where the landslide debris has been carried down to the low-lying flood plains. This has caused a corresponding build-up and sediment inundation across the floodplains. It estimates that future inundation of over 50cm is possible at the subject site.

11.2.3 Risk Analysis

The following figure presents a qualitative/semi-quantitative risk assessment matrix that can be applied to the site (adapted from Auckland Council (2023)).

1. Assessment of the likelihood of slope failure: The site is underlain by weak sedimentary rock, which is susceptible to shallow landslides. It has been deforested, which removes the original stabilising support of vegetation. The site is moderately sloped, and similar slopes in the adjacent area have failed. Therefore, it is deemed likely that the site will fail at some point in the future.

2. Assessment of the level of consequence: Based on the slope's remote location, it is very unlikely that be any damage to an asset or loss of life for an individual. However, there is the possibility that the landslide debris will inundate the floodplains and have an impact on the adjacent river. Therefore, the consequence is deemed to be minor.

Using the risk matrix from Figure 11.3, the risk for this site is deemed to be medium.

		CONSEQUENCE				
LIKELIHOOD		Insignificant 1	Minor 2	Moderate 3	Major 4	Extreme 5
	Almost Certain 5	Medium 5	High 10	Very high 15	Extremely high 20	Extremely high 25
	Likely 4	Low 4	Medium 8	High 12	Very high 16	Extremely high 20
	Moderate 3	Low 3	Medium 6	Medium 9	High 12	Very high 15
	Unlikely 2	Very low 2	Low 4	Medium 6	Medium 8	High 10
	Rare 1	Very low 1	Very low 2	Low 3	Low 4	Medium 5

Figure 11.3 Example of a colour-coded qualitative/semi-quantitative risk assessment matrix (adapted from Auckland Council, 2023).

11.2.4 Target Performance Criteria

There are no residential or commercial properties or assets within the vicinity of the subject site. Therefore, the stability solution does not have specific target performance criteria.

11.2.5 Solution Requirements

Given the site's remoteness, the absence of properties or assets within the area, and the minor consequence of any failure, the intention is to provide a solution that improves the stability of the subject site without being designed to a specific performance criterion.

The solution will need to be constructable in remote areas and keep disturbance or destruction of the surrounding area as minimal as possible.

Limited funds have been allocated for remediation, so any solution will need to be cost-effective for both design and construction.

11.2.6 Optioneering

Taking into account the desired solution requirements above, the following options were considered as part of the initial design process.

The preferred option is the **bioengineering** solution due to its low cost, ease and speed of installation in a remote area, natural finish, and corresponding sustainability benefits.

This option is suitable for this site as the solution does not need to meet any target performance criteria and the risk of loss of life, or damage to assets is low.

11.2.7 Choosing a Bioengineering Solution

Several bioengineering solutions can stabilise a slope, each with its own benefits and challenges. Choosing the appropriate solution will require a site-specific assessment to determine the site's needs and requirements.

11.2.7.1 Choice of Bioengineering Measure

As mentioned above, the required criteria for the solution at the subject site are as follows:

- Able to stabilise shallow landslides
- Reduce the disturbance or destruction of the land as much as possible
- Solution is easy to install due to the remoteness of the site
- Economical

Table 11.3. Considered mitigation options

Option	Benefits	Challenges
Buttress and Shear Key Installation of a buttress with shear key, if necessary, to provide support to the toe of the slope.	• Able to key into stronger underlying strata. • Robust solution for landslide remediation. • Allows for key construction observations during excavations.	• Extensive earthworks required and corresponding ground disturbance. • Requires heavy earthworks machinery. • Can encounter issues when the groundwater table is intercepted.
In-ground Palisade Wall Construction of an in-ground palisade wall to provide additional resistance at the critical location of instability.	• Adaptable to various depths and geometries. • Robust solution for earth stabilisation.	• Heavy earthworks machinery required. • Requires detailed geotechnical investigation to design properly. • Expensive.
Soil nails Construction of soil nails to provide increased resistance across the entire slope.	• Minimally invasive. • Effective for stabilising existing slopes. • Relatively economical.	• Grouting and corrosion protection are necessary for long-term durability. • Requires machinery for installation.
Use of **bioengineering** Installation of bioengineering measures to provide increased resistance across the entire slope.	• Very economical. • Improves drainage and soil cohesion over time. • Provides sustainability benefits. • Reduces surface erosion. • Easy and fast to install. • Will grow into and become the natural environment.	• Can take time to establish. • Cannot currently be 'designed' for. • Vulnerable to drought, pests or fire.

The following flow chart shows the steps for determining which bioengineering is suitable to satisfy the required criteria.

Live stakes are deemed the most suitable bioengineering solution for the subject site. Live branch cuttings and tree stems are inserted into holes in the soil to grow into new shrubs and trees. The holes can be dug using handheld augering equipment without the need for large earthworking equipment. The stakes can then be easily installed into the holes by hand.

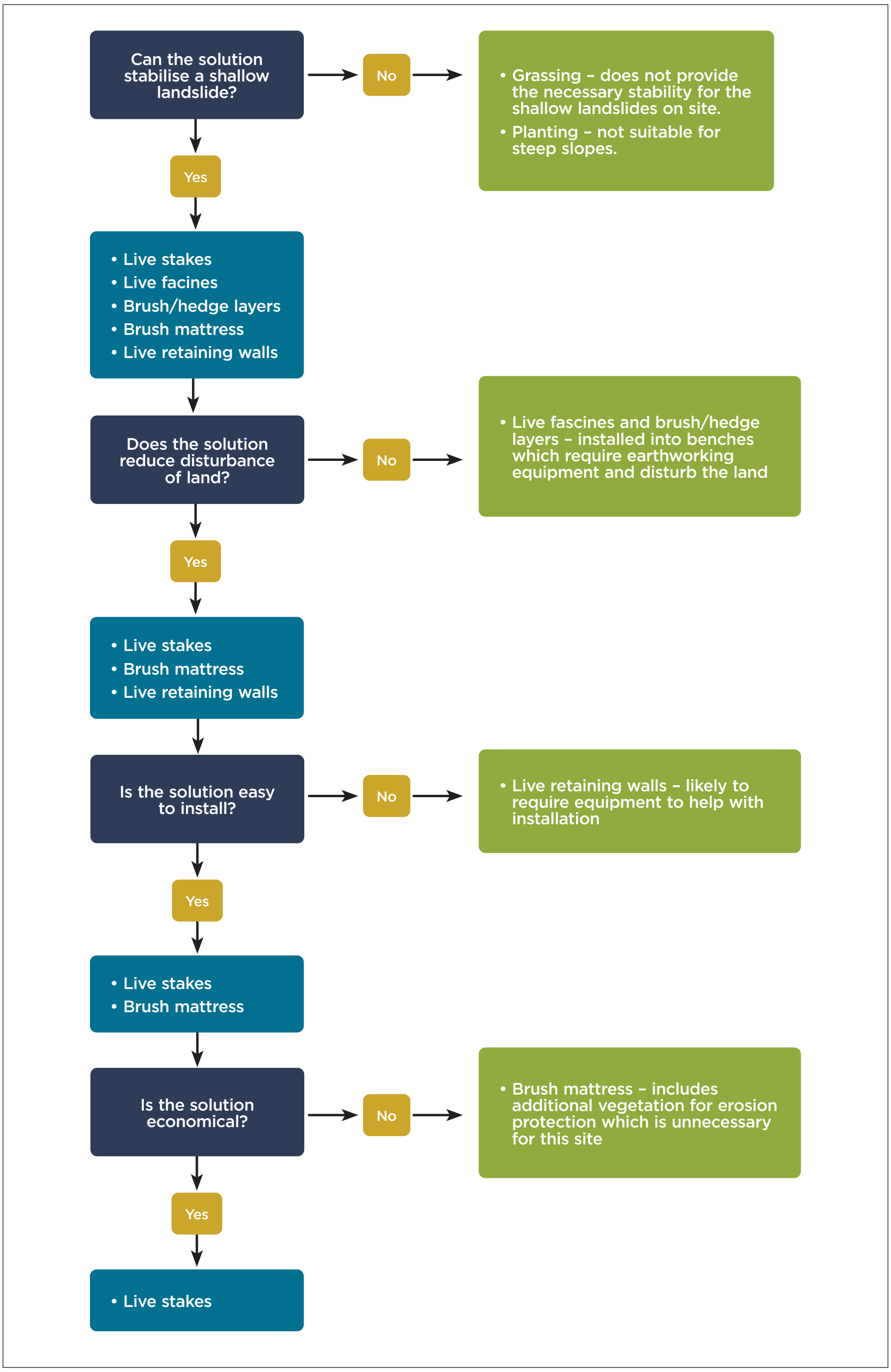


Figure 11.4. Steps for determining which bioengineering measures to adopt

11.2.7.2 Choice of Plants

Studies following the Cyclone Gabriel event within the Hawkes Bay have shown that New Zealand native forest species were more effective in reducing the number of landslides than corresponding exotic plants (McMillan et al., 2023). However, native plants have been shown to take longer to establish than their exotic counterparts.

The subject site does not require immediate establishment and long-term stability is favoured, therefore native species are deemed appropriate. Options such as ponga tree ferns would be suitable for this case.

11.2.7.3 Maintenance

An effective maintenance regime is required to ensure the establishment of bioengineering. Consideration should be given to the time of year that the planting is undertaken. If the stakes are installed outside of planting season, watering will likely be required to avoid the stakes dying. Other maintenance measures such as weeding, pest control, and mulching are also to be considered.

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