Rockfall Protection Structures Design Guidance

Waka Kotahi

June 2023

Version 1.0

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WAKA KOTAHI
NZ TRANSPORT AGENCY

Te Kāwanatanga o Aotearoa
New Zealand Government

Rockfall Protection Structures Design Guidance for Waka Kotahi Infrastructure

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Waka Kotahi NZ Transport Agency
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This document is available on Waka Kotahi NZ Transport Agency’s website at www.nzta.govt.nz

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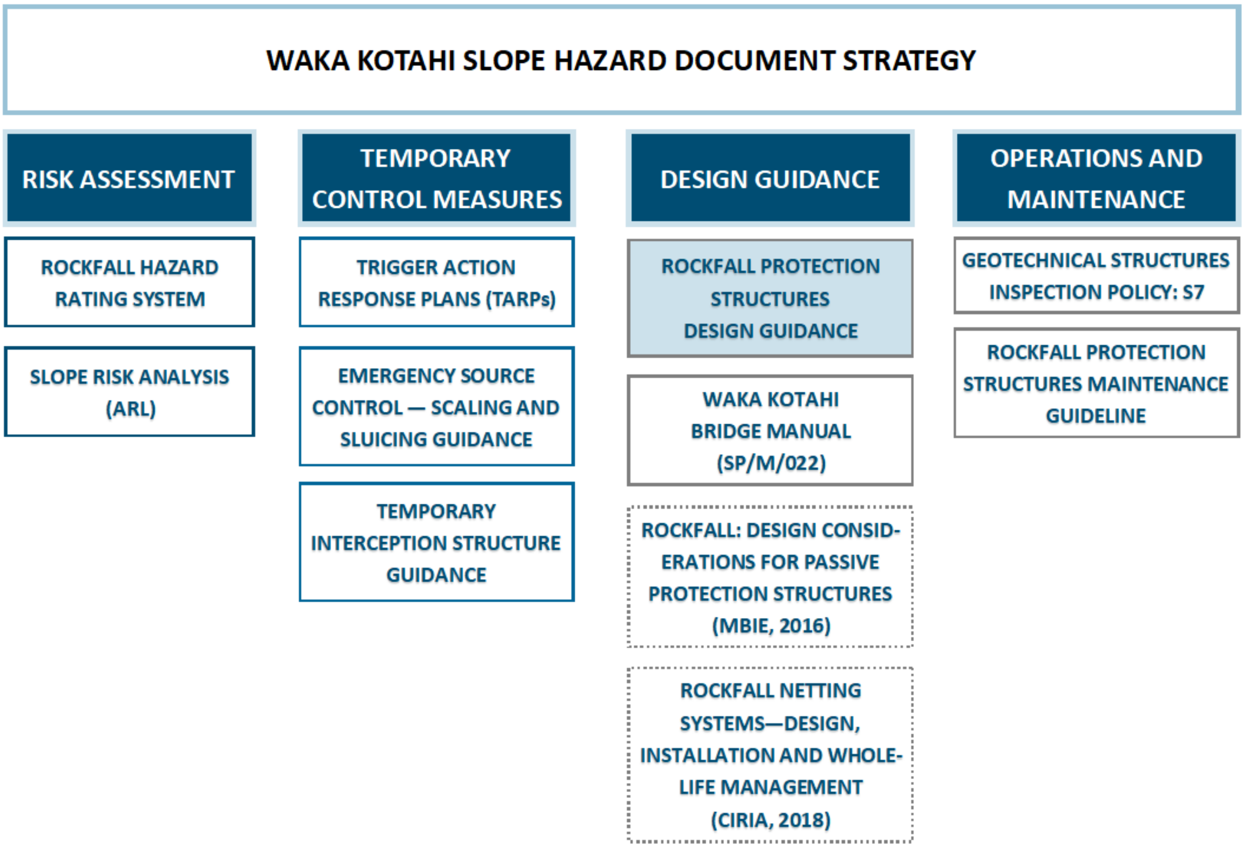
1. Foreword

The aim of this document is to outline considerations for the design of rockfall protection structures (RPS) for Waka Kotahi infrastructure.

This guide provides high-level Waka Kotahi specific guidance, considerations, and design references for the development of rockfall protection structures protecting Waka Kotahi infrastructure. The intention of this document is to align with the risk levels output from the New Zealand country amendment of the New South Wales (NSW) Roads and Maritime Services (RMS) Assessed Risk Level (ARL) risk assessment approach[6], the level of service associated with the applicable corridor, and the consideration of future maintenance.

This guide is in addition to the industry wide guidance provided by the Ministry of Business, Innovation & Employment (MBIE), 2016 "Rockfall: Design considerations for passive protection structures"[5], to provide a more roading specific design approach to rockfall protection design. The relationship of the Waka Kotahi Rockfall Protection Structure Design Guidance to other documents in the Waka Kotahi Slope Hazard document strategy is illustrated below. This document also aligns with the Waka Kotahi NZTA Bridge Manual[8].



2. Introduction

2.1. Purpose and Scope

The purpose of this document is to provide guidance for the geotechnical design approach for Rockfall Protection Structures (RPS) to Waka Kotahi infrastructure.

Design for RPS on roads is mainly focused on the life safety risk, however the approach needed slightly differs from that used for residential structures, as the design needs to consider life safety risk as well as the operational requirements of the road (level of service), route security and resilience (network importance), and the differing classifications of roads (level of usage and condition).

This document is intended to be used in conjunction with existing associated guidance for rockfall protection structures; Ministry of Business, Innovation & Employment (MBIE), 2016 "*Rockfall: Design considerations for passive protection structures*"[5].

The various types of slope hazards (e.g., rockfalls, rockslides, shallow debris slides etc), considered within this design guidance are covered under the terms 'rockfall' relating to falling, toppling, and sliding hazards. RPS are considered to cover protection measures designed to mitigate the above landslide hazards. This document does not include the considerations for the risks posed by slope-wide landslides or debris flows which require a different approach and considerations compared to rockfall.

2.2. Terms and Definitions

The following terms and definitions apply to this guide

Term	Definition
Active Mesh	Steel mesh secured with ground anchors and/or rock bolts, installed over a slope with surficial instability, to secure surface material from travelling downslope. This system can provide both 'active' stabilisation to improve the overall stability of slopes and/or 'passive' stabilisation for surface rockfalls (commonly referred to as 'anchored mesh').
Anchor	A mechanical rod installed and grouted into the ground to restrain or provide support for engineered slopes and other structures (include the following sub-categories - ground anchor, rock bolt.)
Assessed Risk Level (ARL)	The approach to assess risk to road users by determining the likelihood of a hazard occurring and consequences of the occurrence, using the New South Wales (NSW) Roads and Maritime Services (RMS) Assess Risk Level (ARL) risk assessment approach (and NZ Country Amendment).
Asset Owner	The controlling authority of the geotechnical structure, Waka Kotahi (NZ Transport Agency)
Attenuator	An engineered system installed on a slope to progressively reduce the energy, velocity, and bounce heights of rockfall, and direct material into a catch area or structure downslope.
Bund	An embankment that is used as a passive rockfall protection structure, can be constructed from a variety of materials including, earth/rock (sometimes reinforced), concrete blocks, gabion baskets
Catch Area / Debris Flow Basin	Areas designated for the catchment of rockfall, slope material and debris flows. May be standalone engineered ditch or incorporated into other structures such as the areas upslope of fences, barrier and bunds where material may collect.
Designer	An engineering geologist or geotechnical engineer, who is responsible for undertaking the initial assessment, determining the suitability of the

	structure, and calculating the required loads and support elements for a structure. Designers' must have at least five years' experience in the design of geotechnical structures.
Design Reviewer	Responsible for the verification of design and confirmation of suitability of the structure and supporting design calculations. As a minimum must be a chartered member (CPEng or PEng Geol) geotechnical engineering or engineering geologist with at least 10 years of relevant experience, including rockfall protection design and infrastructure works and should be approved by the Waka Kotahi NZ Transport Agency Lead Technical Advisor - Geotechnical
Debris Flow Barrier	Proprietary systems designed to contain soil and water torrents (debris flows), often placed in natural gullies, channels, or chutes.
Drape (Draped Mesh)	Steel nets or mesh draped over a slope supported by a bearing rope system anchored to the top of the slope. The draped mesh allows for surficial slope failures to occur behind the mesh, but guides material down to the toe of the slope, restricting outward movement (commonly referred to as 'simple drapery' and 'draped netting')
Geohazard	An object, feature or activity related to the natural or engineered ground (including geotechnical structures) that has the potential to have adverse effects or undesirable consequences.
Hazard	An object, feature or activity that has the potential to have adverse effects and undesirable consequences.
Low-Energy Rockfall Fence	Non-proprietary systems intended to intercept rockfall these systems vary in construction, are generally untested or certified, and unlikely to be designed to a specific standard.
Monitoring	The recording of quantitative information to document the changes in characteristics.
Network Criticality	The attributes of the road network at a given location and time that relate to its importance.
Network Outcome Contract (NOC)	The Waka Kotahi contract to manage the operation and maintenance of the roading networks within each region.
Rigid Barrier	Non-proprietary system constructed from rigid (non-flexible) components, such as concrete blocks, steel posts or timber, intended to contain or deflect rockfall or slope material and retain within a catch area.
Rock Bolting	Rock bolts or anchors installed as a single system intended to support single blocks or boulders.
Rockfall Sheds	Reinforced concrete roof structures that are covered with an energy-absorbing material or angled such that material is deflected over the structure.
Rockfall Barrier	Proprietary rockfall protection systems designed to contain rockfall through energy dissipation, and that are certified to EAD 340059-00-00106[4] (supersedes, ETAG-027) or equivalent. Including flexible rockfall fences, shallow landslide barriers, rockfall canopies and rockfall galleries.
Rockfall Protection Structure (RPS)	An engineered system design to reduce the risk from rockfall (and in some cases shallow debris slides).
Significant Event	A natural event, such as seismic, weather or volcanic, that is beyond the expected conditions. Thresholds for a significant event will be specific to

	each section of roading network.
Source	The location at which rockfall or debris material is released from the slope, often an outcrop of rock or shallow failure.
Triggers	A factor or event that causes a hazard to be realised.

2.3. New Zealand Assessed Risk Level (ARL)

Waka Kotahi has adopted the New South Wales (NSW) Roads and Maritime Services (RMS) 'Guide to Slope Risk Analysis' Version 4, dated April 2014, assessed risk level (ARL) risk assessment approach[6] for cut slopes and has published a New Zealand country amendment that identifies country specific changes to the guide.

Slopes scoring a high rating using the existing rockfall hazard rating system (RHR) are to be assessed using the ARL approach resulting in sites being determined to have a specific assessed risk level (ARL). This will be used by Waka Kotahi to identify high-risk sites and enable prioritisation of sites for remedial works and funding.

The intention for this Rockfall Protection Structure Design Guidance is to provide guidance for the design of remedial works once a slope hazard has been identified as requiring remedial works using the New Zealand modified ARL approach. The design guidance within this document focuses on developing remedial solutions to improve overall life safety and level of service rather than specifically targeting parameters within the ARL assessment. An improvement in the overall risk to life safety and level of service can be captured as an updated ARL post-remediation to reflect the overall improvement to risk levels. ARL risk reduction targets will be provided on a project-by-project basis by Waka Kotahi.

2.4. Desktop Study/Assessment

Prior to undertaking design, a desktop study/assessment should have been undertaken, including a site inspection, as a Preliminary Geotechnical Appraisal Report required by SMO30 State highway professional services contract proforma manual[14], the applicable Networks Outcome Contract and/or as part of a geotechnical assessment and options report.

The designer should obtain such reports as they contain useful background information including, but not limited to: -

- Geological and contour mapping
- Topographic surveys, included area wide LiDAR
- Aerial imagery (available from LINZ databases, as well as RetroLens for historic imagery)
- Site photographs and UAV/drone imagery
- GNS Landslides database
- GNS Active Fault database
- Climatic conditions, including NIWA HIRDs assessment
- Previous reports or site documentation

The ARL risk assessment should also have considered a number of similar data sources as part of the slope risk analysis which, if not supplied with the ARL rating, should be sought from the accredited assessor.

3. Framework for Rockfall Hazard Analysis and Protection Design

Key to a design philosophy is the management framework surrounding it. The rockfall protection design framework outlined within this guide is based around the underlying principles of the Landslide Risk Management approach developed by the Australian Geomechanics Society (AGS) in 2007[1]. Adaptions to this approach have been made to incorporate the specific Waka Kotahi focus around the New Zealand specific modified ARL approach and One Network Road Classification (ONRC), as well as applying learnings from recent Waka Kotahi large-scale rockfall remediation projects.

The proposed framework is outlined in Figure 1 and detailed in the four key Sections of this document: Risk Analysis, Risk Assessment, Optioneering / Concept Design and Detailed Design.

Figure 1: Proposed Rockfall Design Framework

Each of the dashed boxes relate to critical elements within each step of the mitigation process and are detailed further within each corresponding Section of this document.

3.1. Simplified Approach

The framework outlined in Figure 1, and resulting Sections within this guide, should apply to the majority of rockfall protection structures designs for the state highway network and Waka Kotahi operated infrastructure.

However, in some situations a ‘simplified approach’ can be applied to better align the design processes with the scale of remediation being undertaken. This aims to minimise time, resources, and cost for smaller scale slope problems and is discussed further within Section 7.1 *Detailed Design Process*.

4. Risk Analysis

The Risk Analysis phase of the framework consists of Risk Estimation, to determine the scale of risk requiring remediation, as shown in the upper part of Figure 2, below.

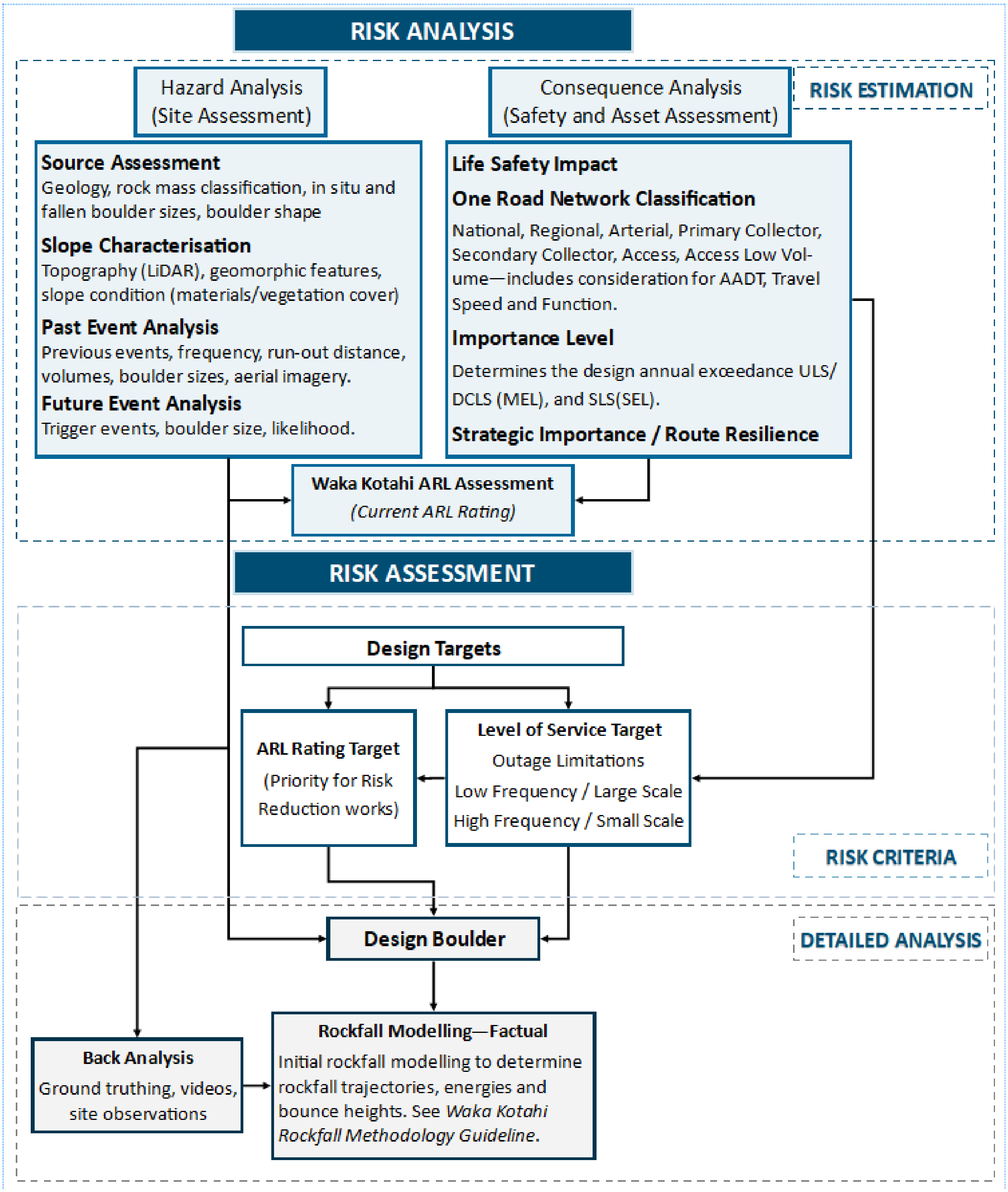


Figure 2: Risk Analysis and Assessment Framework

4.1. Risk Estimation

This initial Risk Estimation is the outcome of the analysis providing the initial ARL rating for the section of road relating to the identified slope hazards.

The risk estimation completed within the ARL assessment will consider two key areas, the hazard assessment, and the consequence assessment. A review of the assessment inputs used to determine the ARL rating should be validated for use in the design process adopting the following guidance.

4.1.1. Hazard Analysis – Site Assessment

The hazard analysis is the site assessment phase, with key considerations focusing on the failure mechanisms, slope vulnerability, and to assess the potential for each of the identified failure mechanisms to affect part or all of the transport corridor. This will highlight the possible hazards generated during a future triggering event (rainstorm and seismic) causing instability in the future.

Source Assessment

In order to understand the hazards, the source areas will need to be assessed. This will include an assessment of the detailed geology, identifying the driving failure mechanisms, the boulder size distribution (in-situ and fallen) and boulder shape.

Slope Characterisation

To characterise the slope and potential travel paths for rockfall and debris, the following should be considered:

- Site inspection including visual inspection and mapping
- LiDAR with vegetation removed
- GIS mapping to rapidly identify key features and materials for input into the detailed analysis
- Historic and recent aerial photography
- GNS Science landslides database and
- Ground “truthing” techniques

Outputs from slope characterisation will provide information on the likely size and extent of future failures (i.e., runout and volume), as well as slope materials to inform the spatial occupancy of debris slide and rockfall hazards across the transportation corridor.

Past Event Analysis

A review of the past events enables the probability and frequency of differing hazards to be assessed. Sources of historical records include previous reports, data from the Waka Kotahi’s geohazard database through to anecdotal evidence from the local Network Outcomes Contract (NOC) contractor(s). This will give an indication as to the background level of risk that Waka Kotahi has been exposed to.

GNS Science estimates of the probabilities of different levels of seismic shaking (PGAs) can be used to further inform the risk assessments. Used in conjunction with the slope susceptibility / event size / geographical extent of debris-slide/rockfall, a probabilistic-based assessment is possible.

This data provides essential information to determine magnitude/frequency characteristics of the various types of rockfall hazard (e.g., rockfalls, rockslides, shallow debris slides etc).

Future Event Analysis

To determine the probability of future failures, it is important to consider all viable triggers (seismic, rainfall etc.) as each has a unique hazard profile.

Determining the potential available boulder sizes and volumes of materials during particular triggers enables the development of the future event profiles. In addition, the probability of detachment and temporal probability require consideration.

This data will provide essential information to determine the likelihood characteristics of each slope hazard.

4.1.2. Consequence Analysis – Safety and Asset Assessment

Where rockfall and debris interact with an ‘element at risk’ (i.e., road user, roading asset) the consequence of that interaction should be identified. The consequence of the interaction of the hazard and the ‘element at risk’ will depend upon the magnitude of the hazard (e.g., runout reaches road) and the frequency at which the ‘element at risk’ is exposed.

The main consequence to consider is the life safety risk of the road user, as determined by the ARL assessment.

A secondary consideration of the consequence analysis is the impact of disruption to the operation of the asset and focuses on the One Network Road Classification (ONRC), and the strategic and resilience importance of the asset (NZTA Bridge Manual Sections 2.1 and 2.2 and AS/NZS 1170.00).

The ORNC includes considerations for Averaged Annual Daily Traffic (AADT), travelling speed, road function and Important Level (further outlined in AS/NZS 1170.00).

A consequence analysis will have been undertaken as part of the ARL assessment. This should be reviewed and considered, as well as the required risk criteria and design targets, as part of the design.

5. Risk Assessment

The Risk Assessment phase of the framework identifies the Risk Criteria, and requirements for Detail Analysis, as shown in the lower part of Figure 2, above.

5.1. Risk Criteria

The Risk Criteria considers the outputs of the Risk Estimation, sets the objective of design to reduce the overall the risk to life, and the serviceability and functionality of the corridor to minimise closures. The risk criteria are defined by two critical design targets, primarily life safety (as outlined in the ARL Target) and secondly level of service.

The design targets should consider both lower frequency larger debris events and high frequency small scale rockfall events affecting road users.

5.1.1. ARL Target

The targeted tolerable ARL rating will be provided by Waka Kotahi project manager as part of the initial design brief.

At specific sites where the ARL target is deemed to be uneconomical, higher risk ARL targets may be agreed with Waka Kotahi. In these cases, an “as low as reasonably practicable” (ALARP) principal can be applied.

The advantages of using an ALARP criterion for geotechnical design rather than quantified numerically defined criteria are:

- It incorporates a key safety principle from Section 22 of the Health and Safety Act 2015 directly into the geotechnical design
- It allows designers the flexibility to consider a wide range of approaches to slope hazard risk management in different corridor sections where the mix of safety and closure risk vary

5.1.2. Level of Service Target

In addition to the primary aim to achieve a tolerable life safety risk, as determined through an ARL assessment, achieving a Level of Service against rockfall events to ensure route security and resilience is required to establish design requirements and inputs.

Based on the ONRC, an initial Level of Service for rockfall event outages are outlined in Table 1. For each project the specific Level of Service targets to be used should be confirmed with Waka Kotahi, with input from the local Waka Kotahi Regional Systems Manager.

Table 1: Level of Service Targets for Rockfall Event Outages based on One Network Road Classification

	One Network Road Classification (ONRC)						
	National	Arterial	Regional	Primary Collector	Secondary Collector	Access	Access (Low Volume)
AADT	**>20,000**	**>12,500**	**>4,000**	**>2,000**	**>800**	**<800**	**<100**
Duration of Outage (days)	**Target Return Period (years)**						
½	5	5	1	1	0.5	0.3	0.1
1 – 2	10	10	5	5	1	0.5	0.3
3 – 5	25	25	10	10	5	1	0.5
6 – 14	50	50	25	25	10	5	1
15 - 49	75	50	50	50	25	10	5
50 - 120	100	75	75	50	25	25	10
120+	100	100	100	100	50	25	10

[*Note: This table uses preliminary data estimated for the One Network Road Classification (ONRC). Site specific level of service targets should be discussed with Waka Kotahi and the local Network Managers. This table is provided for consideration purposes only.*]

5.2. Detailed Analysis - Rockfall Modelling

Determining the potential for rockfall threat requires estimation of the run-out distance of falling boulders as well as quantification of kinetic energies and bounce heights along their fall paths. Rockfall simulation models are used alongside engineering judgement to characterise the rockfall hazard down a slope.

The predominant approach is to conduct 2D simulations based on representative slope profiles to define the kinetic energies and bounce heights of falling rocks within a rockfall prone area. This approach has generally been adopted across the industry due to its simplicity and repeatability.

General comments based upon design experience to date in relation to this approach, including inputs and considerations, are provided in Appendix A – Rockfall Modelling Notes, and further information can be sought from the following documents.

- MBIE, 2016. “Rockfall: Design considerations for passive protection structures”[5]
- UNI 11211-4, 2018. “Rockfall Protective Measures – Part 4: Definitive and executive design” Ente Nazionale Italiano di Unificazione (UNI)[11]
- ONR, 2017. “Technical Rockfall Control – Terms and definition, effect of actions, design, monitoring and maintenance”, ONR 24810 (translated from German)[10]

Recent computer advancements allow combining detailed 3-D topographic surveys obtained from LiDAR or UAV surveys with sophisticated mechanical principles. However, 3-D rockfall modelling can be computer intensive and is generally reserved for use in limited situations with complex slope geometry where 2-D simulations would only partially reflect the specificities of the three-dimensional slope.

6. Selecting Rockfall Protection Structures

Selecting the optimal risk mitigation solution is a critical part of addressing any rockfall hazard. Addressing the life safety risk is paramount and should drive the design decisions for selecting a rockfall protection structure.

The scale of the optioneering exercise will vary based on the size of the project and significance of the hazard(s). For small projects this may be a simple table outlining the advantages and disadvantages of the available solutions. For larger projects this process will likely include a detailed cost-benefit analysis for the whole of life of the systems considered.

The optioneering of the chosen solution(s) should be reported and included in the final design documentation.

The optioneering and concept design phase of the framework consists of Optioneering and review of Design Considerations, as shown in Figure 3.

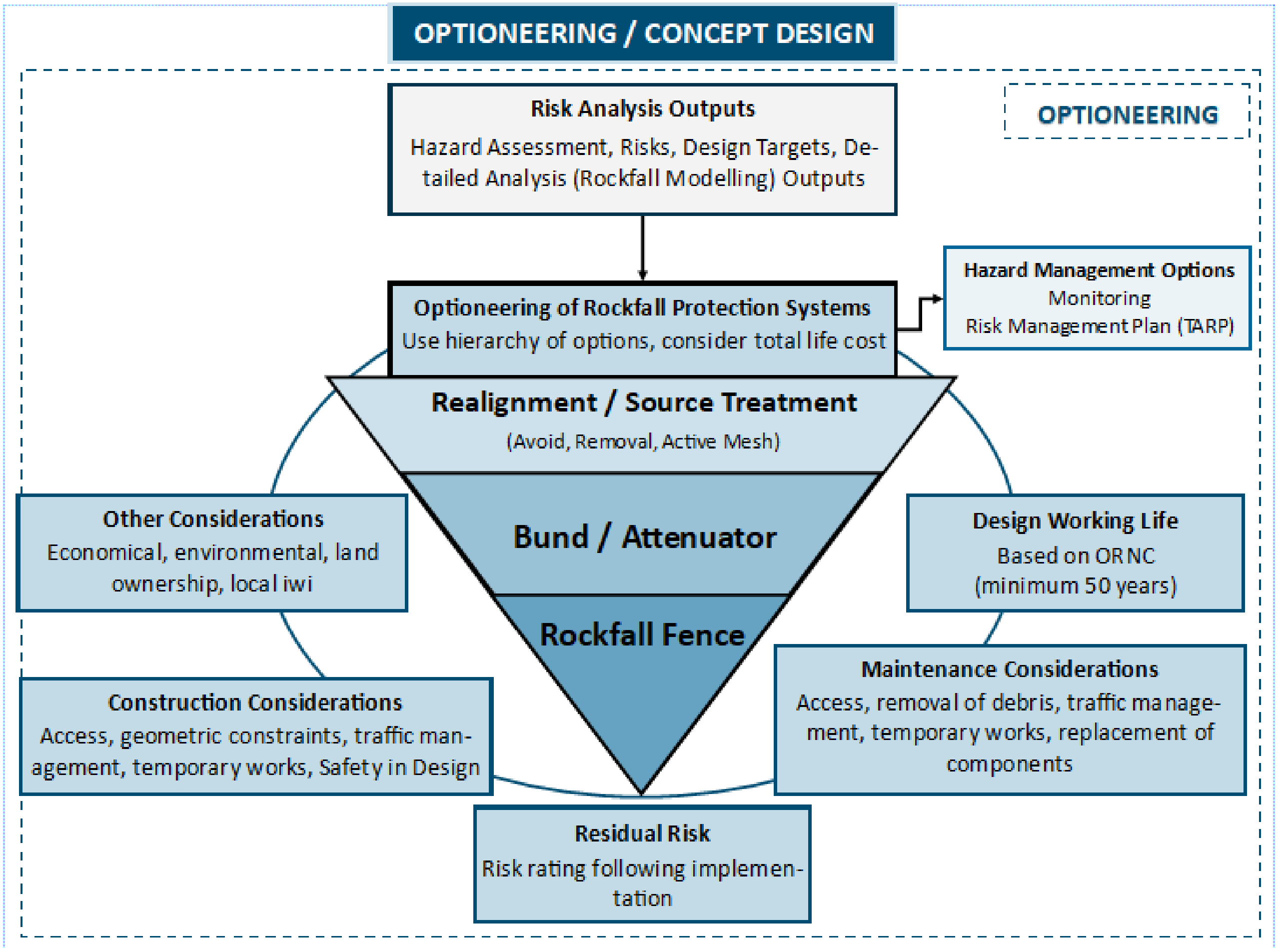


Figure 3: Optioneering and Concept Design Framework

6.1. Optioneering Hierarchy

The optioneering process for roads will be highly dependent on, but not limited to, the following factors;

- Rockfall hazard (impact energies, bounce heights, volumes, frequency)
- Design targets (including the residual risk to be achieved)

- Site location (road geometry, available space, accessibility, nearby assets)

Consideration of these factors should be completed alongside the need for ongoing maintenance of these structures. Based on the impact to the Level of Service for a road as a result of high maintenance structures, the following hierarchy of options is generally adopted:

1. ***Realignment*** – removing the asset from hazardous area. Most suitable for major projects or new infrastructure, where the option to reduce the spatial impact of a hazard can be made more easily.
2. ***Source Treatment*** – reducing the hazard through treatment of the source area (options include; source removal through scaling and sluicing/monsooning, active mesh, anchors)
3. ***Low Maintenance Passive Structures*** – constructing structures close to the toe of the slope and road with easy access for debris removal. (options include; bunds, rockfall shelters, hybrid attenuators, canopies, and drapes)
4. ***On-Slope Passive Structures*** – constructing rockfall protection structures on-slope, maintenance accepted to be moderate to high, and options generally only used when no other option is available (options include; rockfall fences)

As part of the optioneering process, Hazard Management Options should also be considered when applicable (see Section 7.2.1). Hazard Management Options, such as scheduled monitoring or risk management plans, are generally only suitable for a hazard with a very low to low likelihood of failure and higher consequence, and as such requires managing any changes to the hazard and indications of failure.

A summary of options is provided in *Table 2: Summary of Rockfall Mitigation Options* of MBIE, 2016 "*Rockfall: Design considerations for passive protection structures*"[5]. However alternative solutions, modifications and innovations should be considered alongside these to optimise a solution to suit the particular site hazards and constraints.

6.2. Design Considerations

6.2.1. Design Working Life

Rockfall protection structures, especially passive systems, are designed to reduce the impact of rockfall to the road users by physically stopping falling rocks. The working life of these structures is therefore generally controlled by the number and frequency of rockfall impacts the structure experiences.

For design purposes the design working life for rockfall protection structures should be no less than 100 years, based on no degradation by rock impact, in accordance with the NZTA Bridge Manual[8].

It is understood that rockfall protection structures are likely to sustain impact damage, often serious, in order to absorb rockfall energies. There is no expectation that the design working life would cater for all such impacts over 100 years; more that the structure would remain capable of meeting design expectations if no impact were endured until the 99th year.

It is also recognised that elements of the protection system may require routine replacement during the design working life of the structure outside of repair and replacement following an impact. Table 2 is reproduced from the Waka Kotahi RPS Maintenance Guideline and presents the anticipated working life (or replacement cycle) for components during the design working life of RPS. Where specific evidence of longer, or shorter, replacement periods can be provided and accepted by Waka Kotahi, periods other than those in Table 2 may be adopted. Whichever replacement cycles are used, they should be considered in structure options assessment to ensure Waka Kotahi understands the whole of life cost of each option, not simply the initial capital cost.

Table 2: Expected Replaceable Elements Working Life

Replaceable Element	Expected Working Life* (years)
Shackles	10
Wire Rope Clips	10
Wire Ropes (inc. braking elements)	10 – 15
Mesh**	10 – 50
Posts and Base Plates***	30 – 50
Anchors (inc. FlexHeads)	50
Terramesh Bunds (Gabion Mesh)	50

*** The expected working life quoted in this Table specifically excludes damage caused by rock/debris impact to the structure.**

**** The variability in working life is dependent on the manufacturer and environment.**

***** The life of posts may be extended by painting them with a suitable protective coating prior to the onset of corrosion as noted in regular maintenance inspections.**

In relation to corrosion, the following guidelines should be considered, which provide guidance on the durability of different mesh coating types;

- EN 10223:3 – steel wire and wire products for fences
- ISO 17745:2016 – steel wire ring net panels
- ISO 17746:2016 – steel wire rope net panels and rolls.

6.2.2. Construction

Constructability should be considered during the development of concept design solutions. Early contractor involvement (ECI) enables input by specialist contractors which can be invaluable.

Construction considerations will generally include but are not limited to:

- *Safe Access* – select solutions that require minimal use of specialist equipment (roped access, elevated work platforms, etc.). Consider the location and expected machinery required to complete the construction. Benching of slopes for the installation of RPS is not recommended, although this may provide a platform for construction, these cuts in the slope often lead to on-going slope instability issues.
- *Temporary protection works* – consider any temporary protection measures required to reduce risk to those tasked with the construction of the RPS. Preferably reduce the need for temporary works as much as practicable, using systems that can be installed to provide partial protection during the remaining construction works (examples include, draping mesh and anchoring through, and installing bunds using an outside-in construction approach).
- *Traffic management* – consider the impact of construction activities to the road, including but not limited to traffic management and temporary/partial road closures. In addition, consider the limitations of partial road closure and temporary traffic management on the ability to construct systems efficiently.

6.2.3. Maintenance

Maintenance of rockfall protection systems can be considered in two categories: -

Scheduled Maintenance – the repair and replacement of damaged or corroded components at regular intervals to ensure the system is working and performing as intended.

Post-Event Maintenance – the removal of debris, and the repair / replacement of damaged components following a rockfall event and/or impact into the system, including full replacement of the structure.

Both types of maintenance require consideration during the development of concept design solutions. These considerations include, but are not limited to:

- *Safe Access* – the system should be accessible to inspect and undertake maintenance, including component repair/replacement, preferable without the use of specialist equipment (roped access, elevated work platforms, etc.)
- *Debris clearance* – the approach for clearing systems of fallen debris must be considered to protect those tasked with clearance activities.
- *Traffic management* – consider the impact of maintenance activities to the road, including but not limited to traffic management and temporary/partial road closures.
- *Temporary protection works* – consider any temporary protection measures required to reduce risk to those tasked with maintenance activities (inspection, replacements, clearance), as well as road users exposed while the system may not be functional. Preferably reduce the need for temporary works as much as practicable, with clearance areas accessible from road level.

6.2.4. Residual Risk

During concept design and optioneering the residual risks should be considered once the proposed mitigation system is implemented. The ongoing risk management required must be communicated during the design process and reported clearly and is considered further in Section 7.3.3.

6.2.5. Other Considerations

Collaboration and engagement with the key stakeholders of the project is critical for any project. Additional design considerations relating to these stakeholders, may influence the concept design development and include but are not limited to:

- *Environmental* – consider the environmental impact of the proposed RPS, including the visual impact in the surrounding landscape, impact of debris retention, construction and clearance works. Environment and sustainability requirements can be found through the Waka Kotahi Highways Information Portal at https://www.nzta.govt.nz/roads-and-rail/highways-information-portal/technical-disciplines/environment-and-sustainability-in-our-operations/
- *Land Ownership* – RPS systems can be located either adjacent to the road or much further upslope depending on the mitigation solution chosen. Consider land ownership including the impact construction and maintenance access, and impact of debris retention. Liaise with the Waka Kotahi project manager and/or Systems Manager on land ownership matters.
- *Iwi and Cultural* – many areas across the road network have high cultural significance. Consideration should be given to the impact the RPS within the local area, as well as the impact of debris clearance from culturally sensitive areas. It is recommended to collaborate with the local iwi during concept design development through the Waka Kotahi project manager and/or Systems Manager.
- *Economical* – the whole of life cost of each solution should be carefully considered during design development, to ensure the solution provides the best value to mitigate the risk.
- *Consenting* – depending on the type and location of structures, resource and/or building consent may be required, including consultation with the third parties (through the Waka Kotahi project manager). Building consent considerations are discussed further in Section 7.4.3.

7. Detailed Design Process

The proposed detailed design approach for rockfall protection structures, as shown in Figure 4, aligns with similar industry adopted guidelines for rockfall structures; Ministry of Business, Innovation & Employment (MBIE), 2016 "*Rockfall: Design considerations for passive protection structures*"[5], and Section 3.1 of the Highway Structures Design Guide (Waka Kotahi, 2016)[9].

Design of rockfall protection structures should be undertaken and completed by a geotechnical engineer or engineering geologist with at least five years' experience in the design of geotechnical structures, responsible for undertaking geotechnical hazard assessment, developing the suitability of the selected structure(s), and, for the RPS selected from the options report by Waka Kotahi, completing the appropriate design calculations required to confirm loading and support elements for the structure.

Designs should also be reviewed, including checks of the overall design, suitability of the structure and the verification of supporting design calculations, by a chartered member (CPEng or PEng Geol) geotechnical engineering or engineering geologist with at least 10 years relevant experience in rockfall protection design and infrastructure works and should be approved by the Waka Kotahi NZ Transport Agency Lead Technical Advisor – Geotechnical.

Where required by Waka Kotahi, rockfall protection structure designs should be peer reviewed to assess the applicability and suitability of the RPS design. Peer Reviewers should have the same minimum experience as the design reviewer but must be from a separate organisation to the designer and design reviewer and be independent of the project.

'Design' and 'Design Review' certificates and/or Producer Statements should be produced in accordance with Section 3.1.4 of the Highway Structures Design Guide[9].

7.1. Simplified Approach

In some situations, a simplified approach can be applied to better align the design processes with the scale of remediation being undertaken to minimise time, resources, and cost for smaller scale slope problems typified by network dropouts or slope failures that occur in isolated areas as single events (as opposed to a series of failures within any section of corridor or widespread failures following weather events such as cyclones). Agreement should be sought from Waka Kotahi before proceeding with the simplified approach to ensure adoption is appropriate.

Two typical situations where a simplified approach may be adopted are simple drapery and low energy barriers, particularly where a proprietary system is adopted. Design and review requirements should still be followed including the provision of certification.

7.1.1. Simple Drapery (Draped Mesh)

Key to adopting a simplified approach to simple drapery is the ability to identify the main source area(s), potential block sizes, and to identify a 'low probability of wider slope failures', which requires a high level of engineering judgement.

Design would be expected to typically include the use of proprietary software by manufacturers of drapery systems, such as;

- Maccaferri's MAC.RO – used for rockfall netting applications in rock, with consideration for rock joint roughness, dip angles and loose blocky surficial failure mechanisms.
- Geobrugg's Ruvolum - used for rockfall netting applications and anchor support checks for loose surficial slope failures, where no global stability has been identified.

In-house spreadsheet-based design approaches may also be adopted.

In both cases, proprietary or in-house, the software should be verified and demonstrated as such within the detailed design submission.

In addition, the design process should include a review by the designer of the geotechnical hazards on site, slope conditions including the assumed ground conditions for anchoring, and the EAD certification for any propriety system installed.

7.1.2. Low Energy Barrier (Fences and Bunds)

As for simple drapery, a high level of engineering judgement is needed to identify the main source area(s), and potential block sizes. The potential energies should be assessed to ensure that they are less than the capacity of the low energy barrier. Generally, this would require good historical evidence of rockfall events, with bounce heights and travel distances being well understood.

For the simplified approach, a simple system may be developed with supporting design justification, which should include a review of the geotechnical hazards on site, expected rockfall trajectories including frequency and magnitude, and simple structure dimensioning.

Proprietary software methods or in-house spreadsheet-based design approaches may be adopted with software being verified and demonstrated as such within the detailed design submission.

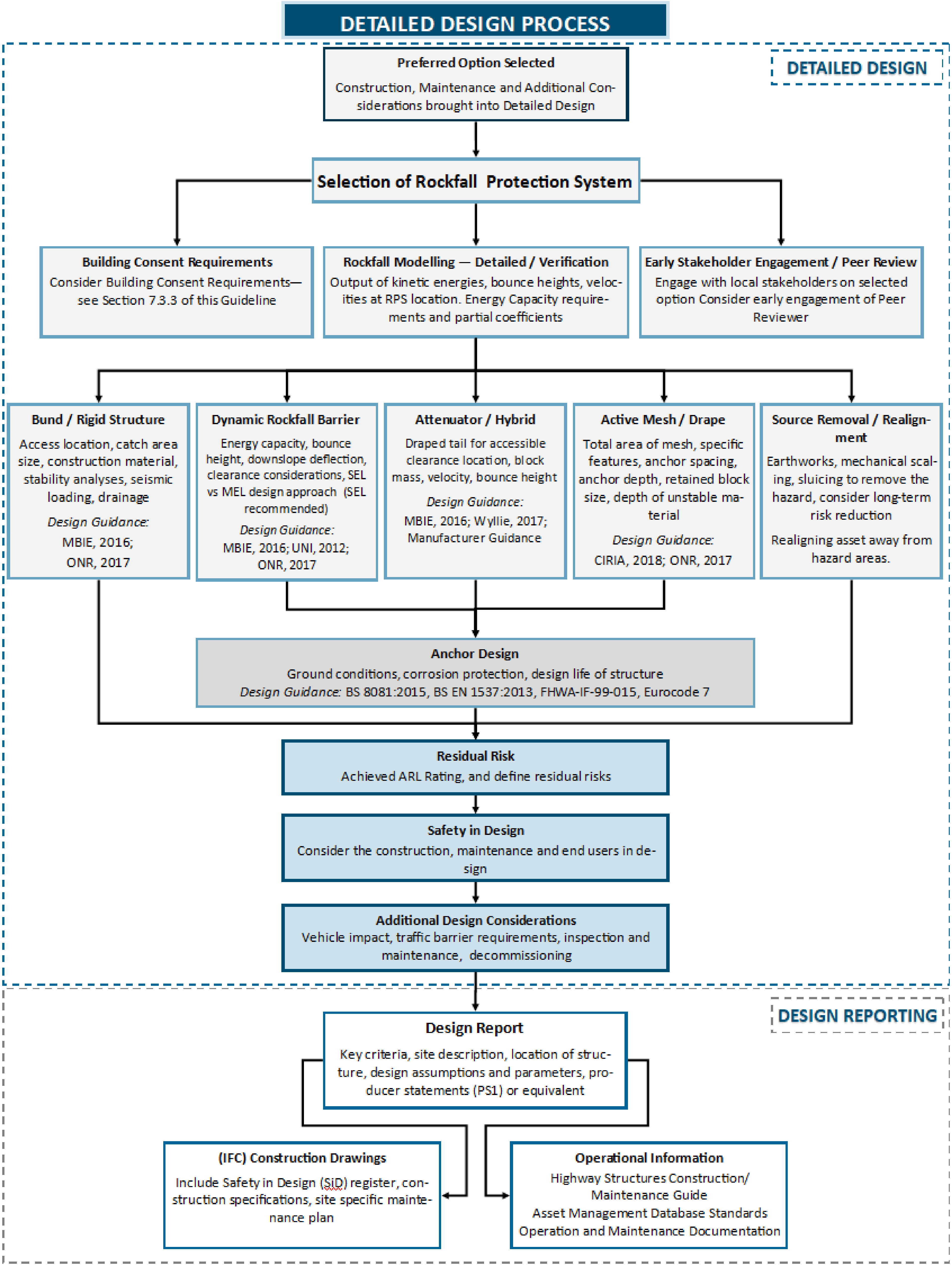


Figure 4: Detailed Design Process Framework

7.2. Design Approaches for Rockfall Protection Systems

The design approaches are considered based on type, with an overall section discussing the design of anchors used independently or as part of a rockfall protection system (including both anchored mesh, and foundations for passive structures). These sections are outlined as follows:

- Hazard Management Solutions
- Active Source Treatment and Realignments
- Active Mesh and Drapes
- Dynamic Rockfall Barriers
- Rigid Barriers (Bunds and Walls)
- Attenuators / Hybrid Fences
- Anchor Design

7.2.1. Hazard Management Solutions

Non-engineered solutions, as outlined for consideration in Section 6 *Selecting Rockfall Protection Structures*, include systems that are implemented to manage the risk of the hazard without constructing physical barriers or actively treating source areas. This maybe as a mitigation measure or temporarily pending physical works. The main types of non-engineered solutions suitable for the road corridor include monitoring and risk management plans.

Monitoring

Monitoring hazards as a form of mitigation is generally limited to large scale hazards that are impracticable or uneconomical to mitigate through physical barriers or source treatment. These hazards generally have a low likelihood of failure but a high consequence, and as such require monitoring to notify Waka Kotahi or the controlling party of any changes to the hazard and/or indications of pending failure. Monitoring can take many forms and will generally include but not be limited to:

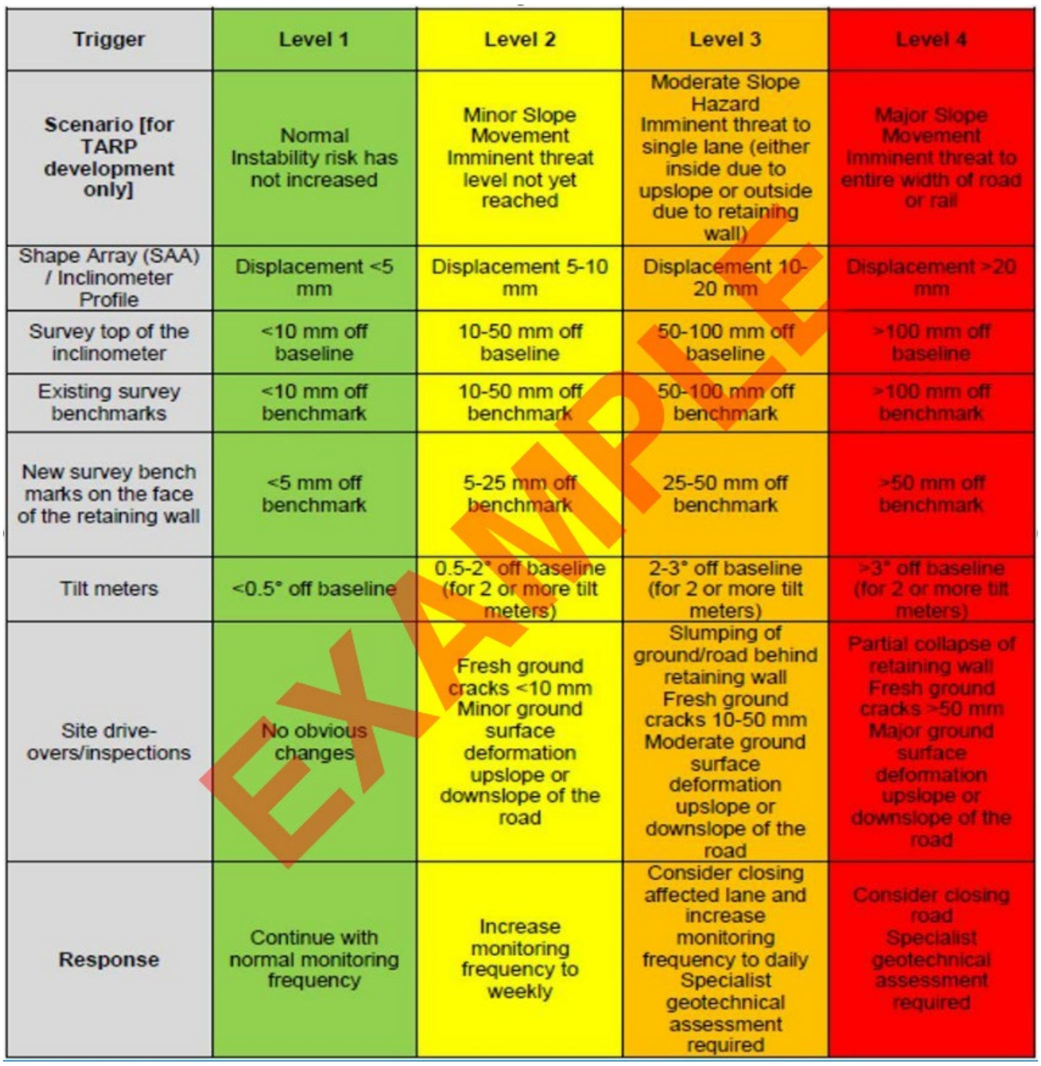
- Slope Movement Observations - actively capturing all rockfall/minor slope failures.
- Weather Monitoring – monitoring for inclement weather events
- LiDAR / Survey Assessments – monitor for change in a digital elevation model.
- Visual Monitoring – scheduled and post-event visual assessments (using UAV/drone, binoculars, or other optical equipment)
- Displacement Monitoring – instrumented monitoring to measure slope changes (consideration for automated systems, UAV change models and InSAR techniques)

Risk Management Plan

Site specific risk management plans are often developed in the form of a Trigger Actions Response Plan (TARP). TARPs rely on having clear triggers, which can be developed from monitoring, environmental (rainfall, wind), seismic or visual. Each trigger will have a corresponding level which results in a required action and response, such as increasing monitoring activity or partial road closures. The suggested responses will be based on the severity and urgency associated with each of the TARP trigger levels.

An example TARP from a South Island site is shown in Figure 5 as an example of the aspects typically considered.

TARPs may well include, and therefore incorporate, monitoring systems.



Trigger	Level 1	Level 2	Level 3	Level 4
Scenario [for TARP development only]	Normal Instability risk has not increased	Minor Slope Movement Imminent threat level not yet reached	Moderate Slope Hazard Imminent threat to single lane (either inside due to upslope or outside due to retaining wall)	Major Slope Movement Imminent threat to entire width of road or rail
Shape Array (SAA) / Inclinometer Profile	Displacement <5 mm	Displacement 5-10 mm	Displacement 10-20 mm	Displacement >20 mm
Survey top of the inclinometer	<10 mm off baseline	10-50 mm off baseline	50-100 mm off baseline	>100 mm off baseline
Existing survey benchmarks	<10 mm off benchmark	10-50 mm off benchmark	50-100 mm off benchmark	>100 mm off benchmark
New survey bench marks on the face of the retaining wall	<5 mm off benchmark	5-25 mm off benchmark	25-50 mm off benchmark	>50 mm off benchmark
Tilt meters	<0.5° off baseline	0.5-2° off baseline (for 2 or more tilt meters)	2-3° off baseline (for 2 or more tilt meters)	>3° off baseline (for 2 or more tilt meters)
Site drive-overs/inspections	No obvious changes	Fresh ground cracks <10 mm Minor ground surface deformation upslope or downslope of the road	Slumping of ground/road behind retaining wall Fresh ground cracks 10-50 mm Moderate ground surface deformation upslope or downslope of the road	Partial collapse of retaining wall Fresh ground cracks >50 mm Major ground surface deformation upslope or downslope of the road
Response	Continue with normal monitoring frequency	Increase monitoring frequency to weekly	Consider closing affected lane and increase monitoring frequency to daily Specialist geotechnical assessment required	Consider closing road Specialist geotechnical assessment required

Figure 5: Example TARP from State Highway Network for consideration ONLY

7.2.2. Active Source Treatment and Realignments

Source Removal

Earthworks to remove the hazard source to reduce the residual risk to an acceptable level which may include mechanical scaling, and/or sluicing. Note that sluicing operations need careful consideration as the technique can result in the hazard deteriorating further with minimal reduction in risk.

The long-term sustainability of this approach in relation to weathering of the exposed source area should be considered. Source areas are likely to require increased inspections and regular scaling with their associated long-term costs. Health and safety should also be a significant consideration.

Realignments

Realigning the road to remove the asset and road users away from the hazardous area. This can be costly for existing infrastructure but can result in very low on-going maintenance. This option is likely more appropriate for large scale recovery projects or newly proposed infrastructure routes.

7.2.3. Active Mesh and Drapes

Anchored mesh and fully or partially anchored mesh drapes provide a simple solution to larger surface areas with high frequency small scale rockfall. Active mesh systems generally target the weakened and weathered upper surficial layer (within 2m of the surface) of the slope, rather than addressing any larger global instability.

Consideration is needed for the total area of mesh, any specific features that need anchoring, anchor spacing, anchor depth, the retained block size and depth of unstable material.

These factors can be considered with further design guidance provided in:

- Sections 7.3 to 7.7; CIRIA, 2018[3]
- Section 6.1.4 “Netting”; ONR, 2017[10]

Proprietary software from Geobrugg and Maccaferri (Ruvolum, and MacS / Mac.RO, respectively) can be used to validate proposed active mesh and drape solutions against specific propriety materials.

In active mesh in particular, it is important to consider the effect of movement of the surficial layer behind the mesh (often a weathered rock or overlying soil), and the resulting bending and shear demands on the section of anchor within this weaker layer. This calculated shear demand requires consideration in anchor design with guidance provided in Section 7.4 of CIRIA, 2018[3].

In drape mesh in particular, a key consideration is the effect of dynamic puncturing of the mesh, this should be checked during design, as detailed in Section 7.3.4 of CIRIA, 2018[3].

Mesh systems should be checked to ensure appropriate certification in alignment with EAD 230025-00-0106 (Flexible facing systems for slope stabilization and rock protection).

7.2.4. Dynamic Rockfall Barriers

Dynamic rockfall barriers (flexible barriers) can be used for rockfall, shallow debris slides and a combination of these hazards, depending on the specific product. Rockfall barriers provide a good solution when the footprint for installation is minimal and impact energies are considered to be moderately high (100 – 10,000kJ). Low energy fences (<100kJ) may also be effective in certain situations where low energy rockfall occurs frequently. The fences are generally tested and certified to the following standards EAD 340059-00-0106 (>100kJ) and EAD 340086-00-0106 (<100kJ) (which supersede ETAG 027).

Design of rockfall barriers should consider the impact energies and bounce heights obtained through rockfall modelling (see Section 5.2). In addition to these two key inputs, consideration should be given to the downslope deflection distance of the barrier, the residual barrier height post-impact and catchment, the lateral gap (i.e., consideration for the edges and extents to which the barrier extends across the slope and its reduction as material is caught), corrosion protection, and foundation design, as well as long-term maintenance requirements.

These factors can be considered with further design guidance provided in:

- Section 4.5 “Flexible Barriers”; MBIE, 2016[5]
- Section 5 “Design and Checks”; UNI, 2012[11] and UNI 11211:4:2018
- Section 6.2 “Rockfall Control Nets”; ONR, 2017[10]

Seismic, Wind and Snow/Ice Loading

As outlined in Clause A1.3 in MBIE, 2016[5], due to the nature of the loads RPS are designed to be largely independent of the forces applied by seismic, wind and snow, and therefore do not directly apply to the design. The exception to this is for bunds, where seismic loads must be considered in the slope stability analysis, and for RPS systems directly above the carriageway (such as a rockfall shelter or rockfall canopy), where failure would result in the structure falling onto the carriageway. In these cases seismic, wind and snow/ice loading are considered in accordance with NZS1170 Parts 1 to 5.

MEL vs SEL

Within UNI 11211:4-2012[11], RPS may be designed at serviceability or ultimate limit states. Energy capacity requirement is therefore determined from the serviceability energy limit (SEL), or the maximum energy limit (MEL) introduced in ETAG 027 (now, EAD 340059-00-00106). SEL is normally used when the site is vulnerable to multiple impacts whereas MEL is normally adopted when there is a low frequency of rock falls. Fence energy capacity is generally quoted as the MEL design load, which is considered to be 3 x SEL (i.e., a 3,000kJ fence will have an MEL design capacity of 3,000kJ and an SEL capacity of 1,000kJ).

For New Zealand roads the energy distributions encompass frequent, medium size events and less frequent, larger size events. As such, it is anticipated that protection structures are hit repeatedly by the aforementioned energy range. It is therefore recommended that dynamic fences for roads are designed using the SEL approach to remain serviceable under these conditions.

Occasionally, a designer may decide to verify the capacity of an RPS against individual blocks that are not captured in the block size distribution used in the rockfall modelling. As discussed in Section 5, these larger events are likely to occur with a much lower frequency and suitability of the fence may then be assessed from the MEL. Specific modelling using a deterministic block size rather than a size distribution should be performed to derive the corresponding MEL with an acceptable level of confidence. Note that only one approach MEL or SEL should be used for design.

7.2.5. Rigid Structures (Bunds and Walls)

Rigid barriers (including deformable rigid barriers) are most often constructed as reinforced earth embankments, sometimes including gabions or concrete blocks. There are a number of design approaches for the construction of bunds, with comprehensive guidance provided in Section 4.6 MBIE, 2016.

Design of rigid barriers should consider the location and footprint of the structure, and the impact energies, bounce heights obtained through rockfall modelling (see Section 5.2). In addition, consideration should be given to the volume of the debris catch area behind the bund, availability of construction material, internal and global stability analysis, and drainage.

These factors can be considered with further design guidance provided in:

- Section 4.6 “Deformable Rigid Barriers”; MBIE, 2016[5]
- Section 6.3 “Rockfall Dams”; ONR, 2017[10]

7.2.6. Attenuators / Hybrid Fences

As stated in Section 4.1 of MBIE, 2016[5] there is currently no published design approach for attenuator or hybrid attenuators. The difference between an attenuator and hybrid attenuator is that with an attenuator system, rocks are slowed and released from the system with a reduced energy and are generally installed mid-slope. In contrast a hybrid fence has an extended mesh tail which reduces the energy and directs the material downslope into a debris collection area and are generally installed closer to the toe of the slope.

Design of an attenuator or hybrid fence requires collaboration with manufacturers of attenuating systems to ensure suitability of the propriety structure. Design inputs include bounce heights, boulder velocities and size, and attenuator tail length.

These factors can be considered with further design guidance provided in:

- Section 4.7 “Attenuators”; MBIE, 2016[5]
- “Design Method for Attenuators”; Wyllie et al., 2017[13]
- Specific Manufacturer Guidance

7.2.7. Anchor Design

Anchors are commonly used as part of active meshing and providing foundation support to rockfall protection structures. Guidance for the design of these anchors is provided by

- BS 8081:2015, Code of practice for ground anchors
- BS EN 1537:2013, Execution of special geotechnical work – ground anchors
- FWHA-IF-99-015, Ground anchors and anchored system
- Eurocode 7 (BS EN 1997-1:2004+A1:2013)

To reflect A 100-year design working life of the RPS, as outlined in Section 6.2.1 of this guidance, it is considered that the anchors used within RPS will have the same design working life of no less than 100 years. It is recognised that this may be difficult to achieve in certain situations, and therefore departures should be considered in these cases, noting that a reduction in design working life of anchors may require strict monitoring and testing programmes to be developed as part of the departure and included in the maintenance manual for each structure.

In relation to corrosion protection for anchors, the Bridge manual requirements apply, normally requiring Class 1 protection. Recognising the difficulties in installing double corrosion protected prefabricated anchors, alternatives may be considered by Waka Kotahi. As anchors are constructed differently in differing ground conditions there is no generic alternative that can applied and therefore departures are required. Epoxy coated galvanised solid bars have been accepted, by departure, subject to location, ground, and atmospheric conditions provided that they satisfy the following criteria:

- Solid bars are hot-dip galvanised to HDG600 in accordance with AS/NZS 2312. Epoxy coating factory coated with an average coating of 200 – 300 μm dry-film thickness (DFT), which complies with ASTM A 775 Standard Specification for Epoxy-Coated Reinforcing Steel Bars. The epoxy powder and application and testing procedures of the fusion bonded epoxy coating meeting the requirements of ASTM 775-07b (2014).

Hollow steel bars may only be used through an accepted departure and only as a last resort in lieu of solid bars.

Maintenance requirements for anchors to achieve the design working life need to be considered and included in the structure specific maintenance plan (SSMP). A load test programme after a period determined by the designer, generally around 25 years from installation, to test the capacity of a percentage of the anchors on any given structure, including a suitable coverage across different locations, rockmass and function (i.e., lateral, upslope support etc.), should be considered in relation to the importance of the structure, location in respect to the highway and consequence of anchor failure. The SSMP should include details of the required actions should any of the anchors fail and when to retest if all perform satisfactorily.

7.3. Additional Design Considerations

7.3.1. Safety by Design in Construction and Maintenance

Under the current Health and Safety at Work Act 2015 (HSWA)[12], a 'health and safety by design' approach is critical to any design work. This is also outlined in key Waka Kotahi standards, including Z/44 Risk management practice guide and SM/030 for Professional Services. This focuses on the process of managing health and safety risks through the life cycle of the structures. Due to the hazardous locations that RPS are generally constructed and maintained, thoughtful consideration and collaboration is needed within the design process to reduce the risks posed to those tasked with constructing and maintaining these structures.

Guidance for a safety by design approach is provided by WorkSafe, 2018: *Health and Safety by Design: an introduction*[12].

7.3.2. Roading

Many RPS, mainly passive structures, are constructed adjacent to the road. This is generally due to the improved access for construction and maintenance, as well as commonly being the location with the lowest energies and bounce heights.

As such additional roading considerations must be included in design, these include but are not limited to:

- Vehicle impact of the RPS, considering the damage to vehicles as well as resulting impact to the RPS
- Traffic barrier requirements (especially with consideration of RPS deflection)
- Traffic management requirements for construction and maintenance

For further information on the road safety requirement, Waka Kotahi Road Safety team should be engaged early in the project, with additional overview guidance provided in the Waka Kotahi Highway Structure Design Guide and Austroads Guide to Road Safety (AGRS) Part 6 and 9.

7.3.3. Residual Risk

As each RPS addresses differing aspects of a hazard there will always be a level of residual risk that will need to be communicated clearly in any reporting, as well as updating the ARL rating for the mitigated section of road.

The residual risk should be summarised in a similar table to the example shown in Table 3.

Table 3: Example Table for Residual Risk to Road Network

Identified Hazards	ARL Rating for Site Example 1	
	Pre-Mitigation ARL Rating	Post-Mitigation ARL Rating
Debris Slides	**ARL 3**	**ARL 4**
Rockfall	**ARL 1**	**ARL 3**

The residual risk assessment is generally valid at the date of completion of the RPS. The residual risk should be clearly communicated in the reporting documentation to enable the ongoing management of residual risk to be undertaken by the Geotechnical Management Consultant (GMC) responsible for the asset, in accordance with S7-*Geotechnical Structures Inspection Policy, November 2022.*

7.4. Reporting

Reporting of the detailed design is required to communicate the initial assessments, risk analysis, optioneering, concept and detailed design. The level of detail for site-specific reports will vary depending on the scale of the project, the site and the hazard being addressed.

7.4.1. Design Report

The contents of the design report are generally used for client documentation, technical review and input into the consenting process. Section 3 of the Waka Kotahi Highway Structures Design Guide (HSDG)[9] outlines the requirements for report, specific consideration for rockfall protection design is also presented in Table 9 in MBIE[5], 2016, which provides are summary of information to be included in reports. In addition to MBIE and HSDG, the following considerations should be given to RPS constructed for Waka Kotahi infrastructure:

- Initial ARL ratings, identification of hazards and risk assessments – leading to hazards being mitigated
- Design Targets (ARL and Level of Service)
- Departures to Waka Kotahi guidelines and/or Bridge Manual (if any)
- Post-mitigation ARL, residual risk and any on-going risk management plan
- Maintenance and monitoring requirements.

7.4.2. Construction Drawings

Row 6 of Table 9 in MBIE[5], 2016 provides are summary of information to be included in construction drawings. In addition to this table, the following considerations should be given for inclusion in construction drawings for RPS mitigating risk on Waka Kotahi infrastructure:

- Specifications
- Safety by Design Register (importantly, including those hazards anticipated in construction and maintenance)
- Site Specific Maintenance Plan (SSMP)

7.4.3. Building Code Compliance

Passive protection structures greater than 1.5 m in height are likely to require building consent in accordance with the Building Code 2004. These structures include:

1. Rigid Barriers (and rigid deformable barriers) including (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). These barriers have been designed for impact and debris retention and are characterised by MBIE as wall-type structures.

2. Flexible Barriers (proprietary rockfall fences, other rockfall fences, shallow landslide barriers, debris flow barriers, attenuators, and hybrid fences) are passive structures and should be consented.

For these structures alignment with Appendix A “Regulatory Considerations” of the Ministry of Business, Innovation & Employment (MBIE), 2016 “*Rockfall: Design considerations for passive protection structures*” is needed, including Producer Statements (PS1, PS2, PS3 and PS4) and the provision of a Code of Compliance certification from the local territorial authority.

Source treatment works including 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)) do not appear to require building consent though always check with the relevant territorial authority.

7.4.4. Resource Consenting

The requirement for resource consent will vary greatly depending on the type of structure and the local and regional setting. As such the designer should contact the local and regional authorities through the Waka Kotahi Systems Manager to confirm the resource consenting requirements relating to the particular rockfall protection structure.

7.4.5. Asset Management Data

The design of RPS should include the provision of the asset management data to the Waka Kotahi Asset Management Data Standard (AMDS) for land infrastructure assets. This will include specific attribute, characteristics, properties, location, and performance to enable life cycle asset management.

The specific data required for RPS to be recorded and provided for construction and maintenance can be obtained through the web portal: nzta.govt.nz/s-and-rail/asset-management-data-standard/.

7.4.6. Operation and Maintenance

RPS, especially passive structures, are designed to ‘catch’ and retain material. As such, they require regular monitoring and maintenance over their working life. Depending on the system used, many proprietary barrier systems are able to be installed with active monitoring which are integrated into the system and able to monitor for impacts and automatically notifies the required personnel.

Maintenance is generally only required if inspections reveal significant debris deposits, damage to the structure, and/or changes in the hazards on the slope.

General details for maintenance are outlined in the *Waka Kotahi Rockfall Protection Structures Maintenance Guideline.*

8. References

1. Australian Geomechanics Society (AGS); Guidelines for Landslide Risk Management; Australian Geomechanics Vol42 No1, March 2007.
2. Christchurch City Council (CCC); Technical guideline for rockfall protection structures guidelines for rockfall structures, Version 2 Final, March 2013. SUPERSEDED.
3. CIRIA; Rock netting systems – design, installation, and whole-life management, C775 – RP1021, 2018
4. European Organisation for Technical Approvals (EOTA); EAD 340059-00-00106 Falling rock protection kits - (replacing ETAG 027). European Organisation for Technical Approvals, November 2018
5. Ministry of Business, Innovation & Employment (MBIE); Rockfall: Design considerations for passive protection structures, October 2016
6. New South Wales (NSW) Roads and Maritime Services (RMS) Guide to Slope Risk Analysis, Version 4, July 2011.
7. North Canterbury Transport Infrastructure Recovery Alliance (NCTIR); NCTIR Document, Design Philosophy Report – Slope Risk Management, Document Number: 100001-CD-GT-DP-0001[4], May 2019.
8. New Zealand Transport Agency (NZTA); Bridge Manual, Third Edition - Amendment 3, October 2018.
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10. Australian Standards Institute (ASI) (ONR); “ONR 24810: Technical Rockfall Control – Terms and definition, effect of actions, design, monitoring and maintenance” (translated from German), February 2017.
11. Ente Nazionale Italiano di Unificazione (UNI); UNI 11211-4 - Rockfall Protective Measures – Part 4: Definitive and executive design, 2018. (The Italian approach is referenced in English in Grimod and Giacchetti; Design approach for rockfall barriers tested according to ETAG 027, 2014.)
12. WorkSafe; Health and Safety by Design: an introduction, 2018.
13. Wyllie D., Shevlin T., Glover J., Wendeler C.; Development of Design Method for Rockfall Attenuators, 68th Highway Geology Symposium (HGS), May 2017
14. Waka Kotahi NZ Transport Agency, State highway professional services contract proforma manual (SMO30), Version 9.1. March 2021 and previous versions

9. Acknowledgements

This document is a collation of information from a variety of sources, including the NCTIR Design Philosophy Report: Slope Risk Management (100001-CD-GT-DP-0001[4] 15/5/2019)[7], authored by Richard Justice and Mark Easton, and reviewed by Greg Saul and Clive Anderson, and the NCTIR Design Philosophy Report : Rockfall Modelling (100001-CD-GT-DP-0004 26/4/2018), authored by Cedric Lambert and reviewed by Mark Easton.

Appendix A
2D Rockfall Modelling Notes

NOTE: The following notes are based upon design experience to date to provide designers with the benefit of previous experience. As design methods and approaches develop the content will become less current but nonetheless is expected to provide some valuable insights from those who have gone before.

The conventional approach for rockfall trajectory studies typically involves a critical preparation phase that includes the following steps that are dependent upon the size and complexity of the site:

- Field study to characterise and map the release zone(s), including boulder size distribution
- Mapping of slope characteristics in the transit and deposition zones, including assessing stiffness and roughness of slope material
- Mapping of signs of rockfall activity, including but not limited to size and location of the deposited boulders, rockfall scar, impact craters, etc.
- Creation of a slope profile from a digital terrain model (DTM), generally using an aerial (UAV) photogrammetric approach, laser scan or existing LiDAR.
- Characterisation of bounce behaviour by performing in-situ boulder roll experiments, this may not be practicable for some sites, however, should be considered where possible.

Following the preparation phase, trajectory modelling is performed to inform on energy levels, trajectories (bounce heights) and the run-out of rockfall.

General Considerations

2-D rockfall simulations are best performed using the latest version of proprietary software, typified by *RocFall* by Rocscience. *RocFall* is a statistical analysis program designed to assist with the assessment of slopes at risk of rockfalls. Energy, velocity and “bounce height” envelopes for the entire slope are determined by the program, as is the location of rock endpoints.

Rockfall trajectories are obtained either using the *lumped mass* method or the more recent *rigid body mechanics*. The *lumped mass* approach models each boulder as a particle with a mass (i.e., the specific block shape including its physical size is not considered), whereas *rigid body mechanics* offers the ability to explicitly represent block size and shape.

The *lumped mass* approach is currently the preferred approach due to its simplicity and its 30 years of extensive use as a modelling tool. *Rigid body mechanics* introduces additional uncertainties on boulder shape or material parameters and is to date primarily considered as a research tool.

Fragmentation of the rockfall is not explicitly considered within 2D modelling software however different elements of fragmentation can be adjusted for when assigning boulder distributions and scaling functions, which are discussed below.

Rockfall Paths

Energy and bounce height parameters for RPS design are generally based on the simulations of rockfall trajectories along one or more critical paths. Selection of critical rockfall paths (which represent the materials and topography within the general area) should broadly follow paths derived from “water drop analysis”. “Water drop” paths are straightened to capture local irregularities encountered along the path.

Site observations and engineering judgment should be used to assess whether there may be other possible critical trajectories, especially if the site contains gullies, ridges or launch features that may not be captured in the site survey (LiDAR or UAV) or have appeared since the latest survey was performed. Therefore, selected rockfall path(s) should not all be straight lines but should follow the topography.

Slope profiles are generated along selected path(s), depending on the accuracy of the survey resolution should be in the order of 0.5 m to 2.0m between two consecutive grid points. For low resolution slope profiles with sampling points >2.0m the outputs will need additional verification from site observations and historic rockfall. The resolution of the rockfall path should be documented in any reporting, as this needs to be considered when using outputs for design.

Verification (Back-Analysis)

Nearly all the literature that discusses rockfall modelling stresses the importance of verifying and calibrating rockfall models against actual observed or inferred rockfall that has occurred at the site.

Calibration involves altering the slope model parameters (coefficients of restitution, slope roughness, etc) to match, or approximate, observed boulder run-out distances, bounce heights and velocities. Rockfall observations typically include estimated bounce heights and velocities (average and upper percentiles (~95th%)) to gain an understanding of the distribution.

Ideally, the actual rockfall behaviour on the slope is evaluated using observations made during rock-rolling experiments carried out at the site or during sluicing / scaling operations, however this will likely occur only on a selected number of project sites. As it may not be practical to perform such an exercise prior to the modelling stage, then prior to construction and once the final slope profile has been exposed, it is recommended that, where the extent of works merit the cost, rockfall field calibration should be performed as a validation exercise. Observed bounce heights and run-out distances should then be compared with model predictions to verify the assumptions underlying the modelling. The model may need to be revised to reflect field observations, as field evidence should take precedence over modelling, and design recommendations should be adjusted as necessary.

Slope Properties

Slope properties assigned can be differentiated into two categories: mechanical and geometrical properties, whereby mechanical properties (restitution coefficients and friction) control rebound dynamics and geometrical properties (roughness) define geometrical characteristics that are not captured by the slope survey and can act as launching points.

To define these properties a number of parameters need to be calibrated during modelling including:

- The size of the modelled boulders
- The initial conditions of the boulder (failure mechanism)
- Coefficients of Restitution (COR) for the materials
- Roughness of the slope.

By way of an example, the values presented in Table A1 are those adopted in the GNS CR 2011/311, and are specific to the Port Hills, Christchurch weathered volcanic materials and were obtained through back analysis at specific sites where seismically triggered rockfall was released (Massey et al., 2012).

Table 1 - Slope Parameters

Parameter	Assumed Value	Consideration
Initial Conditions		
No. boulders modelled	Min. 2,000	Considered statistically suitable
Individual rockfall volume	See Section 4.6	
Boulder unit weight	See Section 4.6	
Boulder mass	See Section 4.6	
Starting Conditions		
Horizontal velocity	0 – 1.5m/s	Determined through back-analysis considering initial bounce marks. Peak Ground Accelerations (PGAs) can also be considered to determine seismically triggered rockfall.
Vertical velocity	0 – 1.0m/s	
Project Settings		
Velocity cut off	0.1m/s	Consider if boulders will stop once reaching below critical velocity
RN scaling	Velocity, K=9.144m/s	Considers some fracturing of higher velocity falling boulders
Random number generation	Pseudo-random	
Friction angle (Phi)	From Materials	Consider as this is function of boulder shape (rolling blocks will have lower friction angle, but tabular blocks sliding will have a higher friction angle), however if a variety of boulder shapes on site, then can be considered a function of material.
Angular velocity	Consider	Allows for the consideration of rotation during modelling
Materials		
Clean hard bedrock and rock at/near surface	Rn = 0.53 ±(0.04), Rt = 0.99 ±(0.04) Phi = 40° ±(2) Roughness = 5*	For guiding purposes only – materials should be refined to site specific materials based on back analysis. Consider reviewing Rocscience Coefficient of Restitution Table in RocFall.
Talus with vegetation	Rn = 0.5 ±(0.04), Rt = 0.85 ±(0.04) Phi = 20° ±(2) Roughness = 5*	
Rock at near surface covered with talus	Rn = 0.5 ±(0.04), Rt = 0.85 ±(0.04) Phi = 20° ±(2) Roughness = 5*	
Colluvial loess with vegetation[1] (rough)	Rn = 0.3 ±(0.03), Rt = 0.85 ±(0.03) Phi = 8° ±(2) Roughness = 11*	
Colluvial loess with vegetation[1] (smooth)	Rn = 0.3 ±(0.03), Rt = 0.85 ±(0.03) Phi = 4° ±(2) Roughness = 0*	

**Roughness may vary depending on the observed slope roughness and resolution of topographic data used to define the modelled, see Section 4.4.1.*

[1] *Vegetation considerations should be used for back-analysis purposes only, but do not use for design model purposes. RocFall forest dampening option may be suitable for back analysis on site with limited data.*

As the modelled boulders contact the slope their velocities (normal and tangential) are reduced by coefficients of restitution, Rn and Rt respectively. The Coefficients of Restitution (COR) are the ratio of outgoing velocity to incoming velocity. The range of values is between 0 and 1, if 0 the boulder will be stopped by the material, if COR = 1 the boulder will have the same outgoing energy as the incoming energy. The CORs directly influence the total run out of boulders and the impact forces.

[*Note: It is considered that applying a materials approach to defining CORs, friction angle and roughness allows for a repeatable simple approach as adopted by industry*.]

Slope Roughness

Slope roughness is used for all slope materials to capture small scale irregularities that are not captured by the slope survey and may act as launching points for falling boulders.

An assessment of the slope roughness can be made by a visual comparison of the observed slope profile, survey profile with standard profiles shown in Figure 1 below (Alejano et al. 2008).

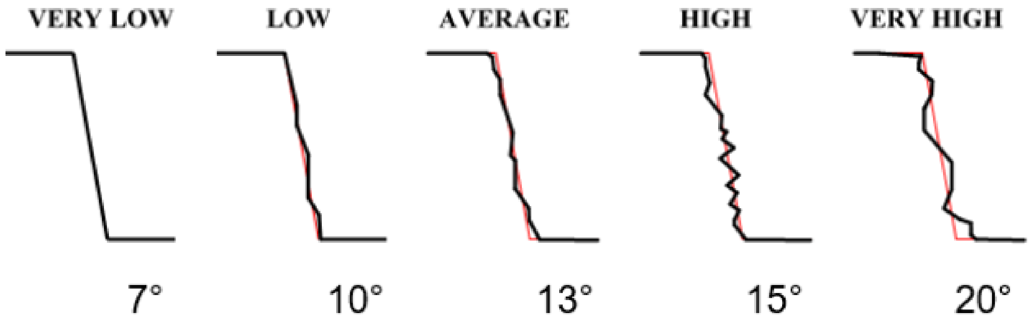

Figure 1 – Slope Irregularity classes (NCTIR modified after Alejano et al, 2008)

The varying irregularity classes can be applied depending on the slope roughness between two survey profile points. For low resolution survey profiles (i.e.>2m point spacing) and a highly irregular slope, a higher roughness factor should be applied. For a high-resolution survey profile (<0.25m point spacing) on a uniform slope, a lower roughness factor can be applied. If the survey and slope irregularity are equivalent, a nominal roughness not exceeding 5° can be applied.

As the roughness is a scale dependent parameter, that is, the roughness will appear higher for smaller boulders than larger boulder, the approach provides conservative estimates and judgment may be used to adject the roughness parameter to match back-analysis.

Design Boulder

General

Identifying the design boulder size is a significant source of uncertainty and requires informed engineering judgement. It is considered that the design boulder is a factual exercise to determine a realistic distribution of the falling boulders.

In a traditional rockfall trajectory study, a discrete boulder size is used. This discrete boulder size is chosen to be representative of the in-situ or fallen boulder size distribution depending on available data. The general approach is to simulate extreme events with the boulder size selected from the larger end of the distribution, bearing in mind the required design event/requirements specified (i.e.: ensuring that the design boulder reflects the design event being considered rather than the largest possible under any event).

Design guidance from MBIE (2016) suggests a design boulder corresponding to the 95th percentile size. ONR (2017) recommends a design boulder between the 95th and 98th percentile depending on rockfall frequency and consequence from impact. While conveniently simple, these approaches do not acknowledge that:

- Small events are more frequent than large events (Dussauge et al., 2003; Corominas & Moya, 2008). As noted earlier, highly frequent, small magnitude events, may result in a similar risk compared to low frequency, high magnitude events. Hazard assessment based on the behaviours of extreme events may underestimate the higher frequency rockfall risk within a transport corridor.

- Small boulders bounce more than large boulders (Mitchell & Hungr, 2017). Similarly, RPS design based on the dynamics of large events may not provide the expected protection (height) for the smaller and more frequent boulders which may result in an underestimation of the achieved residual risk. Conversely, designing RPS's with energies from large boulders and bounces from smaller boulders can result in design requirements that can be difficult to accommodate considering the geographical constraints on the corridor (i.e., generally limited space between slopes and road).

Probabilistic Approach

Studies have demonstrated that a discrete boulder approach results in an overestimation of the rockfall hazard when compared to a probabilistic approach (e.g. Lambert et al. (2012)). A probabilistic approach should therefore be used to characterise the overall rockfall hazard rather than the extreme event, with the boulder size defined by a mass distribution of in-situ blocks observed in the source area and the fallen blocks within the deposition area. The size distribution in the model should be calibrated to match: -

a) the typical boulder/block size (or most probable boulder/block size) and

b) the estimated 95th boulder/block size (extreme event).

The rockfall trajectory analysis will therefore provide bounce heights that are controlled by small boulders with an energy distribution that captures larger events.

A rock mass distribution is fitted to the observed in situ boulder size distribution. The in-situ boulder size distribution can be surveyed via traditional methods (scanline) or non-contact methods (such as laser scanner and/or UAV photogrammetric survey). The shape of the mass distribution is adjusted on a site-by-site basis to the corresponding statistical distribution that best reflects the recorded in-situ boulder distributions. This distribution can then be input into software.

Fallen Blocks / Fragmentation

Fallen block size data should be collected and compared to in-situ block size data for assessment of fragmentation. The level of fragmentation considered within the modelling and represented in a shift of the block distribution depends upon the location of the RPS downslope. Modelling inputs should be modified to reflect likelihood of fragmentation and documented in the reporting.

Design Percentiles

Across the industry, RPSs are designed for different levels of performance.

The current adopted approach for previous Waka Kotahi projects, is to select design percentiles based on a target for the level of residual hazard (or risk reduction) needed to be achieved by the installation of a protection structure based on the initial ARL risk rating. The percentiles have been considered as follows:

- To achieve a reduction from ARL 2 to ARL 3, one order of magnitude reduction in risk will be needed. This results in using the 95th percentile bounce height and 95th percentile kinetic energy, i.e. 5 % bouncing over, 5% exceeding energy capacity, and a total of 90% being stopped. [*Note: based on this, there is (in theory) flexibility for the designer to select unique percentiles for energies and bounce heights totalling 90% to suit the particular hazard, i.e. 98% bounce heights, 92% energy capacity for a total of 90%*]

- To achieve a reduction from ARL 1 to ARL 3, two orders of magnitude reduction in risk will be needed. This results in using the 99th percentile bounce height and 99th percentile kinetic energy, i.e. 1% bouncing over, 1% exceeding energy capacity, and 98% being stopped.

Design Input for Passive Rockfall Protection Systems

Design Standard and Partial Coefficients

Driving actions for the design of RPS include a *project energy* and a *project bounce height*. These actions are largely based on a given percentile of the cumulative kinetic energy and bounce height distributions (the design percentile). The choice of design percentiles affects the level of risk reduction the RPS will achieve as discussed above.

According to the UNI 11211-4, the design of a RPS can be done considering the serviceability limit state (SEL) or ultimate limit state (MEL). In both cases, partial coefficients are introduced to derive the driving actions, i.e., *project energy* and *project bounce height*, from the rockfall trajectory analysis. Details of corresponding equations are provided in UNI 11211-4 or Grimod & Giachetti (2014) with values for the partial coefficients reproduced in Table A2. These partial coefficients should be considered to ensure they reflect the appropriate level of uncertainty in the rockfall modelling inputs.

Table A2. Values of Partial Factors (Adapted from UNI 11211-4:2012)

Symbol	Name	Notes	Factor
γ_{Tr}	Rockfall trajectory factor	Rockfall simulation validated with rock fall field experiments	1.04
		Rockfall simulation without field validation	1.20
γ_{Dp}	Topographic factor	Rockfall simulation based on up-to-date UAV or LiDAR topographic survey	1.04
		Rockfall simulation based on low accuracy or out of date topographic survey	1.20
γ_{Y}	Density factor	Generally suggested	1.00
γ_{VolF1}	Boulder volume factor	High accuracy block size distribution survey	1.02
		Based on field walkover but without any detailed size distribution survey	1.10
		Based on aerial images or fly-over	1.5
γ_{R}	Risk factor	Place frequented, with high value and difficult to be repaired	1.10
		Place highly frequented, with significant value – or strategic – and impossible to be repaired	1.20
f_{min}	Freeboard	Freeboard to be at least 0.5 m or half the design boulder size, whichever is the highest	-

$$E_d = \gamma_R \times \gamma_Y \times \gamma_{VolF1} \times \gamma_{Tr} \times \gamma_{Dp} \times E_t$$

with: E_t translational kinetic energy computed from the trajectory analysis

E_d *project energy* to be used for the design of RPS

$$h_{tot} = h_d + f_{min}$$

with: h_{tot} total height of the RPS

h_d *project bounce height* computed from the trajectory analysis as a percentile of the modelled bounce height

It should be noted that UNI 11211-4 specifies other partial factors to estimate the fence capacity, height and deformation from the *project energy* and *project bounce height*. These factors are design and site specific rather than modelling related. They should however be addressed during detailed design.

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