Rock slope failure mitigation measures

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1 Introduction

Instability (failure) of rock slopes is mainly governed by one of the following mechanisms:

- Wedge failure by two discontinuities in which intersection lines dip towards the slope
- Toppling of rock columns or slabs created by vertical discontinuities close to the slope
- Circular slip surfaces in heavily jointed / fractured rocks masses
- Rock fall of loose blocks due to slipping, rolling or toppling
- Planar failure along discontinuities dipping in the direction of the slope

Rock slope instability can be triggered by different internal and external sources as illustrated in Fig. 1.1. Typical rock fall mitigation measures and their location are illustrated in Fig. 1.2 (see also Fig. 1.6). Exemplary, Fig. 1.3 shows typical rockfall events. In principle, there are three options to handle rock slope instabilities:

- Eliminating of the instability (removal of dangerous rock blocks)
- Slope stabilization (increase of factor-of-safety)
- Hazard reduction (reduces the risk by specific measures)

Elimination of rock slope instability can be performed by blasting or mechanical detachment of loose rock blocks (scaling) or by relocation of the geotechnical structure. Potential measures for rock slope stabilization are shown in Fig. 1.4. An overview about potential measures to reduce the hazard of rock slope failure is provided in Fig. 1.5. Not mentioned in Fig. 1.4 and 1.5 is dewatering, which is one of the most important measures to increase the factor-of-safety. The following chapters give an overview about some selected measures to stabilise rock slopes or to reduce the risks in respect to potential rock slope failure. Most important for any design of rockfall protection systems is the potential energy of the expected boulders or debris, which is dependent on velocity and mass as illustrated in Fig. 1.7. Comprehensive overviews about rock slope instabilities and corresponding mitigation measures are provided for instance by recommendations like TRL (2011), FOEN (2016) or MBIE (2016).

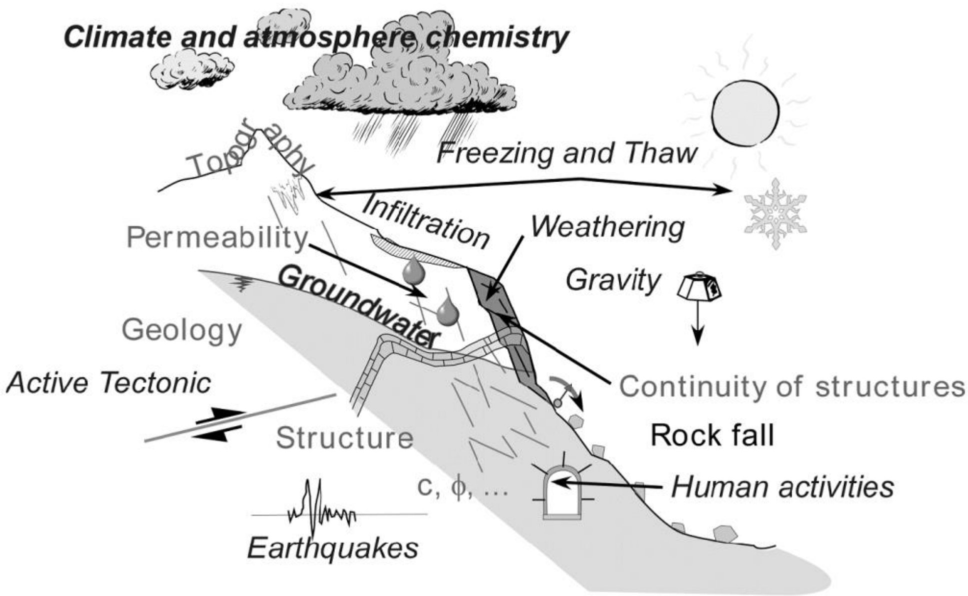


Fig. 1.1: External and internal factors for triggering rockfall (Volkwein et al., 2011)

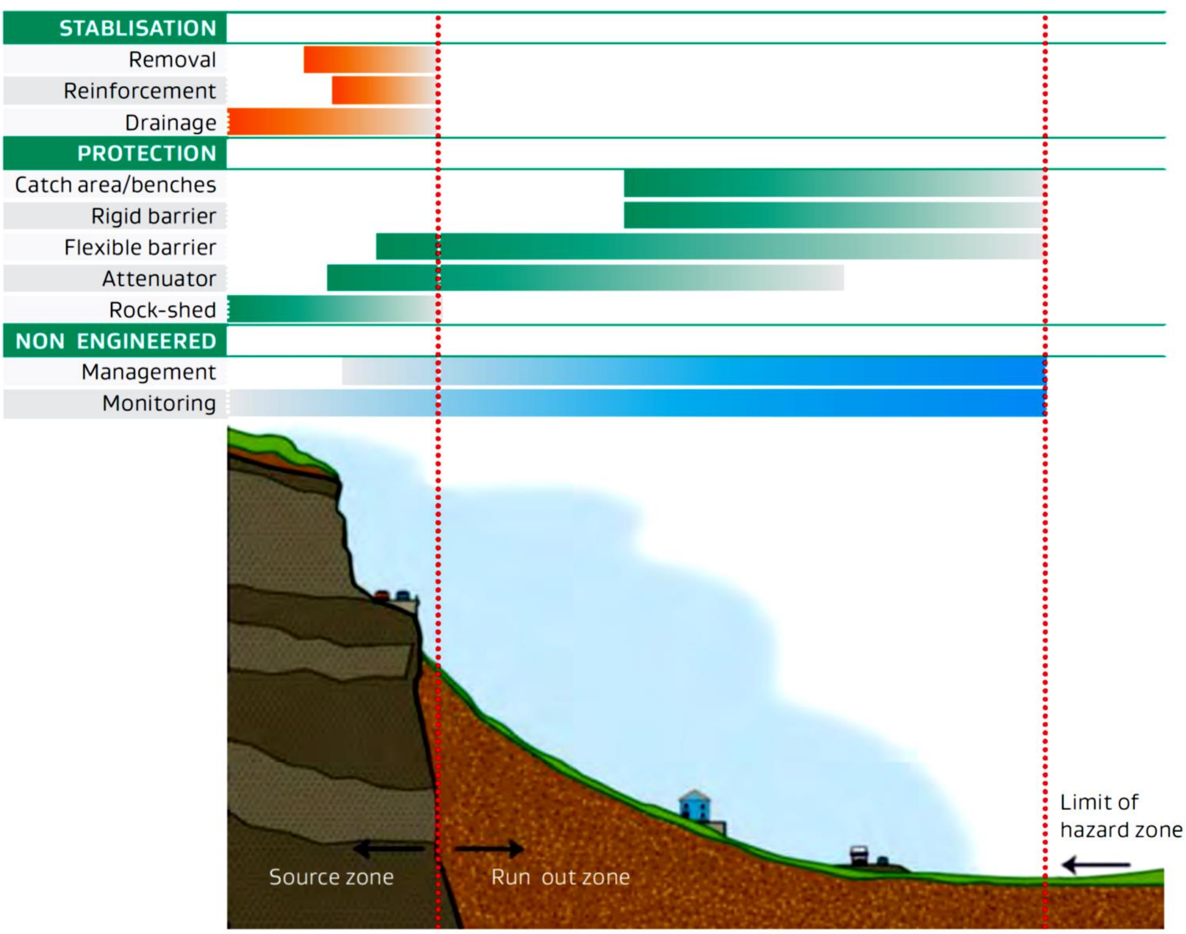


Fig. 1.2: Overview about rockfall mitigation measures (MBIE, 2016)

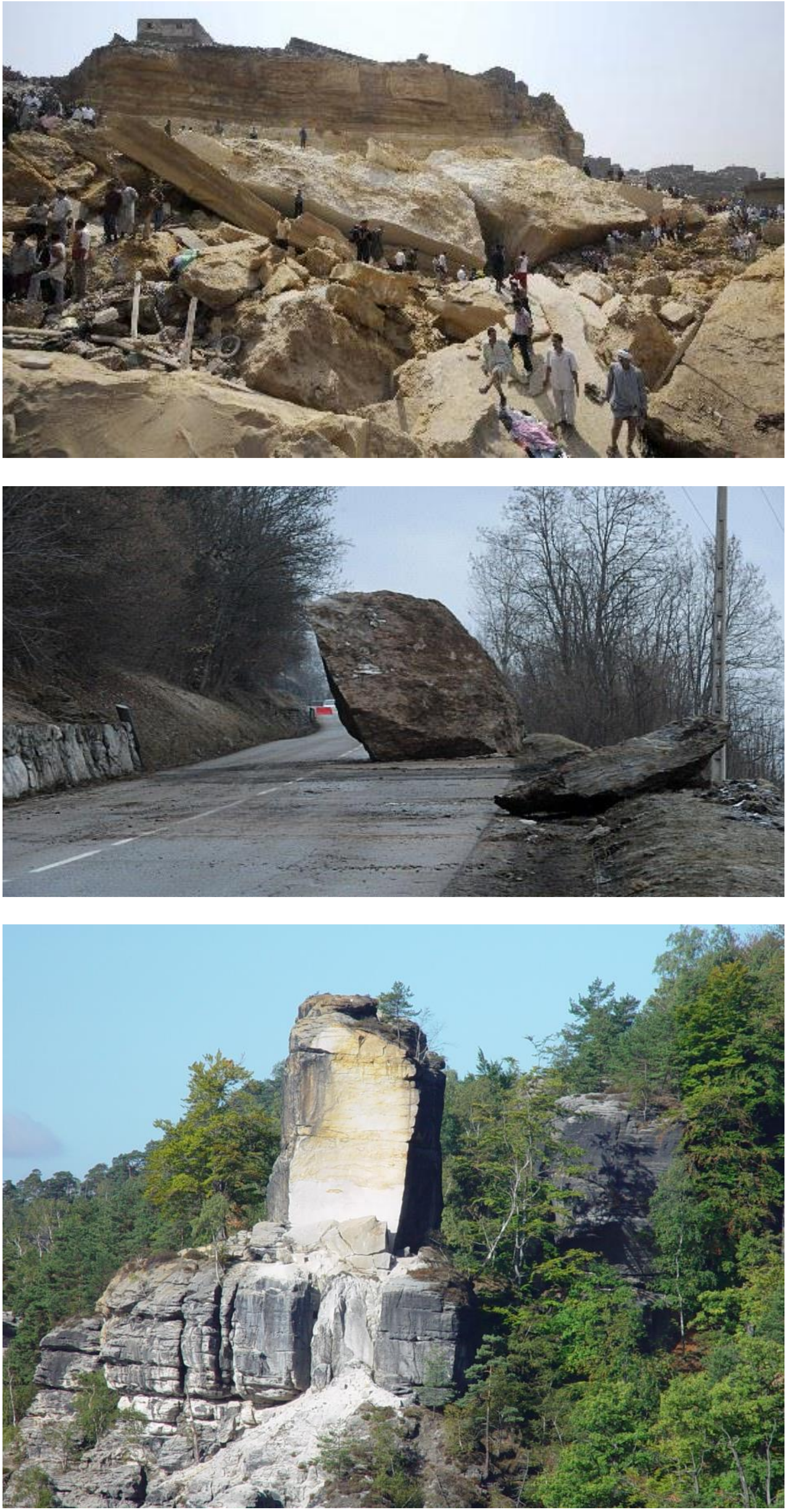


Fig. 1.3: Different rockfall examples

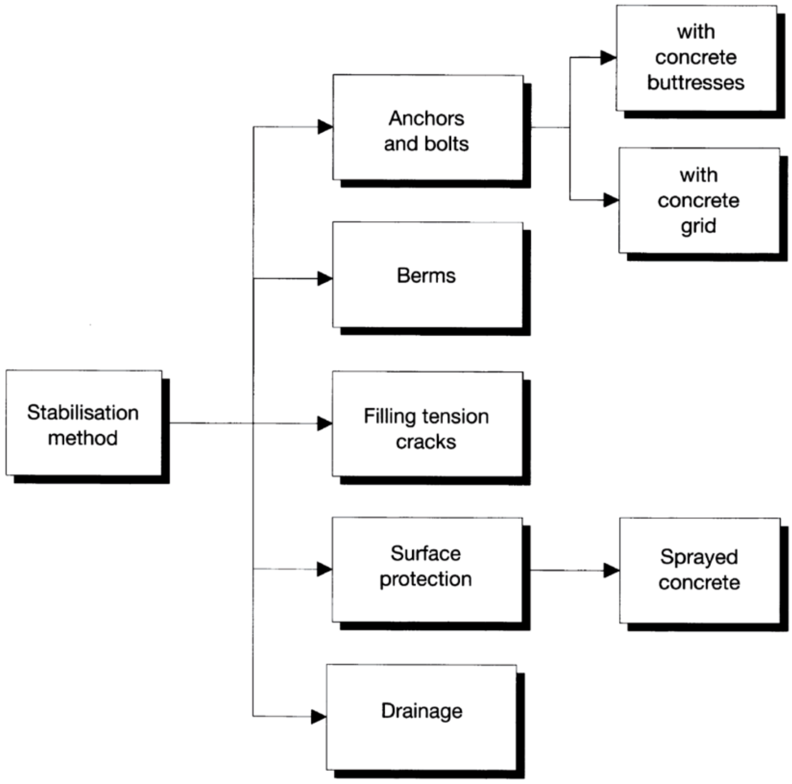


Fig. 1.4: Rock slope stabilisation measures (Ortigao & Sayao, 2004)

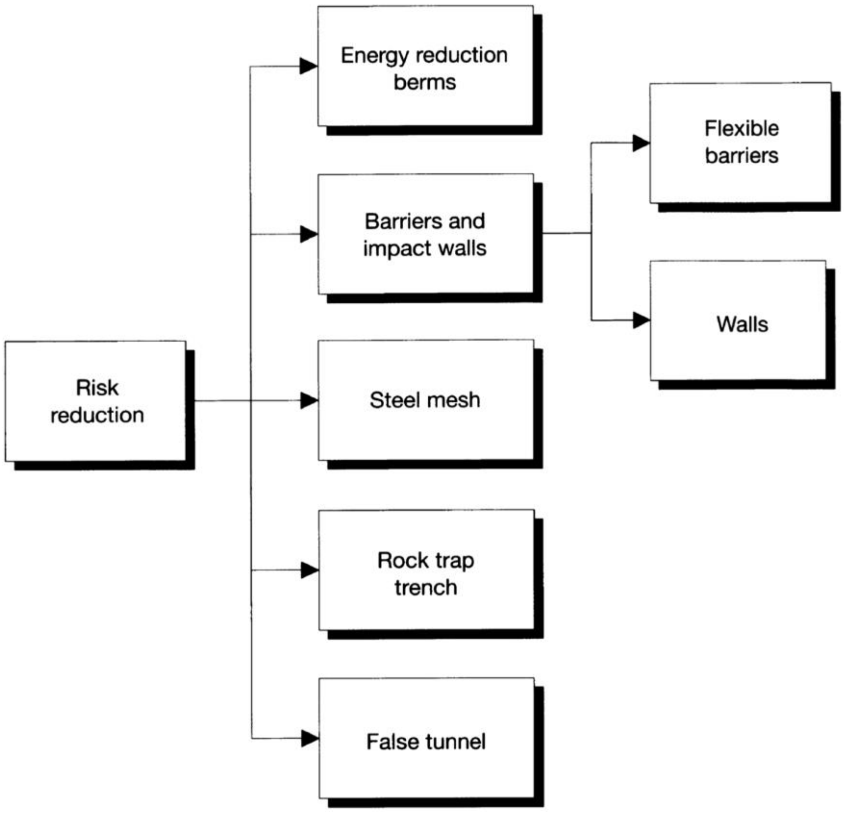


Fig. 1.5: Rock slope hazard reduction measures (Ortigao & Sayao, 2004)

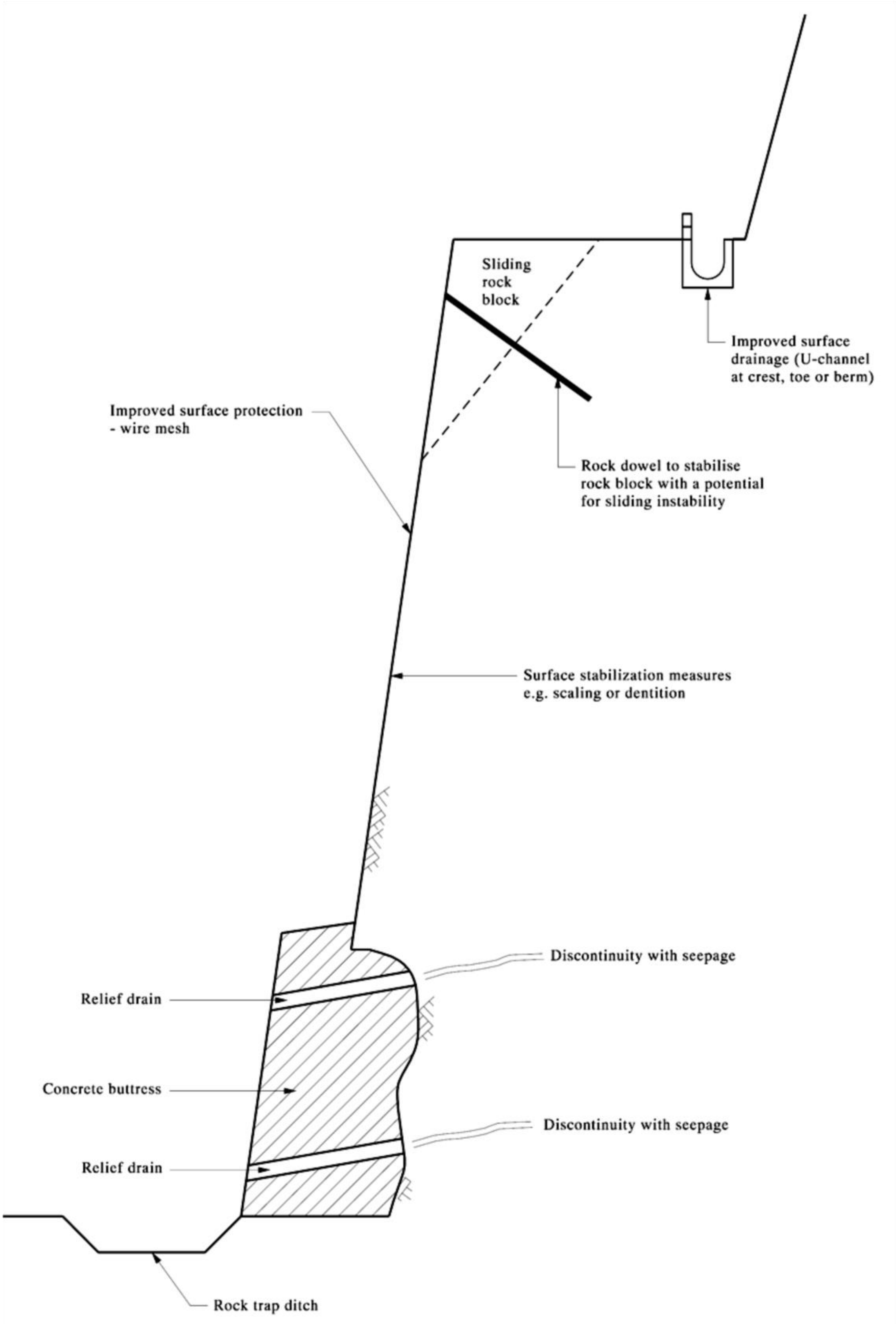


Fig. 1.6: Typical rock slope stability measures (modified after GEOH, 2003)

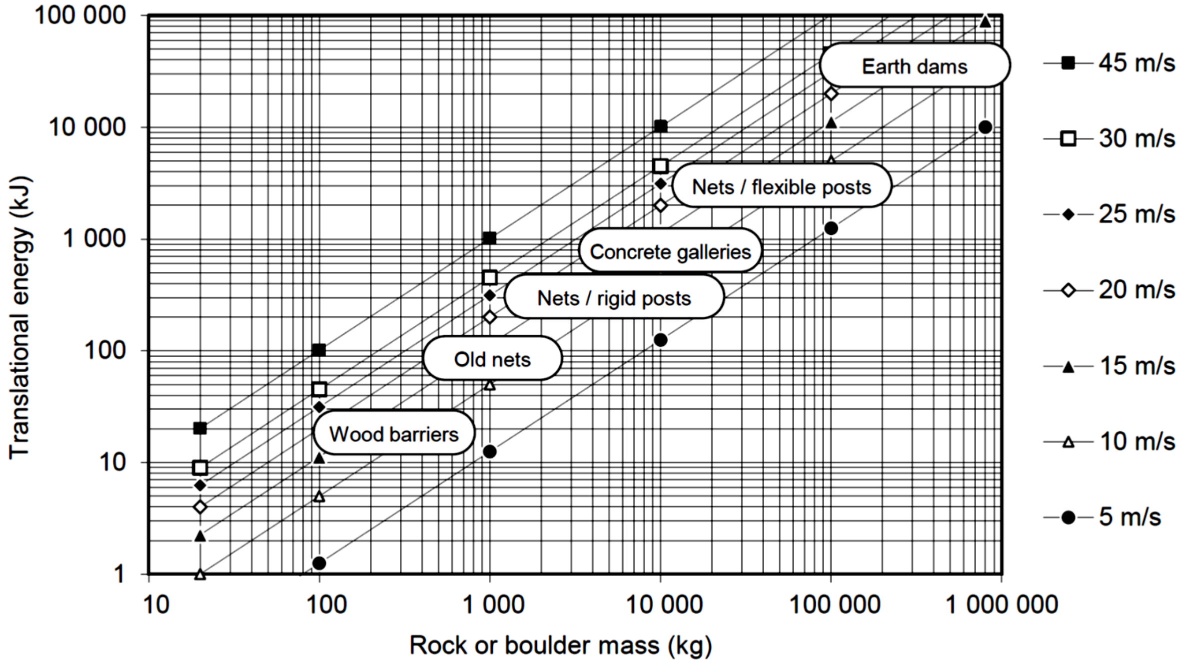


Fig. 1.7: Energy considerations for boulders (FOEN, 2017)

2 Dewatering

Dewatering has four main aims:

- Reduction of joint and matrix pore water pressure
- Reduction of water pressure behind artificial surface sealing (e.g. behind shotcrete walls)
- Reduction / elimination of ice pressure (freeze-thaw cycles)
- Reduction of flushing of joint fillings

Dewatering can be reached by the following measures:

- Surface drainage by channels, trenches or ditches
- Filters (e.g. behind retaining walls)
- Drainage with the help of geosynthetics
- Relief wells

3 Anchorage

Single blocks (see Fig. 3.1) or complete slopes (see Fig. 3.2) can be stabilised by anchors. More information about anchors can be found in our corresponding E-Book 16 “Rock bolting”.

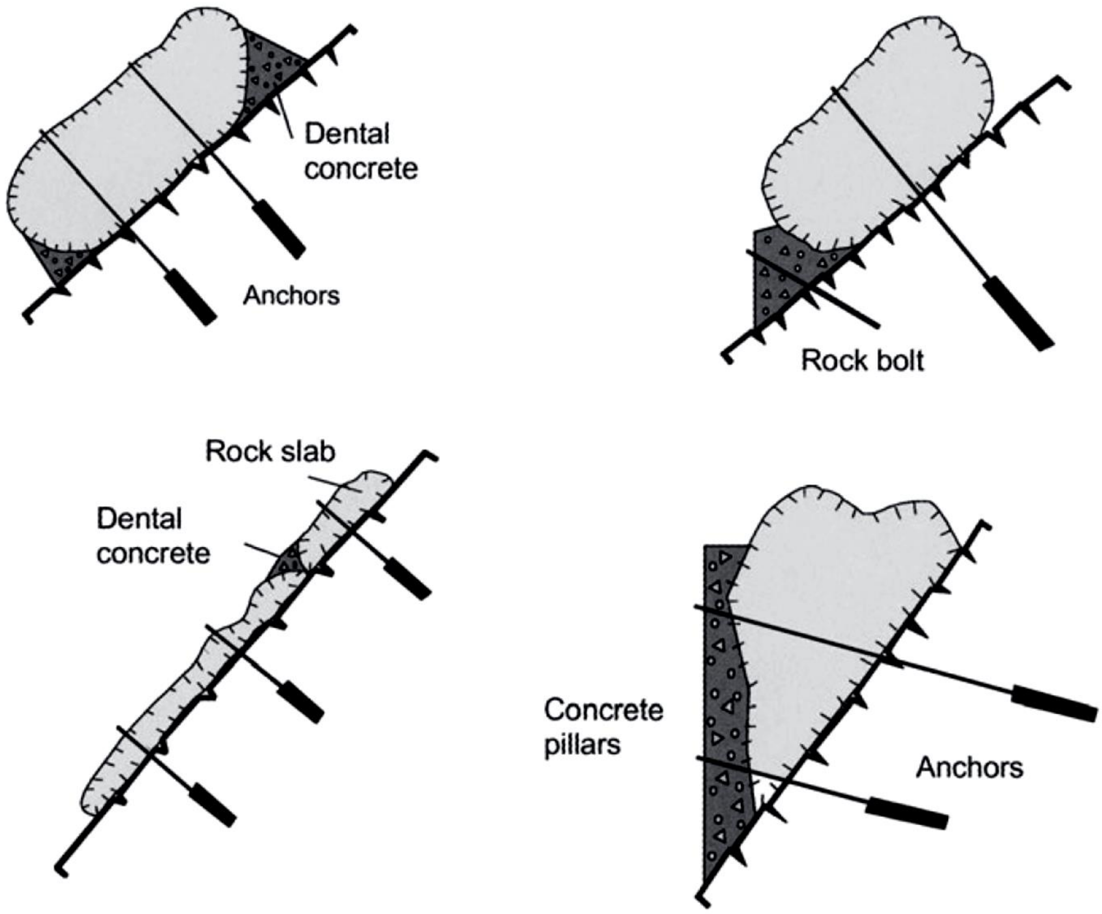


Fig. 3.1: Stabilisation of loose rock blocks with anchors (Ortigao & Sayao, 2004)

Fig. 3.2: Rock slope stabilised with berms, shotcrete, systematic pre-stressed anchorage and relief boreholes for dewatering (water dam project, China)

4 Rockfall barriers

Several types of rockfall barriers are common (see Fig. 4.1):

- Fences
- Flexible barriers (meshes) without rope retention
- Flexible barriers (meshes) with rope retention
- Galleries
- Retention dams (earth embankments, concrete walls, gabion baskets etc.)

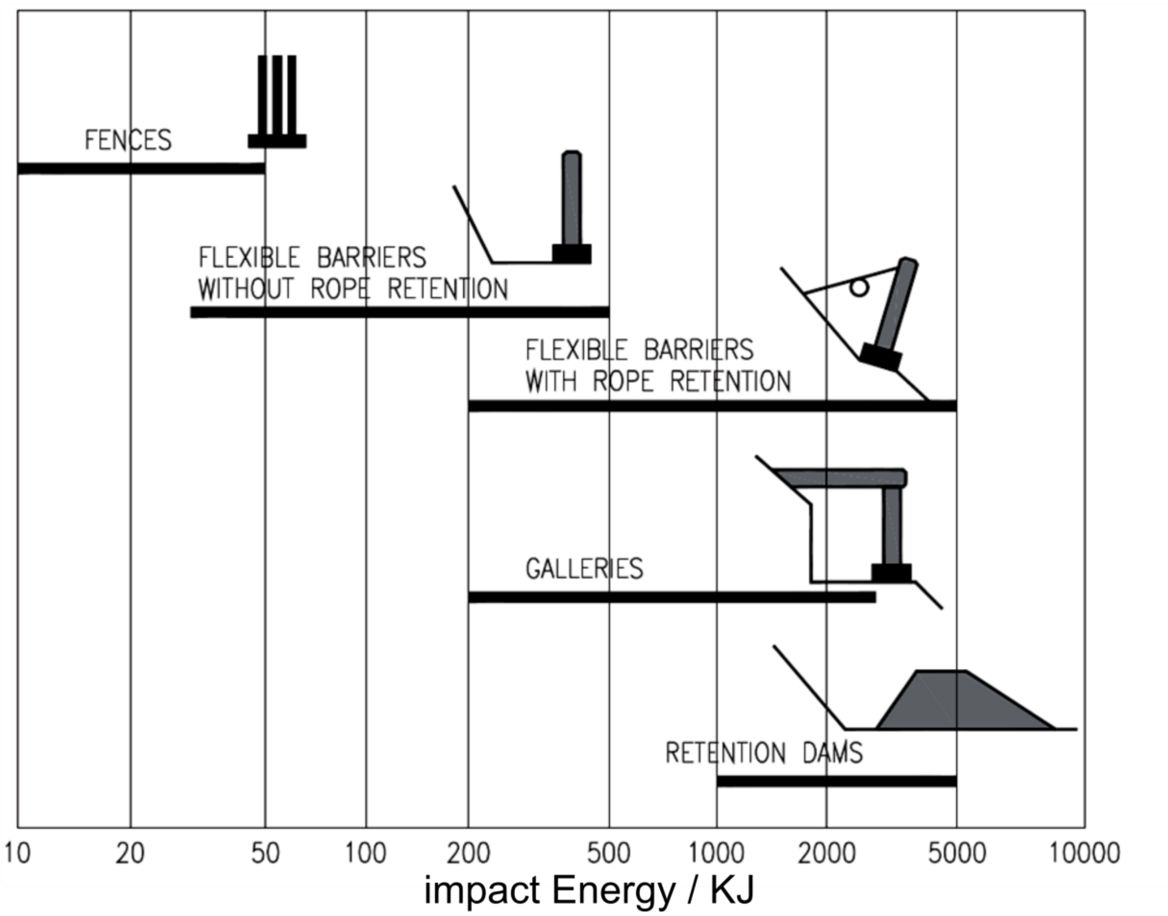


Fig. 4.1: Types of typical rockfall barriers depending on the corresponding impact energy (Grošić et al., 2010)

4.1 Flexible barriers

Exemplary, Fig. 4.2 illustrates the components of a flexible barrier with rope retention. Such a system consists of the following main components (see also Fig. 4.3 and 4.4):

- Foundation for rockfall protection barriers
- Anchors for barrier anchorage
- Base plate
- Posts
- Intermediate and lateral support
- Bearing mesh
- Brake system

Most important parameters for dimensioning and choice of an appropriate system are bouncing height and block energy impact. For design and dimensioning several tools are available:

- Simplified analytical solutions
- Simplified numerical solutions (trajectory models: rockfall simulation software based on jumping, sliding or bouncing spheres)
- Complex numerical simulations based on FEM, DEM or Particle Methods

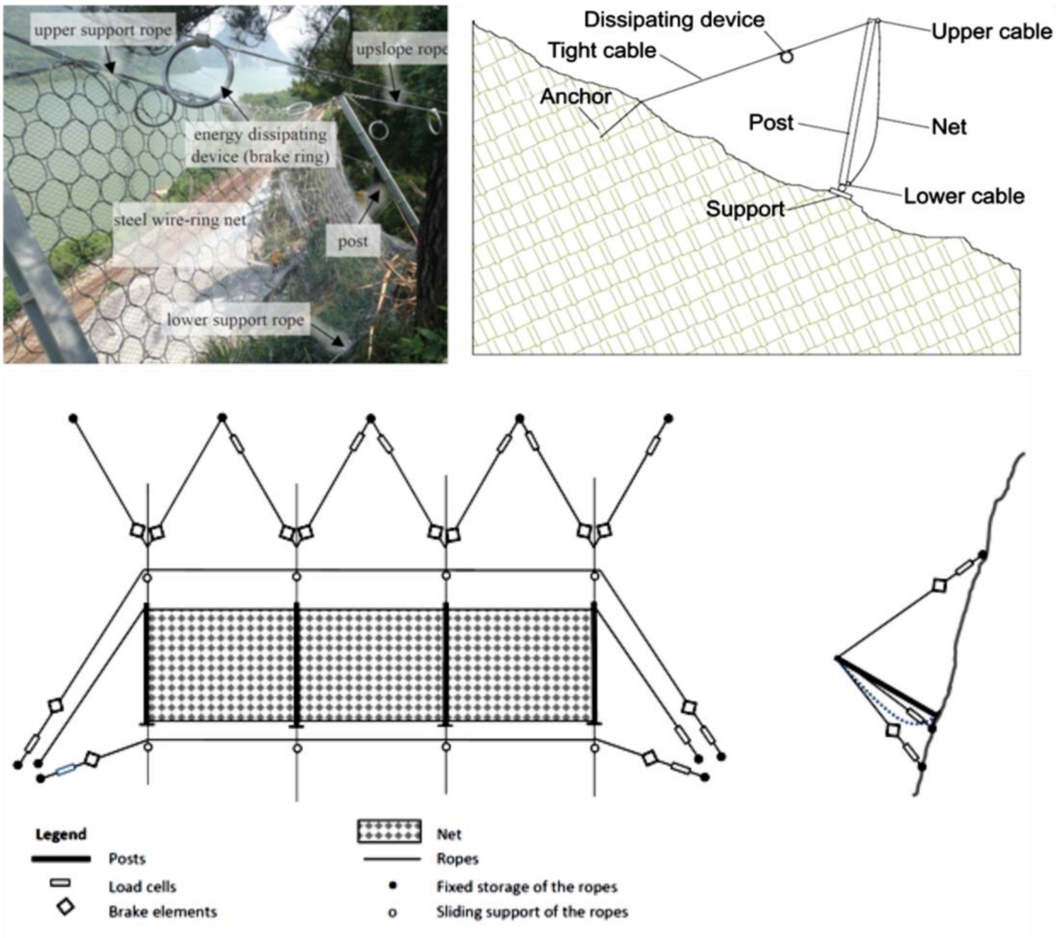


Fig. 4.2: Scheme of flexible rockfall protection systems (Xu et al., 2018; Volkwein et al., 2019; Robles et al., 2017)

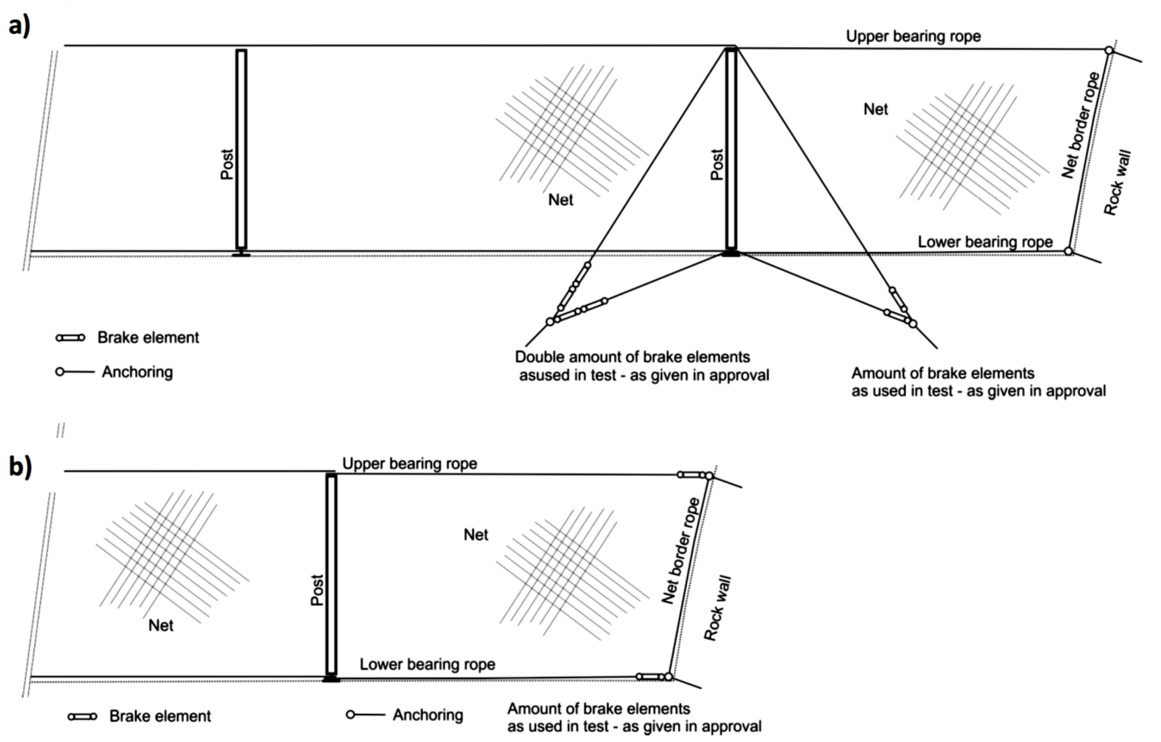


Fig. 4.3: Fence solution with (a): extra internal anchorage and (b): direct connection (Stelzer & Bichler, 2013)

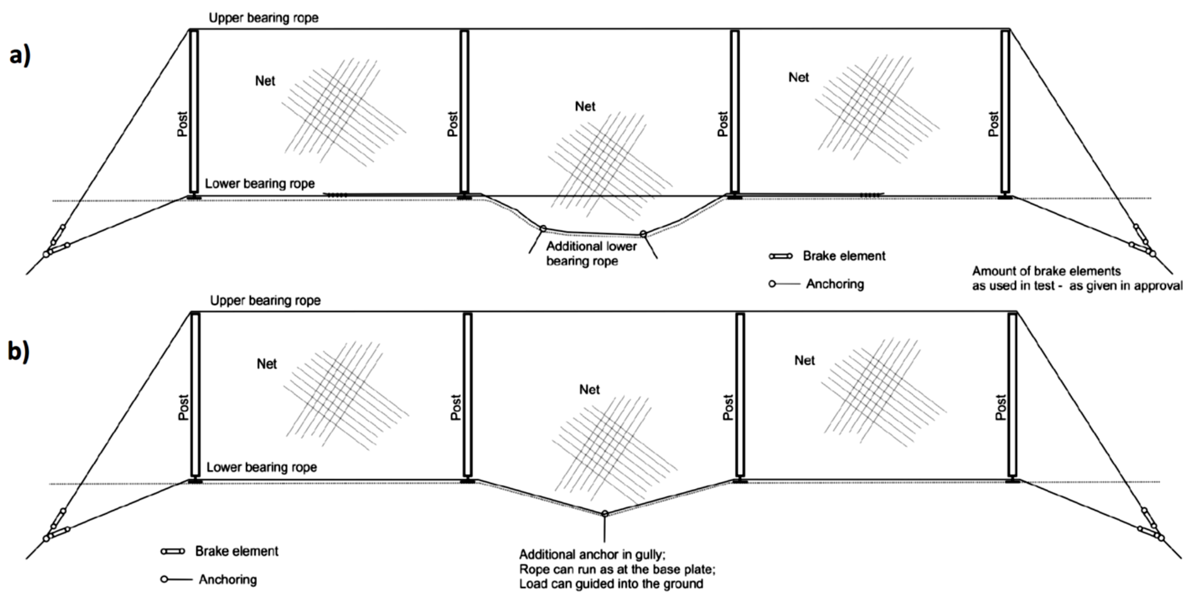


Fig. 4.4: Fence solution with (a): additional anchorage and additional bearing rope (b): additional anchorage with no bearing rope (Stelzer & Bichler, 2013)

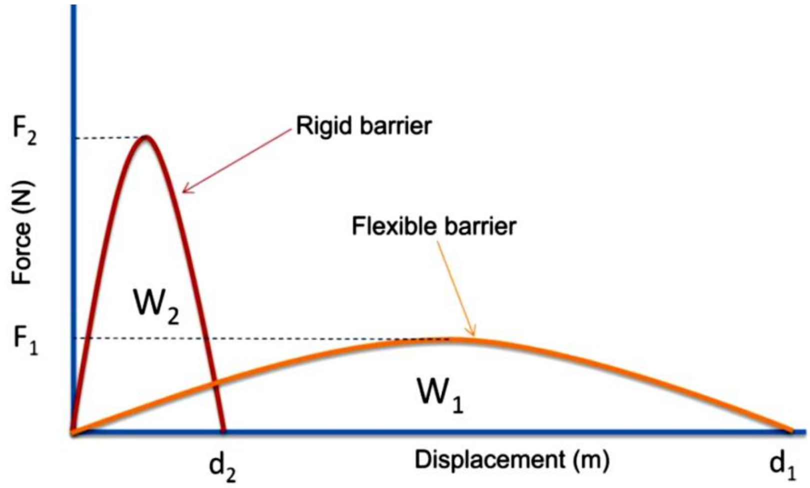


Fig. 4.5: Energetic differences between stiff and flexible barriers (Robles et al., 2017)

Important is to distinguish between stiff and flexible barriers (see Fig. 4.5). Flexible barriers, for instance by using energy dissipating elements, allow to absorb high energy impact. For the use of flexible barriers several guidelines were published, for instance:

- ONR-24810: technical protection against rockfall. Terms and definitions, effects of actions, design, monitoring and maintenance (Stelzer & Bichler, 2013; Bichler et al. 2017).
- ETAG-27: Guideline for European technical approval of falling rock protection kits (EOTA, 2013).
- WA-RD 612.2: Design guidelines for wire mesh or cable net slope protection (WSTC, 2005)
- Gerber, W. (2001): Guidelines for the approval of rockfall protection kits, SAEFL & WSL Berne

ETAG-027 is based on in-situ tests according to a special pre-described procedure and defines two energy levels: SEL “Service Energy Level” and MEL “Maximum Energy Level”. SEL is defined as 1/3 of MEL and the rockfall protection system should be able to retain such a SEL event twice. These energy levels are used to classify the rockfall protection systems (see Tab. 4.1).

A residual height value according to Tab. 4.2 is chosen to categorize the rockfall protection systems. The residual height considers a reasonable height for an impacted net fence that would permit an already impacted modulus to intercept a new falling block (Peila & Ronco, 2009).

Tab. 4.1: Energy level classification according to ETAG-027

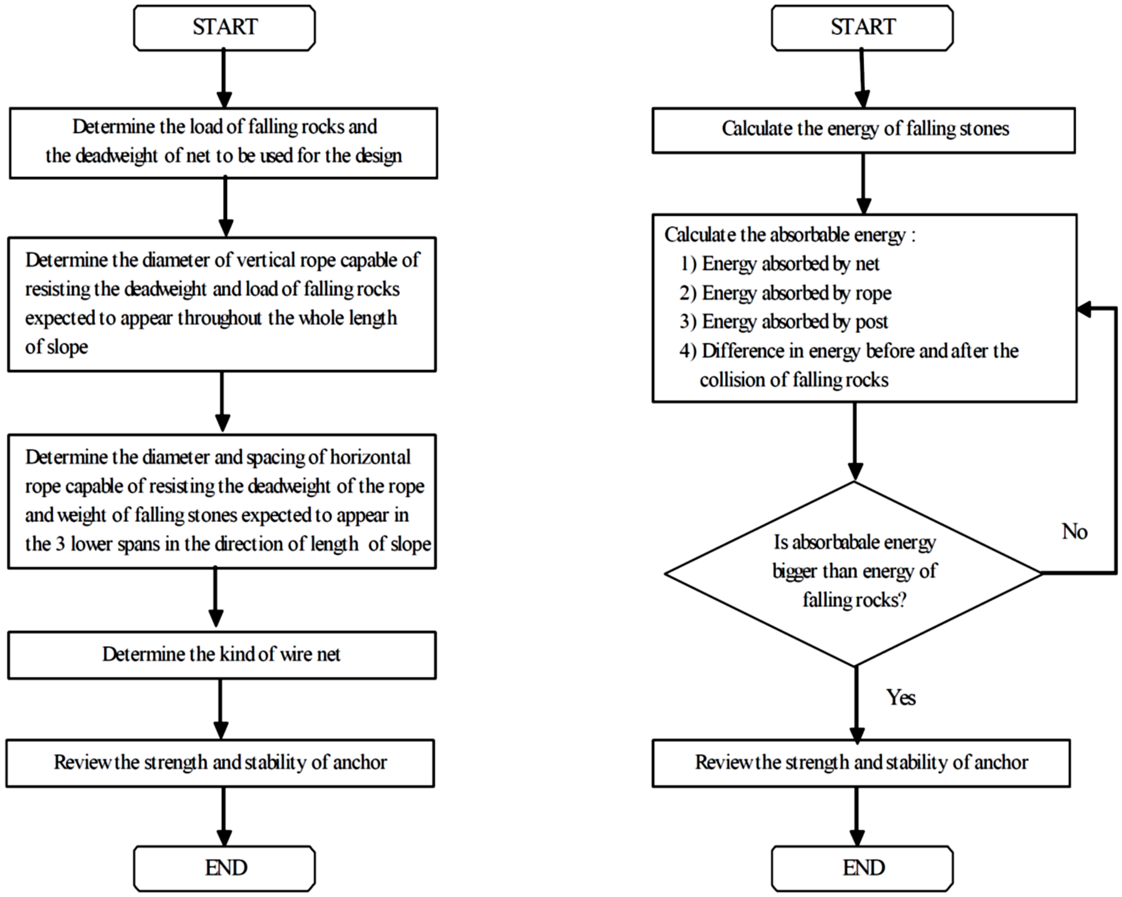
Energy level classification	0	1	2	3	4	5	6	7	8
SEL [kJ]	–	85	170	330	500	660	1000	1500	>1500
MEL [kJ]≥	100	250	500	1000	1500	2000	3000	4500	>4500

Tab. 4.2: Categories for rockfall protection systems according to ETAG-027

Category	Residual height
A	≥ 50 % nominal height
B	30 % < nominal height < 50 %
C	≤ 30 % nominal height

Fig. 4.6: Exemplary: flexible rockfall protection barriers in-situ (company material: Geobrugg)

Exemplary, Fig. 4.7 and 4.8 show flowcharts which can be followed to design fences and flexible barriers (meshes). Such recommendations (published as guidelines) are available in most countries as national documents provided by the corresponding authorities. A very detailed description of the practical application of flexible defences including their dimensioning and construction is given by Cala et al. (2012).



a) Cover type rock fall catch net **b) Pocket type rock fall catch net**

Fig. 4.7: Exemplary design proposal for two different types of catch net flexible barriers (JRA, 2000)

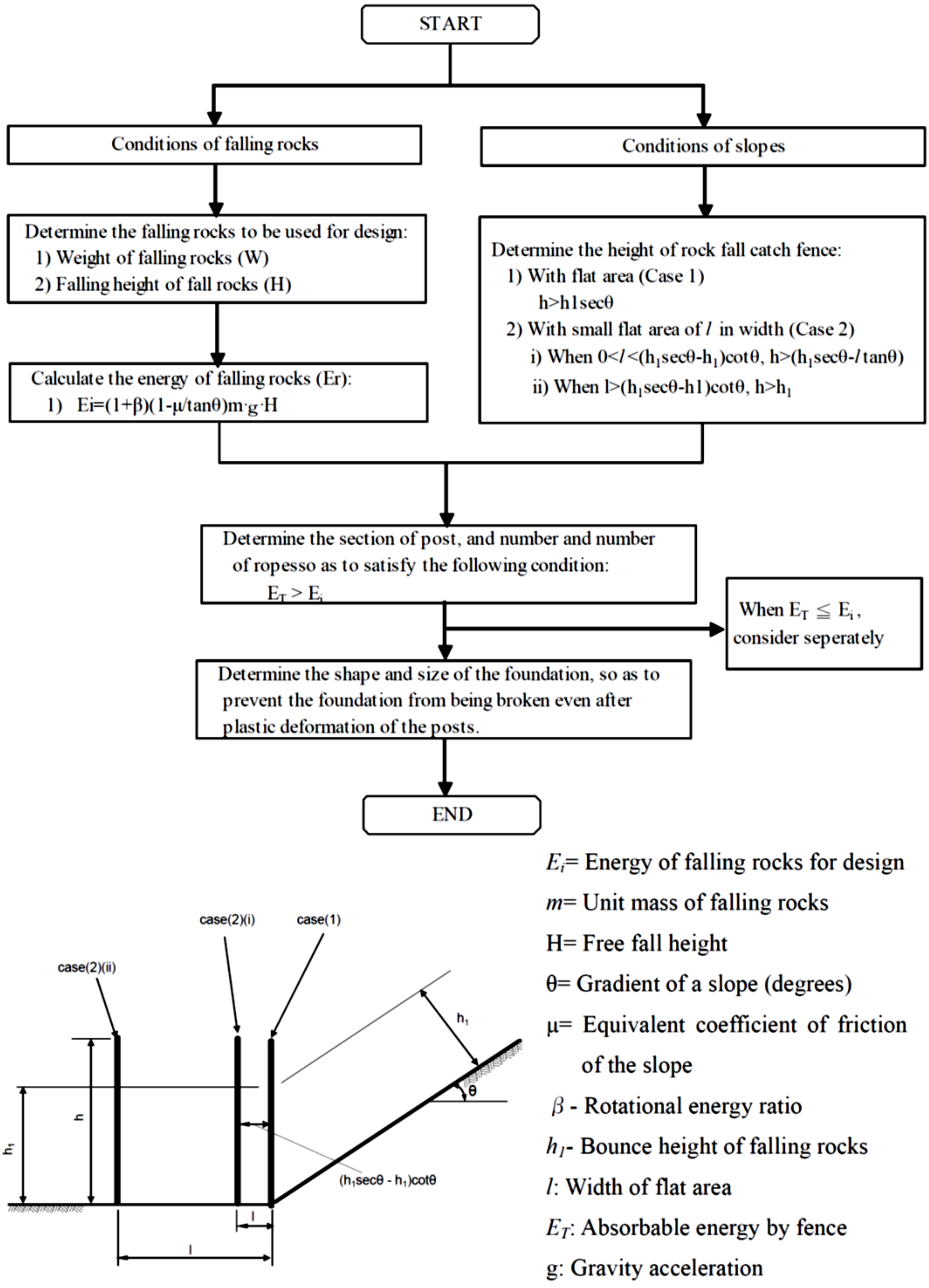


Fig. 4.8: Exemplary: flowchart for design of rockfall catch fences (JRA, 2000)

4.2 Galleries

The guideline ASTRA (2007) is concerned with rockfall protection galleries for road and railway infrastructure against debris flow and snow avalanches (project planning, ultimate limit state proof, serviceability check). Fig. 4.9 shows typical galleries in nature and Fig. 4.10 illustrates typical constructions.

Fig. 4.9: Different galleries to protect roads

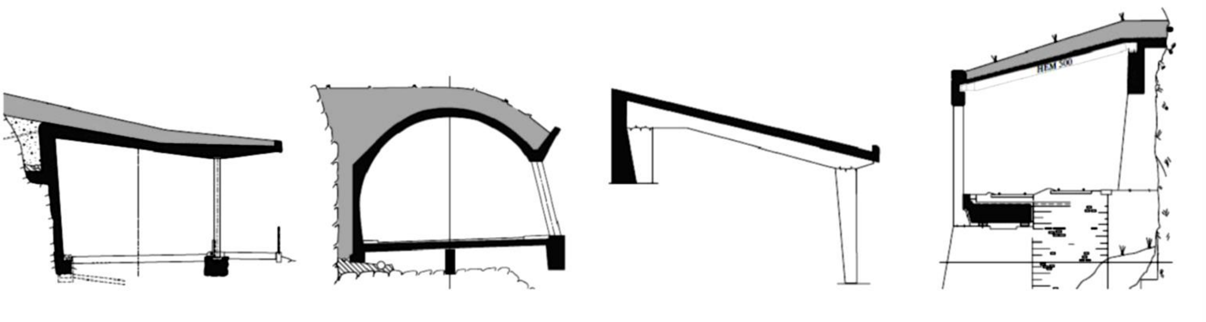


Fig. 4.10: Typical rockfall gallery constructions (Vogel et al., 2009)

4.3 Retention dams and ditches

Retention dams should include ditches (catchment areas for rock blocks and debris, respectively). A typical construction based on retention walls and ditches is shown in Fig. 4.11, which contains the following elements:

- Slope profile modification, scaling, trim blasting etc.
- Ditch (catchment area)
- Retention dam or wall

A comprehensive overview about retention dams is provided by Lambert & Kister (2017).

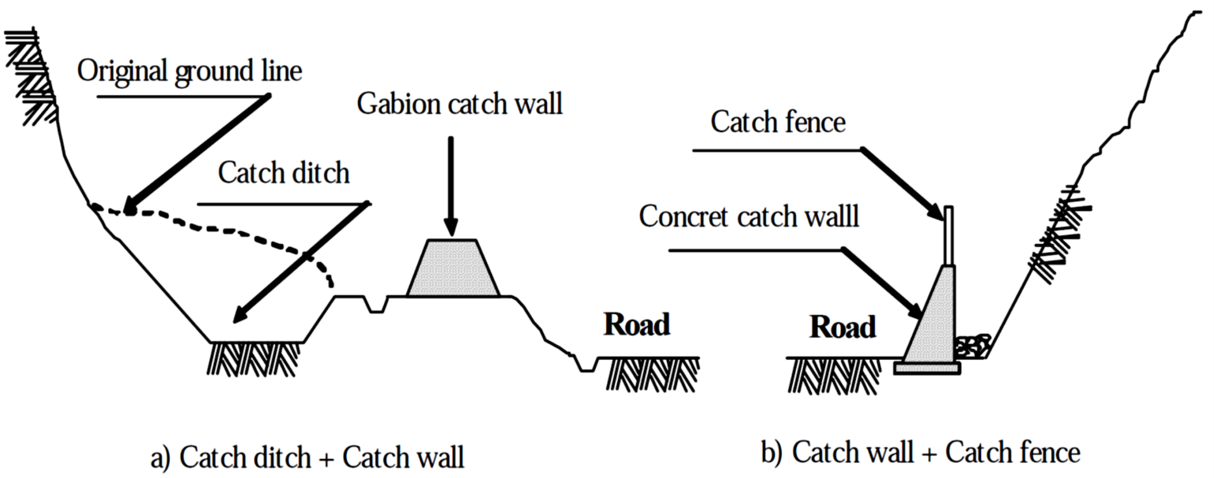


Fig. 4.11: Typical construction schemes of rockfall protection systems (JICA, 2009)

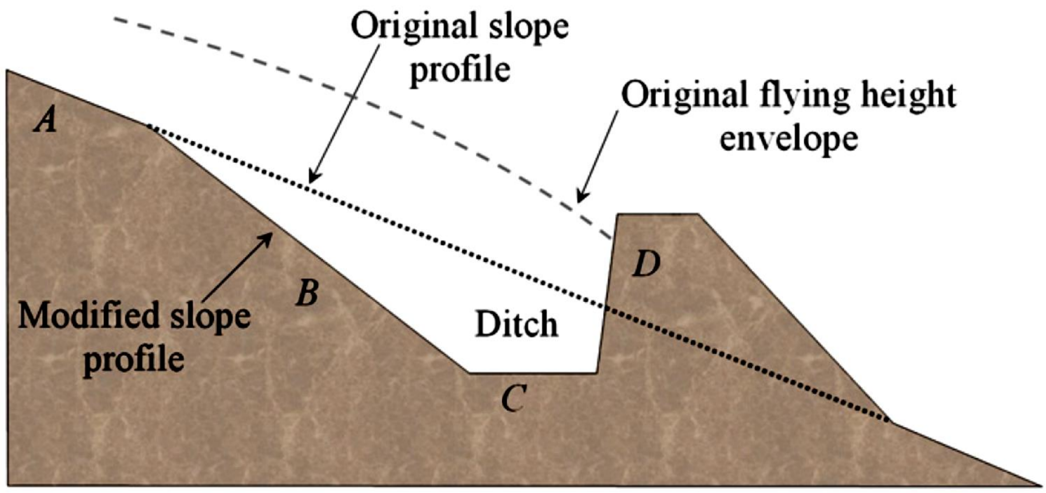
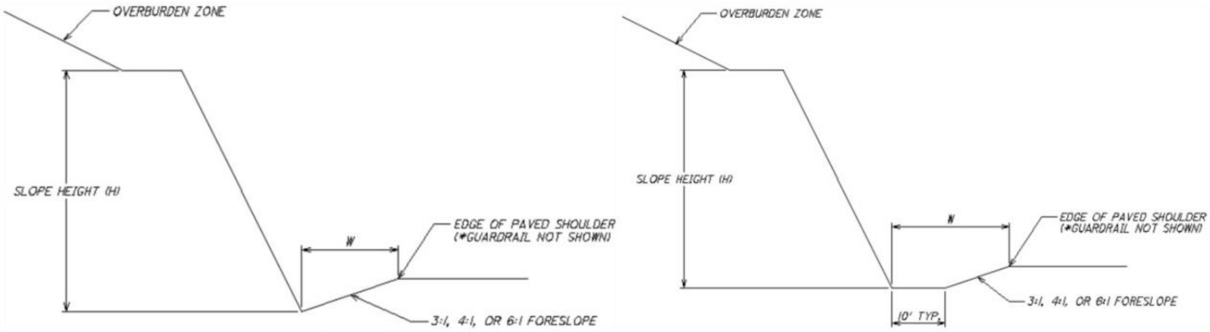


Fig. 4.12: Profile of embankment with natural slope reshaping (Lambert & Bourrier, 2013)

Tab. 4.3: Typical geometrical parameters for ditches (Lambert & Bourrier, 2013)

Rock Cut Heights / m	Catchment Width / m	Catchment Depth / m
0 - 8	3	0.75
8 - 16	4	1.00
> 16	5	1.25



	Cut Slope Height, H (ft)					
	0-40	**50**	**60**	**70**	**80**	**>90*** **
Overall Cut Slope Angle	**Catchment Ditch Width, W (ft)**					
3H:1V Catchment Foreslope Angle						
0.25:1	10	15	15	15	20	25 min.
0.5:1	10	15	20	20	20	25 min.
1.0:1	15	20	20	20/25**	25	30 min.
1.5:1	15	20	20	20/25**	25	30 max.
4H:1V Catchment Foreslope Angle						
0.25:1	10/15**	15	20	20	25	30 min.
0.5:1	15	15	20	20	25	30 min.
1.0:1	15/20**	20	20/25**	25/30**	30	35 min.
1.5:1	15/20**	20	20/25**	25/30**	30	35 max.
6H:1V Catchment Foreslope Angle						
0.25:1	15	20	25	30	35	40 min.
0.5:1	20	20	25	30	35	40 min.
1.0:1	25/30**	25/30**	30	35	40	40 min.
1.5:1	25/30**	25/30**	30	35	40	40 max.

Fig. 4.13: Typical recommended ditch configurations for catchment area (OHT, 2011)

5 Decision making

The decision making process, whether protection measures have to be taken or not and which, respectively, depends on several factors:

- Rock slope failure hazard
- Acceptable risk (see for instance ÖGG, 2014)
- Available money, technology, material, etc.
- Considered time span
- Geology and rock mechanical properties
- Environmental conditions
- Human and natural impacts

Fig. 5.1 lists several important factors which influence the selection of appropriate risk reduction measures.

Factor	Sub-factor
Existing hazard	• Stability • Nature of failure • Failure position and volume • Geometry of slope and road
Existing acceptability of risk	• Society's reaction to a hazard • Financial consequence • Social consequence
Strategic transport considerations	• Type of road • Traffic flow • Traffic volume • Traffic speed
Effectiveness of remedial option	• Mechanism • Relative degree of risk reduction • Residual risk level • Coverage
Remedial work cost	• Cost of design and construction • Cost of materials • Indirect cost (e.g. traffic delays) • Maintenance costs
Durability/sustainability	• Service life • Weathering/corrosion • Revised inspection/monitoring • Failure mechanism • Failure consequence
Influence of option	• Influence on adjacent engineered structures • Influence on adjacent rock mass
Environmental impact of R&M option	• Visual impact • Other impact

Fig. 5.1: Factors influencing the selection of risk reduction approach (TRL, 2011)

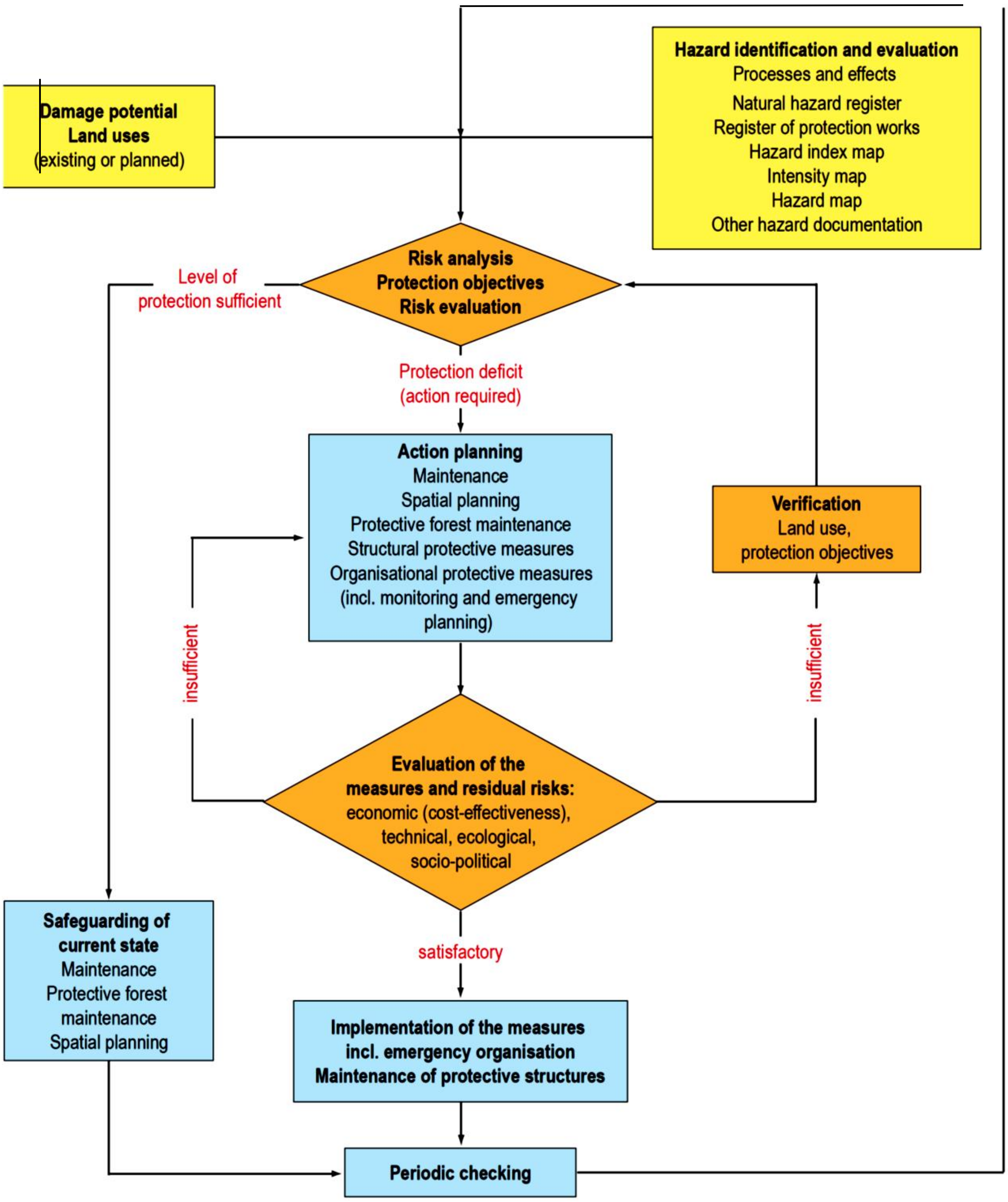


Fig. 5.2: Action planning procedure according to FOEN (2017)

Fig. 5.2 shows the proposed action planning procedure according to FOEN (2017) and Fig. 5.3 to 5.5 illustrate the decision making process according to TRL (2011) incl. potential rock slope failure mitigation measures. Fig. 5.6 shows – according to HNTB (2015) – an evaluation chart for potential rock slope failure mitigation measures.

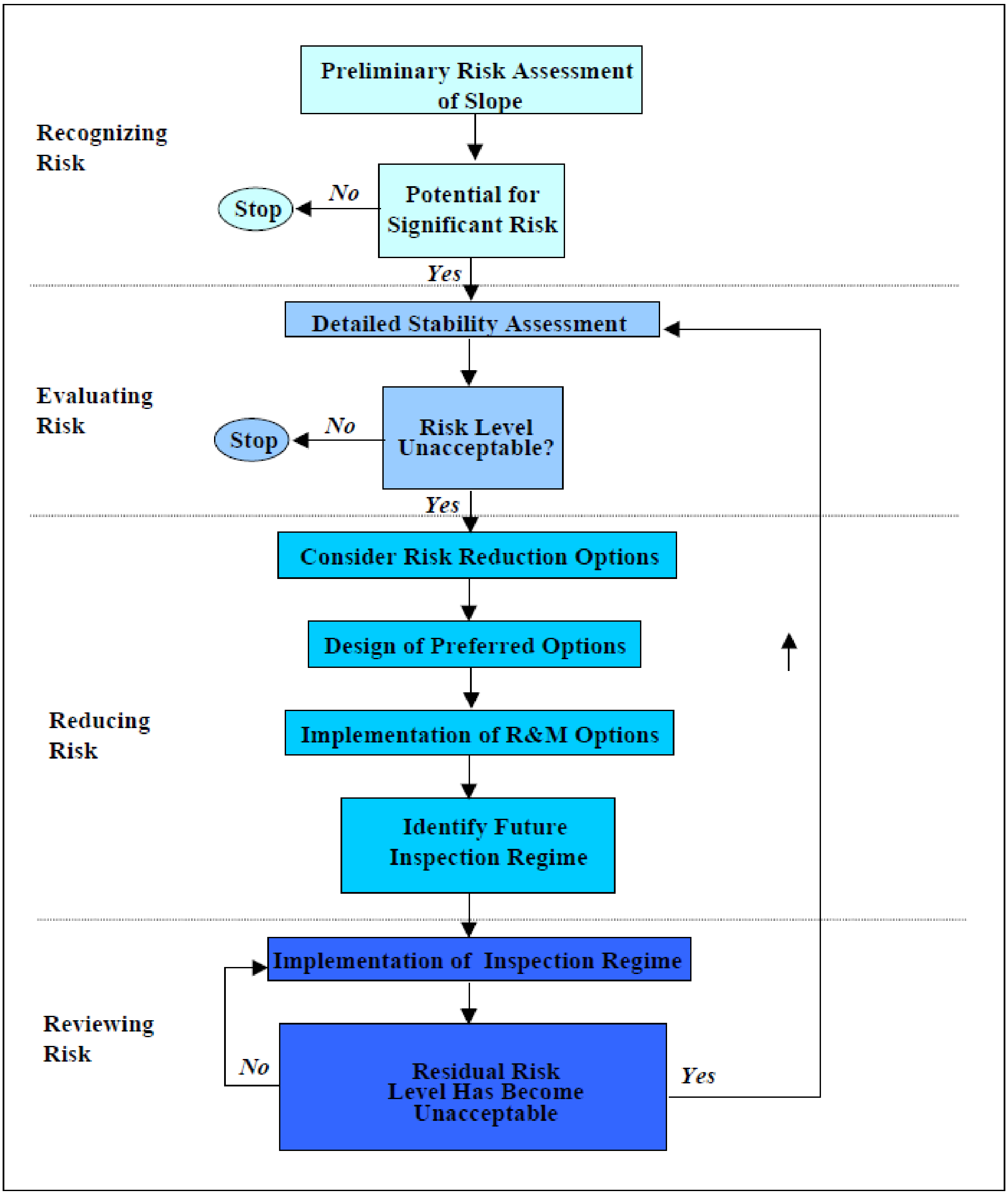


Fig. 5.3: Stages of risk management (TRL, 2011)

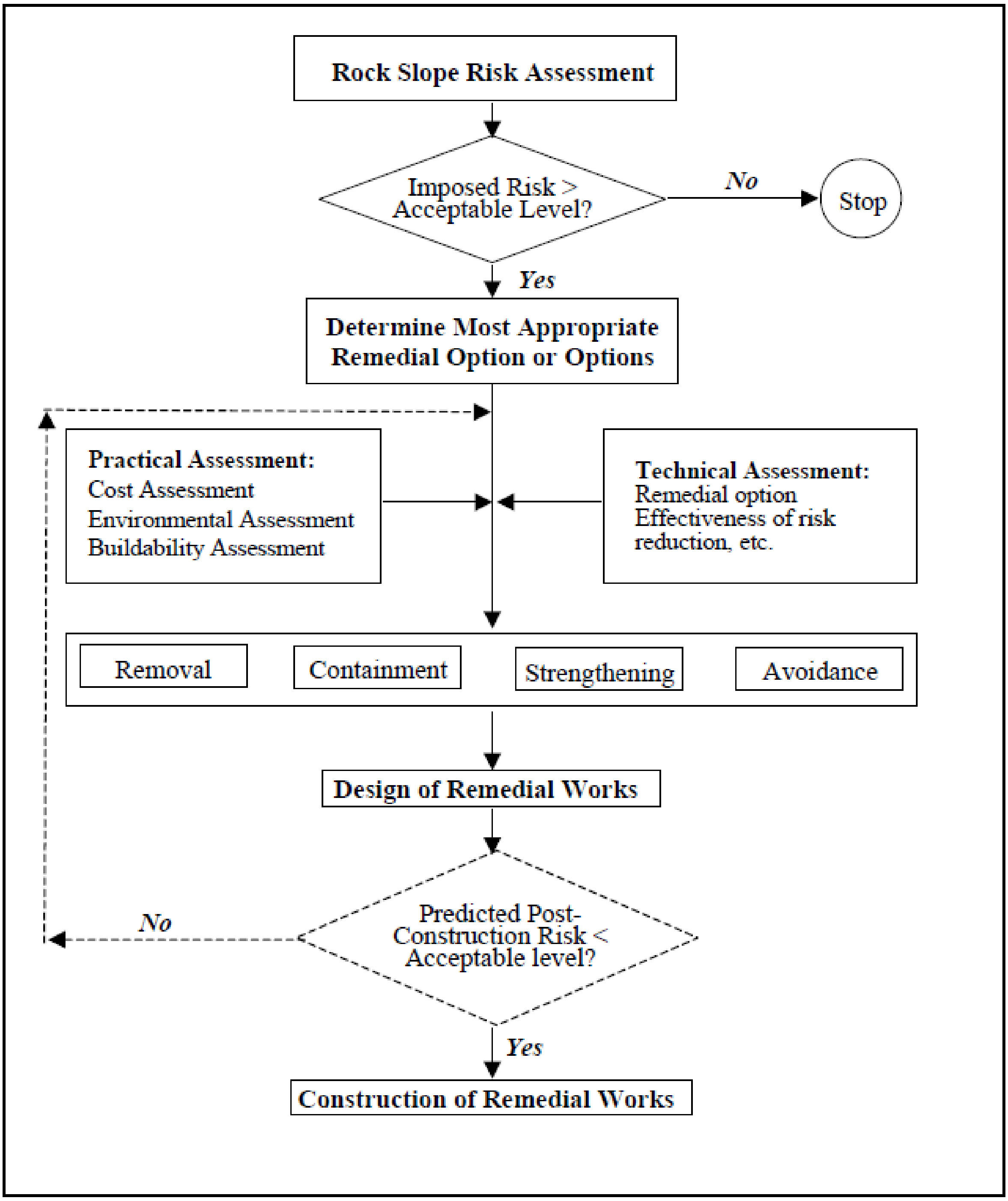


Fig. 5.4: Stages of risk management (TRL, 2011)

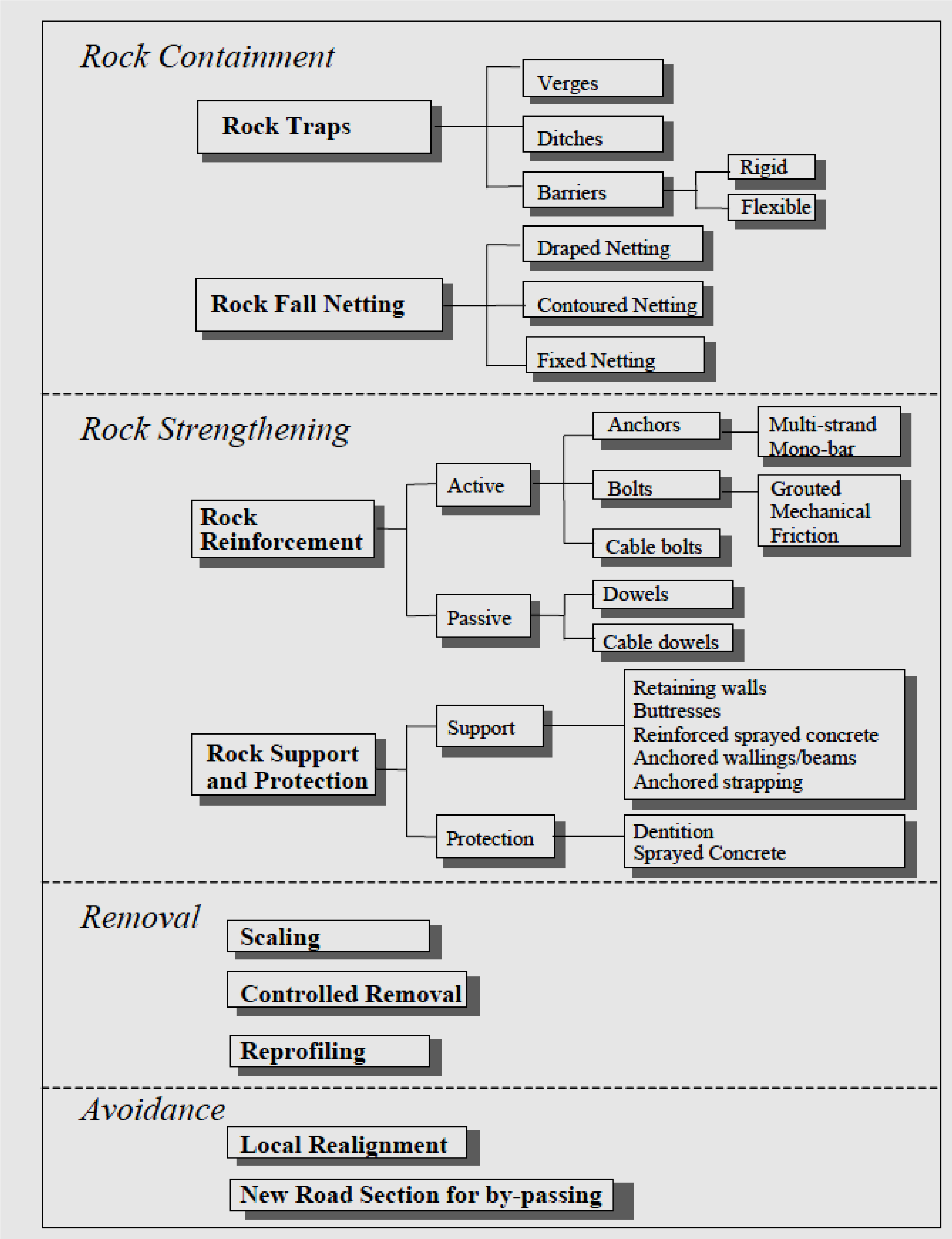


Fig. 5.5: Rock slope failure mitigation measures (TRL, 2011)

Option	Description	Risk Reduction	Outside Right-of-Way	Required Ongoing Maintenance	Anticipated Service Life (Years)	Construction Impact	Construction Difficulty	Construction Duration (days)		Cost ($1,000)		Aesthetic Impact
								Low	High	Low	High	
I	No Action	None	No	Status Quo – Periodic Rock Removal	N/A	None	N/A	0	0	0	0	Low
II	**Warning** - Install Rockfall Warning Fence	Low	May Require TCE	Status Quo + Periodically Repair Fence	20	Low – Shoulder Closing	Moderate	30	60	1,373	4,118	Moderate
III	**Monitoring** – Inclinometer, Tiltmeters, and/or Routinely Scheduled LiDAR Survey	Low	May Require TCE	Status Quo + Maintain Monitoring Equipment	20	None	Moderate	30	60	1,290	3,869	Low
IV	**Removal** - Trim blasting and Rock Removal Using Airbags and Scaling	Moderate	May Require TCE	Moderate – Periodic Rock Removal	20	Low – Local Detour Required	High	30	60	3,131	9,392	Moderate
V	**Reinforcement** – Install Tensioned Rock Bolts, Dental Concrete, and Anchored Mesh	Moderate	May Require TCE	Moderate – Periodic Rock Removal	20	Moderate – 1 Lane	High	150	300	4,513	13,538	High
VI	**Protection** – Install Hybrid System Barrier at Crest of Lower Slope and Draped Mesh below, or Draped Mesh with Sacrificial Fences	Moderate	No	Moderate– Periodic Rock Removal	20	Moderate –1 Lane Required	Moderate	150	300	5,043	15,129	High
VII	**Protection** – Raise Roadway Elevation or Shift Roadway West to Create Catchment	High	No	None	75	Moderate – Lane Shift	High	150	300	5,396	16,188	Moderate
VIII	**Protection** – Rock Shed over Road	High	No	None	75	Moderate – Lane Shift	High	180	360	8,564	25,692	High
IX Fig. 6-3	**Combination** – Localized Trim Blasting, Reinforcement of the Devil's Tea Table and Shotcrete or Dental Concrete.	High	May Require TCE	Low – Periodic Rock Removal	20	Low – Local Detour Required	High	150	300	6,178	18,534	High

Color Key: Desirable | Neutral | Undesirable

Fig. 5.6: Exemplary: chart to evaluate protection measures for a certain rockfall prone area (HNTB, 2015)

6 References

Arndt, B.; Arpin, B.; Higgins, J.D. & Thompson, P. (2015): Guidelines for certification and management of rockfall fence Systems, *Report*, National Cooperative Highway Research Program, Project 24-35

ASTRA (Bundesamt für Strassen der Schweiz) (2007): Einwirkungen infolge Lawinen auf Schutzgalerien, *Richtlinie*, Bundesamt für Strassen der Schweiz, ASTRA 12 007.

ASTRA (Bundesamt für Strassen der Schweiz) (2008): Einwirkungen infolge Steinschlags auf Schutzgalerien, *Richtlinie*, Bundesamt für Strassen der Schweiz, ASTRA 12 006.

Bichler, A.; Stelzer, G. & Hamberger, M. (2017): Technical protection against rockfall – design, monitoring and maintanance according to the Austrian guideline ONR 24810, *GeoRessources Journal*, 4: 16-21

Cala, M. et al. (2012): TECCO slope stabilization system and RUVOLUM dimensioning Method, Geobrugg AG, Switzerland, 240 p.

EOTA (European Organisation for Technical Approvals) (2013): Guideline for European technical approval of falling rock protection kits, ETAG 027, Brussels.

FOEN (Federal Office for the Environment) (2016): Protection against Mass Movement Hazards. Guideline for the integrated hazard management of landslides, rockfall and hillslope debris flows. Bern. The environment in practice no. 1608: 97 p.

GEOH (2003): Guidelines on the use of prescriptive measures for rock cut slopes, Geo Report No. 161, Government of Hong Kong, Geotechnical Engineering Office

Grošić, M.; Arbanas, Z. & Udovic, D. (2010): Designing and construction of rockfall barriers – Experiences in Republic of Croatia, in: Vrkljan: Rock engineering in difficult ground conditions, 703-708

HNTB (2015): Rockfall hazard mitigation report, Route 29 Rockfall Mitigation MP 27.31 to MP 30.43, State of New Jersey, Department of Transportation, 93 p.

JRA (2000): Manual for countermeasures against rockfall, Japan Road Association

JICA (2009): The study on disaster risk management for Narayangharh-Mugling Highway, GED-JR-09-014, Japan International cooperation agency, Nippon KOEI Co. Ltd.

Lambert, S. & Bourrier, F. (2013): Design of rockfall protection embarkments: A review, *Engineering Geology*, 154: 77-88

Lambert, S. & Kister, B. (2017): Analysis of existing rockfall embankments of Switzerland (AERES), Part A: state of knowledge, Publ. Lucerne University of Applied Sciences, 55 p.

MBIE (2016): Rockfall: Design considerations for passive protection structures, MBIE guidance, section 175, building act 2004, New Zealand

ÖGG (2014): Empfehlung für das Schutzziel bei gravitativen Naturgefahren in Österreich, ÖGG Salzburg

OHT (2011): Rock slope design guide, Ohio Department of Transportation

Ortigao, J.A.R. & Sayao, A.S. (2004): Handbook of Slope Stabilization, Springer, 483 p.

Peila, D. & Ronco, C. (2009): Technical Note: Design and rockfall net fences and the new ETAG 027 European guideline, *Nat. Hazard Earth Syst. Sci*., 9: 1291-1298

Robles, J.M.; Peña, Á. & Pinto, H. (2016): Dynamic barriers for protection against rockfall, *Revista de la Construcción*, 15(3): 27-37

Stelzer, G. & Bichler, A. (2013): ONR 24810 – A comprehensive guideline for rockfall protection works: its application to catchment fences, *Proc. GeoMontréal*, Montréal

Schellenberg, K. & Vogel, T. (2009): A dynamic design method for rockfall protection galleries, *Structural Engineering International*, 3: 321-326

TRL (2011): Rock engineering guides to good practice: rock slope remedial and maintenance works, PPR555, Transport Research Laboratory, Great Britain

Vogel, T., Labiouse, V.; Masuya, H. (2009): Rockfall protection as an integral task, *Structural Engineering International*, 3: 304-312

Volkwein, A.; Schellenberg, K.; Labiouse, V. & Agliardi, F. (2011): Rockfall characterization and structural protection - a review, *Nat. Hazard Earth Syst. Sci.*, 11: 2617-2651

Volkwein, A.; Gerber, W.; Klette, J. & Spescha, G. (2019): Review of approval of flexible rockfall protection systems according to ETAG 027, *Geosciences*, 9(1):49.

WSTC (2005): Design guidelines for wire mesh/cable net slope protection, WA-RD 612.2, Washington State Transportation Commission

Xu, H.; Gentilini, C.; Yu, Z.; Qi, X. & Zhao, S. (2018): An energy allocation besed design approach for flexible rockfall protection barriers, *Engineering Structures*, 173: 831-852