Chapter 9

Rockfall Hazard: A Comprehensive Review of Current Mitigation Practices

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Abstract This chapter discusses the kinematics of a rockfall which forms the framework for the selection of mitigation strategies. It is followed by a detailed discussion of various mitigation strategies used to arrest or divert the falling rock and reduce the economic damage and loss of lives in mountainous regions. The mitigation strategies of rockfall protection can broadly be categorised into active and passive measures. Mitigation practices using draped meshes, anchors, and grouting are active measures, while practices using embankments, flexible barriers, rock sheds, catch ditches, and forests are categorised under passive measures. The various design approaches typically used for analysing and designing these mitigation measures are also discussed briefly in this chapter. A concise discussion of the limitations of these measures is also provided to aid the practitioners in selecting an adequate mitigation strategy. The primary objective of this chapter is to provide a thorough understanding of the rockfall and current mitigation practices employed in the field for the practitioners involved in hilly infrastructure projects. The comprehensive discussion on the current rockfall mitigation practices could also serve as a potential framework for future improvements in their respective design.

Keyword Rockfall · Kinematics · Mitigation measures · Active measures · Passive measures

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9.1 Introduction

Rockfall is one of the most dangerous landslide types in mountainous regions due to its high mobility and impacting energy. Primarily occurring in areas of heavy precipitation and frequent earthquakes, rockfall is initiated from the rock face due to discontinuities, pore water pressures, and weathering phenomena (Budetta 2004). The complete mechanism of rockfall involves two stages: First, the detachment of rock blocks from the steep slope and, second, the propagation of the rock blocks down the slope (Cruden and Varnes 1996). Thus, rockfall is the rapid downslope movement of one or a few rock blocks of varying size (Vilajosana et al. 2008; Antoniou and Lekkas 2010) through free-falling, bouncing, or rolling/sliding motions (Varnes 1978). Detached rocks from steep slopes can attain high velocity and energy during the downslope movement and can travel large runout distances, resulting in significant fatalities, even though the volume of mobilized rock mass is very low (Fanos et al. 2018; Moos et al. 2018; Li et al. 2019).

Rockfall events pose a hazard through direct impact and the deposition of rock fragments, thus, hindering the traffic flow. This hazard can be mitigated by stabilizing the fragmented materials on the slope or using countermeasures at the toe of the slope, which can protect the infrastructures downhill. However, these protection measures can only be effective when the travel paths of the falling blocks are well-defined and the simultaneous fall of only a few blocks is expected. The size of falling rocks is not too large, and the source area of potential fall materials is large in extent. Effective and efficient countermeasures can mitigate the effect of rockfall impact on vulnerable structures, reduce economic damage, and prevent human fatalities. The present chapter discusses the details of rockfall mitigation and protection strategies. It first presents a brief overview of rockfall kinematics and its study, which forms the primary basis for designing and selecting appropriate mitigation measures. Subsequently, followed by a discussion on active and passive protection measures. The detailed discussion on passive protection measures includes their features and limitations, observations of various experimental and numerical studies conducted on these mitigation measures, and various design approaches typically used for analysing and designing them. The prime aim of this is to present and discuss the current rockfall mitigation practices employed in the field and to provide a potential framework for their selection and design.

9.2 Rockfall Kinematics and Mitigation

According to Corominas (2013), three main techniques are employed to mitigate the rockfall hazard: (a) rockfall risk reduction by the use of stabilization and reinforcement works, (b) restricting and obstructing the rock mass propagation via protective structures with the resulting decrease in its velocity, magnitude, and runout distance, and (c) protect the exposed elements at risk. For the last two techniques, the parameters of the dynamics of the rocks, such as the velocity, kinetic energy, impact height, and runout distance, must be assessed at the exposed regions. Recent techniques for assessing these parameters use numerical simulations for performing rockfall trajectory analyses. The capacity and efficacy of rockfall protective measures depend on the accurate assessment of these parameters and, thus, form the basis for their selection and design. An adequate protective system is selected depending on the impact energy that the protective structure can absorb without collapse (Vogel et al. 2009). Further design of these sections is done based on the maximum bounce height of the falling rocks and for a typical factor of safety value of 1.5 (Lorentz et al. 2010). Summarily, the selection and design process for rockfall barriers must include: (1) assessing the features of the slope, material, and field conditions via geomorphological and geological survey, (2) evaluating the potentially unstable rock mass volume, (3) evaluating the expected velocity, kinetic energy, and bounce height of blocks through trajectory analysis (Bourrier et al. 2008), (4) designing the barriers as per the assessed velocity and energy, and (5) investigating the dynamic response of the protection structures impacted by rock blocks.

9.3 Rockfall Mitigation Measures

Mitigation strategies are essential where the rockfall hazards exceed tolerable limits and threaten urban areas or roads (Li et al. 2019). For gentle slopes in hilly areas (slopes < 30°), the impact of the rockfall events can be mitigated through natural vegetation cover (Calvino et al. 2001). For steeper slopes, the mitigation measures can be categorised into preventive and protective kinds. The preventive method, also known as active measures, comprises the stabilization methods of precarious rock slopes. The protective methods, or passive measures, uses interceptive structures such as flexible barriers, rock fence, draped mesh, rock sheds, and protection embankments to intercept and/or stop the rockfall in its path in the central or at the end of a slope (Vogel et al. 2009; Dhakal et al. 2011; Bertrand et al. 2012). Figure 9.1 shows the schematic representation of different zones in rockfall and commonly implemented active and passive measures on a slope. The type of mitigation measures required for a slope depends on the catastrophic potential, size, geological and environmental conditions, and the design period of the structures.

9.3.1 Active Measures

The idea of active mitigation measures is to strengthen the stability of dangerous rock, prevent it from falling, and break the chain of rockfall hazards by stopping the rock cells formation process (Chen et al. 2013). Several strengthening techniques are available to hold down the potentially loose rock on a rock-cut slope face. All

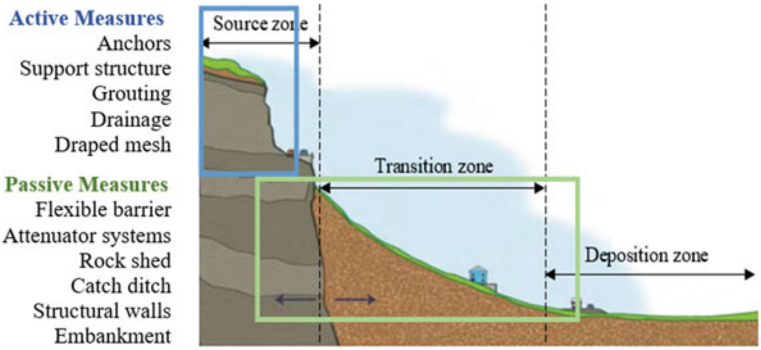

Fig. 9.1 Application of active and passive mitigation measures along a slope profile

of these techniques share the feature of minimising the loosening and relaxation of the rock mass arise from excavation and unloading activities (Hoek 1983). Thus, the active mitigation techniques are utilised to prevent the detachment of unstable rock masses, and to reduce the likelihood of the occurrence of rockfall. Active mitigation techniques include support structures, draped mesh, anchorage, grouting, drainage, and clearing and removal (scaling) of dangerous rock, among others.

9.3.1.1 Support Structures

Support techniques are used to secure the potential fall of rocks and prevent initiating in the first place. These structures, such as arches, pillars, or wall support, create supporting conditions for dangerous rock slopes and prevent them from collapse or failure (Chen et al. 2004, 2006). Under ideal circumstances, support structures are the most significant technique because of their effectiveness and minimal disturbance to the virgin rock mass slope.

9.3.1.2 Draped Mesh

Draped mesh, also known as an anti-breakup safety net, is a preventing system comprising metallic cable nets or wire meshes directly installed on eroded cliffs (Bertolo et al. 2009; Chen et al. 2013). They act primarily by covering the slope, controlling the movement of rock blocks, withstanding the punching force of falling rocks, and preventing the detached rock blocks from freely falling onto the infrastructure downhill. To accomplish these objectives, the mesh needs to be kept as near to the slope as feasible and secured at both the top and bottom of the slope. Additionally, the draped mesh may also be combined with anchors or bolts that are attached to the nets and directly affect the stability of the rock block. This system prevents the rockfall occurrence and controls the rockfall dynamics by directing the falling fragments of the rock into enclosed mesh regions. When the release area is small, and the anticipated rockfall bounce height or kinetic energy is excessive, this type of rockfall mitigation measure offers an effective alternative to rockfall fences or flexible barriers. It can be used in a variety of situations, including when the degree of fragmentation is high or when localised unstable blocks are highlighted. The draped mesh is primarily subjected to a static force that is resisted by the wire mesh and the anchoring system.

9.3.1.3 Grouting

Rock grouting techniques are mainly used for repairing cracks and fractures in rock slopes. Rock grouting is essentially waterproofing a rock mass where there is a network of flow channels, cracks, and excessive fragmentation. It can strengthen the integrity and shear strength of cracked rock mass. If fissures and cracks are densely covered, pre-grouting is required, but grouting with high pressure is not advisable. Grouts are also used for in-situ reinforcement with rock anchor nails and bolts.

9.3.1.4 Anchors

A quick and efficient technical method for controlling rockfall occurrence is anchoring the unstable slope face (Chen et al. 2013). The three basic categories of anchor techniques are anchor bolt, anchor nail, and anchor rope. Rock anchor bolts are post-tensioned tendons inserted in drilled holes. The rock anchor bolt is divided into two segments, free length and bond length. The bond length is the embedment length inside the rock, where forces are transmitted across the surface area of the grout body and the rock. The free length is the stress-free tendon length that can remain unbounded for re-tensioning and re-grouting at any time, where force adjustment is no longer possible. Due consideration must be given to the durability and corrosion resistance of anchor bolts, nails, and ropes. According to AASHTO, unprotected anchors are utilised for short-term applications of approximately 18 to 36 months. Corrosion protection systems are considered for long-term applications with a life span of 75 to 100 years. The anchoring should be performed with minimal disturbance to the original rock mass. The length and strength of the rock anchor bolts used will depend on the size and density of the unstable rock mass as well as the geotechnical properties of the rock in the stable zone, providing the bond resistance for the anchorage. Generally, the anchor bolts and nails are made of solid thread bar systems, which include a bar, plates, couplers, and nuts. To link unstable rock to stable portions beyond the face, steel thread bars must be able to withstand both tensile and shear loads. An increase in design load or the existence of a weak rock necessarily results in larger diameters or longer lengths of bolts. Also, rock anchors alone cannot secure the weathered or fragmented rocks. However, incorporating a high tensile strength steel mesh facing will likely reduce the quantity of rock anchor bolts, ropes and nails required and be highly effective for stabilizing weathered or fragmented rocks.

9.3.1.5 Drainage

Drainage is vital for increasing the stability of vulnerable rock slopes, as the pore water pressure is one of the contributing factors to rock slope instability. It generally comprises both surface and subsurface drainage. Constructing drain holes at the bottom of the slope to create a network of water outlets is the conventional technique for lowering pore water pressure. The crucial parameter in constructing drain holes is to place them to intersect the fractures carrying the water. A perforated casing is used to line the drain holes, with the perforations sized to reduce the infiltration of fine particles that are washed from fracture infillings. The disposal of seepage water is another crucial parameter of drain hole construction. If pore water is permitted to infiltrate the toe of the slope, it may cause low-strength materials to deteriorate or create more stability issues downstream of the drains. It might be essential to collect all the seepage water and dispose of it away from the slope. If surface runoff infiltrates exposed cracks, it is beneficial to construct diversion ditches behind the top of the slope and seal the cracks with plastic sheeting or clay. For large slides, it may be impossible to substantially decrease the water pressure in the slope by small drain holes. In such situations, a drainage tunnel can be driven through the base of the slide slope and, subsequently, drill a set of drain holes into the saturated rock.

9.3.2 Passive Measures

Rockfall simulation and risk analysis are effective and convenient for proper land-use planning in hilly areas. However, when the land-use planning does not control the rockfall hazard or damage to the existing infrastructure, selecting appropriate passive mitigation structures, size, and positioning is desirable (Vogel et al. 2009). Passive protective structures act as obstacles to the runout path of the falling rock mass. These structures do not directly interfere with the rockfall occurrence mechanism but control the dynamics of moving rock blocks. Hence, this type of structure is primarily subjected to dynamic/impact loads and includes forests, embankments, structural walls, flexible barriers, and rock sheds. The preference between these structures is primarily governed by the kinetic energy of the rocks and topographical conditions, as shown in Fig. 9.2 (modified after Sun et al. 2016).

9.3.2.1 Forests

The protective nature of mountain forests against rock falls is a natural and cost-effective protection measure. Forests have traditionally been crucial in maintaining

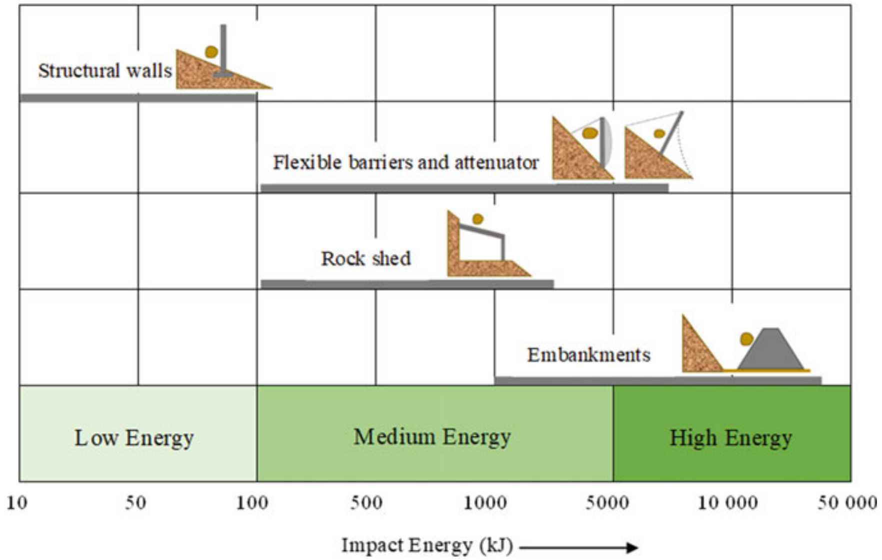

Fig. 9.2 Range of energy capacities for various passive measures

valleys in mountainous areas safe for habitation and travel by reducing the velocity and quantity of falling rock blocks reaching the toe of the slope. However, the region receiving direct protection from the forests is typically small, located below and near the forest. The forests effectively significantly reduce the impacts of rockfall for rocks up to a size of 5 m^3. Three distinct but sometimes overlapping zones can be identified on a slope where rock falls occur: the source zone, the transition zone, and the deposition zone. In the source zone, where blocks are detached, the forest does not perform a significant protective role apart from basic root-holding and water regimentation activities. In certain situations, forests may serve as rockfall-causing factors. The tree roots can get into fractures and increase the effects of frost wedging. Furthermore, roots can produce acidic exudates, which, when mixed with litter, can weather and corrode rocks (in the case of conifers). In addition, when trees sway or are uprooted by severe winds, they can release the pebbles they had been holding. In the transition zone, rocks propagate down the slope through falling, bouncing, rolling, and sliding motions. In this zone, trees work as energy-dissipating components; when the falling rock blocks strike the tree stems, they lose energy (Dorren and Berger 2006; Bertrand et al. 2013). Additionally, the impact against a tree may cause a falling rock to deviate from its travel path or even come to a stop. In the deposition zone, the speed of the rocks either decreases (when the slope diminishes to less than 30°) or comes to a stop (when the slope becomes gentler than 25°). In this terminal zone, the forest may perform a crucial part in reducing rock travel track length by slowing down the rock blocks, similar to the transition zone. The forest can be highly efficient in this zone as the kinetic energy or velocity has already decreased. Thus, even small trees can stop large rocks in the zone of deposition.

9.3.2.2 Flexible Barriers

Among the various types of rockfall protective structures developed since 1951, flexible protective measures show excellent capabilities against rockfall hazards. A cost-energy trade-off study by Yoshida (1999) shows that flexible rockfall barriers are the most attractive substitute for low-to-medium impact energies (<500 kJ) of rockfall events. The flexible protective structures with energy dissipator devices can effectively diminish the damage caused by the rockfall hazard (Peila and Ronco 2009). Rockfall protection fences are extensively employed to protect roadways, rail lines, and structures downstream of a steep slope from falling rock masses of impact energy up to 1,000 kJ and maybe more. A flexible protection barrier has wide protective capacity values varying between 50 and 8,000 kJ (Yang et al. 2019). Flexible protection mainly consists of four components: interception structure, energy dissipators, connecting components, and support cables (Liu et al. 2017), usually made up of metallic elements like nets, cables, and posts (EOTA 2008; Volkwein et al. 2019) as shown in Fig. 9.3. When the flexible barrier is impacted by rockfall, the flexible cable net transforms from a loosed state to a tight state to diffuse the impact force. The complex performance of flexible barriers or fences is characterized by several factors, including huge deflection, dynamic impact, sliding, and contact and/or detachment between components (Yu et al. 2018). Studies reveal that the large deflection of flexible barriers mainly consists of three parts: sliding movements between the components, inelastic deformation, and elastic deformation (Peila et al. 1998; Grassl et al. 2003; Gottardi and Govoni 2010). The plastic deformation of energy dissipation elements is the main cause of energy absorbed due to the inelastic deformation and accounts for 60 to 80% of the entire impact energy on the structure (Grassl et al. 2003). These barriers are usually installed at an inclination to obtain an impact angle of 60° between the barrier and rockfall trajectory (Gerber 2001) or 20° between the barrier and the slope (EOTA 2008).

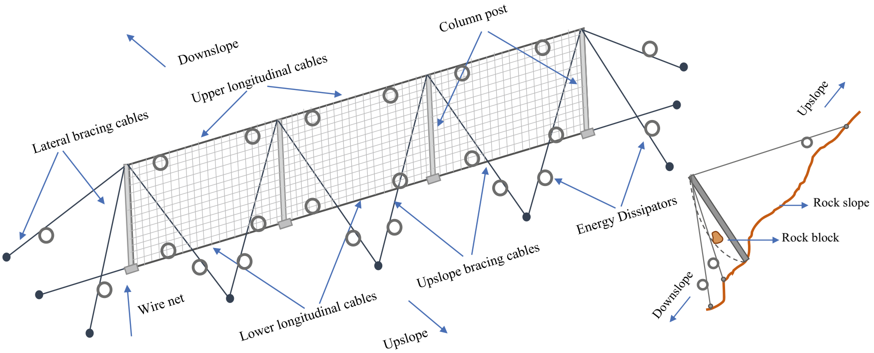

Fig. 9.3 Schematic of rockfall protection flexible barrier

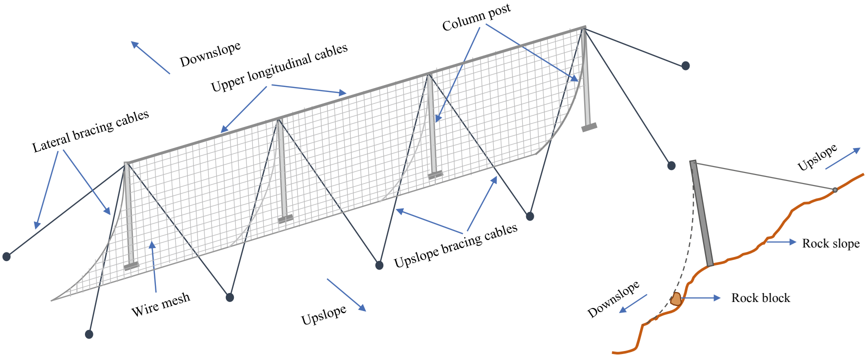

Fig. 9.4 Schematic of rockfall protection attenuator system

9.3.2.3 Attenuator Systems

The studies on rockfall flexible barrier structures have either focused on assessing the performance of flexible barriers (Peila et al. 1998; Gottardi and Govoni 2010; Mentani et al. 2016), or on the performance of the ring nets (Bertolo et al. 2009; Buzzi et al. 2015) and energy dissipators (Castanon-Jano et al. 2017). Over the period, these structures have undergone configuration modifications to improve their capacity and compensate for their limitations. As a result, new flexible rockfall mitigation structures with 5,000 kJ of capacity have been introduced called attenuator or hybrid barrier-drape systems (Badger et al. 2008) in the USA and "pocket-type rock-net" (JRA 2000; Tajima et al. 2009; Dhakal et al. 2011) in Japan. These structures can reduce the damage that occurs due to high-energy rockfall, catch it, and direct it to downslope in a controlled way (Bertrand et al. 2012). A hybrid or attenuator structure is a type of flexible fence system with characteristics of traditional rockfall catchment fences and drape mesh systems used to mitigate rockfall hazards. These are composed of flexible wire nets designed to capture the fallen rocks in the intercept net and to diminish the energy of detached falling blocks. The flexible wire netting is suspended from steel posts with hinged bases (Yang et al. 2019), as shown in Fig. 9.4. Each post is supported with four support cables anchored to the rock face with cable loop anchors and cement grout (Wyllie 2014). Attenuators also include a draping net known as a "tail". Rocks impacting the attenuator system pass under the tail, forcing the blocks to impact the slope surface and losing energy with each impact. Thus, a large structural deformation is not required for energy dissipation, enabling it to be installed on steep slopes next to roads and railways.

9.3.2.4 Rock Sheds

The rock shed, also known as rockfall protection gallery, is a crucial mitigation measure for reducing damage from the regular occurrence of rockfall events on transportation infrastructure on steep hills. There are primarily two types of rock shed structures: the conventional rock shed (Schellenberg et al. 2012) shown in Fig. 9.5, and the structurally dissipating rock shed (SDR) (Delhomme et al. 2007) shown in Fig. 9.6. The conventional rock shed structures consist of a concrete slab covered with a cushion layer of either sand or gravel (Pichler et al. 2005; Schellenberg et al. 2008; Zhao et al. 2018). The cushion layer acts as an energy dissipator and enables the design of the shed under an equivalent static impact load. However, these cushion layers do have certain drawbacks, including their large weights, difficulties in maintenance, and inadequate buffering capacity. Moreover, it is essential to use a thick cushion layer to meet the actual requirements, which raises the construction cost and results in high dead loads. In place of soil cushion layers at the top of the rock shed, recently developed metal energy dissipators have been successfully installed to improve the impact resistance capacity of rock sheds. These structurally dissipating rock shed (SDR) developed by Mougin et al. (2005) and Delhomme et al. (2007) directly absorbs the impact shock energy through plastic deformation of the RC slab in the center, and buckling of the fuse supports during shocks. Even though SDRs have 1.8 times higher shock absorbing capacity than conventional rock sheds, many times, fuse supports do not buckle without a significant threshold load which causes significant damage to the reinforced concrete slab. The SDRs also enable quick and easy repairs for local impact damage by either replacing and reconstructing the localised damaged concrete or replacing damaged supports. Yong et al. (2019) introduced the graded dissipating inclined steel rock shed (GDISR) (Fig. 9.7), a novel form of rock shed system that is cheap, simple to build, quick to repair, and high efficiency against impact. Compared to conventional and SDR sheds, the GDISR shed slabs are inclined, made of steel, and covered with the energy-dissipating layer (EDL). Additionally, energy-dissipating bumpers (EDB) are used as fuse supports beneath the slab. Overall, compared to other passive rockfall protection structures, rock sheds provide a feasible solution for both medium- and high-energy rockfall impacts (~3,000 kJ) (FEDRO 2008).

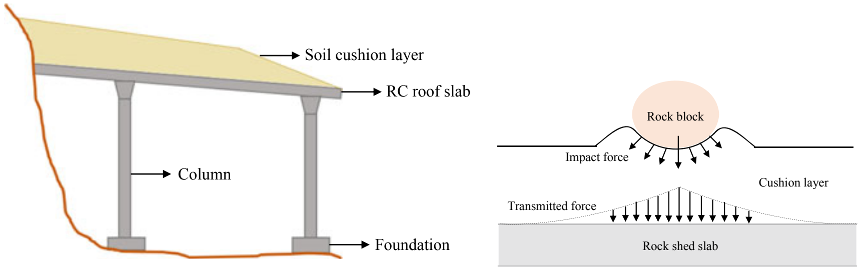

Fig. 9.5 Schematic conventional rock shed for rockfall protection

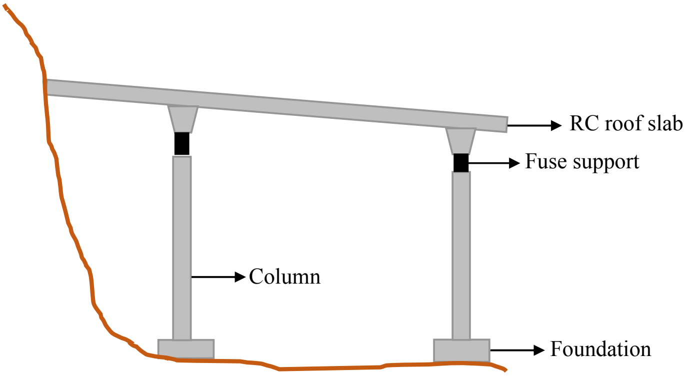

Fig. 9.6 Schematic of structurally dissipating rock shed (SDR)

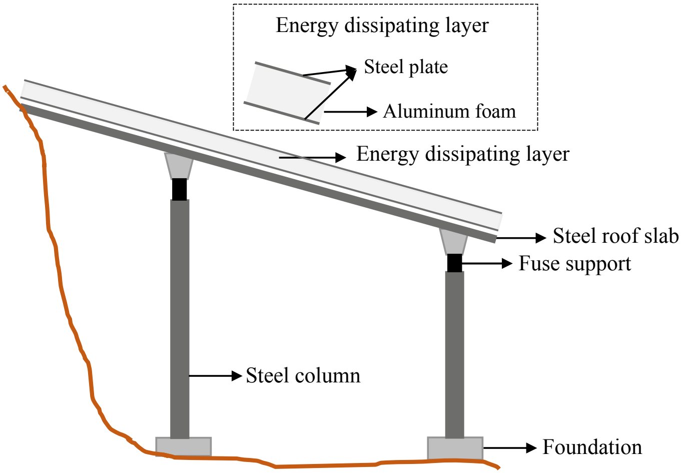

Fig. 9.7 Schematic of graded dissipating inclined steel rock shed (GDISR)

9.3.2.5 Structural Walls

A structural wall is a rigid steep-faced structure made of timber, steel, concrete, and gabion basket. It often has a lower footprint and cross-section area compared to the earthen embankments (Bourrier et al. 2011), as shown in Fig. 9.8. These walls are typically appropriate for lower energy impacts as they are made of stiffer materials (concrete, timber, steel). Instead of dissipating the kinetic energy of falling rocks like flexible nets, structural walls absorb the entire residual kinetic energy and the major portion of the impact. This results in the breaking and destruction of the structures under high-impact loads. Concrete structural walls are adequate for protection when the impact energy is between 60 and 100 kJ (Descoeudres et al. 1999). Concrete walls can also be used along with catchment ditches. If the falling rocks engage

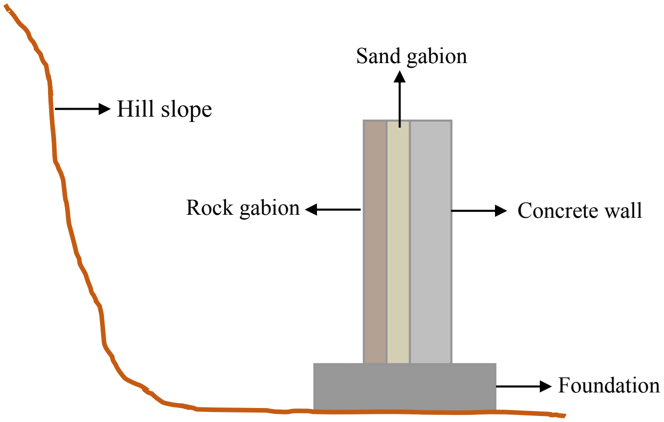

Fig. 9.8 Schematic of rockfall protection structural wall

with the ditch before impacting the wall, the residual energy on the wall is likely to be low; hence, severe damage or collapse of the walls can be prevented. When the rockfall energy surpasses the wall's structural capacity, local and global failures of the walls may happen. Therefore, high-energy rockfall events cannot be stopped by small-sized structural walls. Concrete wall with gabion facia is another common form of installation to provide protection. The primary purpose of a gabion cushion is to prevent localised damage to the protective surface of the structure near the point of contact and to enhance the concrete surface's ability to withstand impacts (Heymann et al. 2011; Lambert et al. 2014; Ng et al. 2016).

9.3.2.6 Embankment

Embankments are extensively used in both mining and civil engineering applications to protect roads and inhabited areas in hilly areas from high-energy rockfall events. These are made up of various components. Three visible sides of the embankment are named upstream side, downstream side, and crest (Calvino et al. 2001), as shown in Fig. 9.9. The major role of the upstream side is to absorb the impact energies of falling rock blocks while maintaining the structural integrity of the embankment, even under multiple impacts. Upstream sides are generally reinforced and are constructed at a slope of 60° or more to ensure stability, and downstream sides comprise a soil abutment of 35° to ensure the stability of the embankment under the rockfall impact. The crest thickness should also be significant, but no exact guidelines are available for this parameter, except that it should be large enough. Various forms of rockfall protection embankments made from compacted soil, reinforced earth, large rock blocks or gabions, etc., have been described (Peila et al. 2007; Kister and Fontana 2015). Originally, ordinary embankments or earthen embankments made of compacted natural soils were designed to obstruct rock impact energies between 1,000 and 5,000 kJ. At

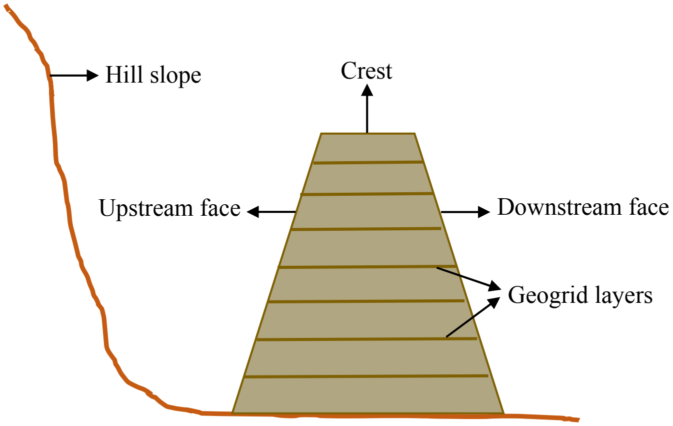

Fig. 9.9 Schematic of rockfall protection reinforced embankment

the end of the 1980s, the concept of ground-reinforced embankments was introduced to resist high energy impacts, even up to 100 MJ (Morino and Grassi 1990). These reinforced embankments for rockfall protection are made from a variety of internal reinforcing elements (such as rip-rap, wood or steel bars, wire mesh, tires filled with compacted soil, and geosynthetic materials) and appropriate facing components (soil, geosynthetics, and rip-rap) designed to resist the high impact energies (Ronco et al. 2009). Over the past two decades, a variety of these embankments have been successfully implemented. The use of reinforcing elements has reduced both their visual impact and footprint (Morino and Grassi 1990; Jaecklin 2006; Brunet et al. 2009; Lorentz et al. 2010). These reinforced embankments have displayed exceptional performance in withstanding external loads owing to their ductile nature due to the closely-spaced reinforcing elements. This ductile nature allows high deformation and compaction in the embankment, thus enabling high absorption of impact energy.

Rockfall protection embankments are preferred over flexible barriers or fences when the energy of impact exceeds 5,000 kJ (Descoeudres et al. 1999). The other benefits are low construction and maintenance expenses and reduced visual impact (Peila et al. 2007; Brunet et al. 2009; Lorentz et al. 2010; Lambert and Bourrier 2013; Lambert and Kister 2018; Kanno et al. 2021). However, these are not suitable for steep slopes and usually require a wide area for construction and easy access for large vehicles. Typically, they have a trapezoidal cross-sectional shape. But in some cases, the concrete wall, prefabricated concrete components, or gabion baskets are used to steep the upstream side (Paronuzzi 1989).

9.3.2.7 Catch Ditches

Catch ditches are a very effective rockfall protection structure with a much less construction cost and a minimal environmental impact (Davis and Shakoor 2005).

These engineered ditches often referred to as rockfall catchment areas are intended to capture and stop falling rock blocks before they impact the vulnerable structure. This technique is often employed along travel paths where the available space and slope geometry permits its construction. When there are constraints on the availability of space, barrier systems may be integrated with catch ditches.

These ditches aim to stop and capture falling rocks by reducing the kinetic energy on the slope profile before reaching transportation routes and inhabited areas (Yepes et al. 2020). The most important aspect of maintaining the efficiency and reliability of the well-designed engineered catch ditch is that it must remain accessible to machinery to remove accumulated rocks regularly. Though rockfall catch ditches exist in various geometrical configurations, the general cross-section of the catch ditch is shown in Fig. 9.10. The currently used design criteria for ditch design assumes the rock-cut slope to be fairly uniform. Natural rock slopes or rock-cut slopes with warping may have undulations that allow initiation of block detachment, causing the blocks to travel far from the toe of the hillslope. The location, shape, depth, and width of the trench are some of the most important parameters to take into account when designing a catch ditch. Therefore, it is important to know the rockfall trajectory, bounce height, impact location, and other relevant dynamic parameters of rocks for designing a rockfall catch ditch. These are the most common and aesthetically pleasing forms of protection since they do not obstruct the view of the surroundings. However, when a wider ditch is constructed on a steep slope, the rock slope cut height may be excessive. Increasing the ditch width could also potentially result in a significant increase in slope height, which would affect its overall stability.

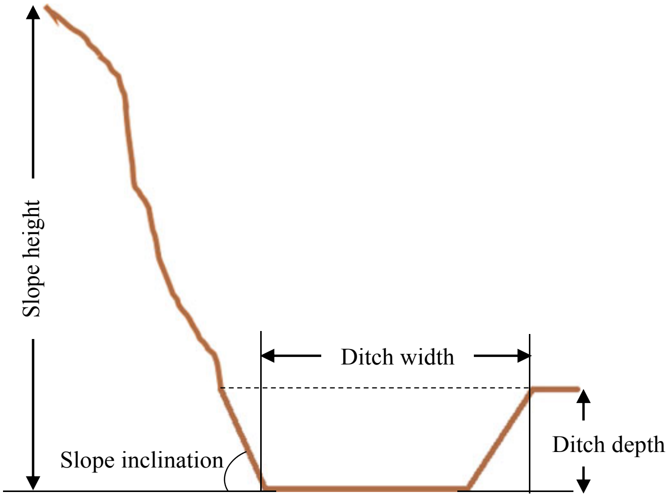

Fig. 9.10 Schematic of rockfall protection catch ditch

9.4 Design Approaches

9.4.1 Analytical Approach

9.4.1.1 Flexible Barrier

Flexible barriers consist of steel wire nets, support cables, posts, and energy-dissipating components and are widely used as natural hazard protection measures. These barriers undergo large deformation to provide energy dissipation. When falling rock strikes the barrier, the impact force is first transmitted to the wire nets and, after that, to the support cables to which energy-dissipating components are installed, resulting in inelastic distortion in these components. The entire process is represented by highly nonlinear mechanical characteristics considering significant sliding, large deformation, contact, detachment, and material yielding. The conversion of work into energy, as shown in Eq. 9.1, is a key part of this process.

$$\frac{1}{2}mv^2 + \mathrm{E}_g = \int_0^{S_{max}} \mathrm{F}(s)ds \tag{9.1}$$

$$\mathrm{E}_{total} = \alpha \mathrm{F}_{max} s_{max} \tag{9.2}$$

where, E_g is the gravitational work after the impact between falling rock and barrier and is dependent on buffer distance; m is the mass of the falling rock; v is the velocity of rock; F is the impact force; s is the deformation; E_{total} is the total energy of the rock; and α is the coefficient obtained from the experiments, ranging from 0.3 to 0.35.

Ye et al. (2010) investigated the rock shape and size influence on the motion modes, velocity, and runout distance and proposed the computation approaches for the impact force based on the impulse theorem. Abad et al. (2013) evaluated the internal force of the supporting cable under the impact force and the vector form of the tangent stiffness matrix. Therefrom, a straightforward method was proposed to analyse the structure of the cable unit, and afterward, a good outcome that more closely matches the actual stress state was obtained by simulating support cables or anchor ropes using a cable unit. Wang et al. (2010) analysed the influence of a single support cable and the net on rockfall and also proposed a computation method for evaluating the resistance capacity of cable nets in rockfall protection. Hambleton et al. (2013) developed the formula for estimating critical velocity and energy by condensing the nets into a two-dimensional model. Liu et al. (2016) proposed a critical preload calculation method based on the energy principle that can be used when the decompression ring is constructed.

9.4.1.2 Rock Shed

The present methods for calculating the rockfall impacting force on reinforced concrete structures are generally developed from the traditional Hertz contact law based on elastic theory. Though, since the rock sheds show signs of plastic deformation, the contact theory has been improved to incorporate this. Thornton (1997) proposed that the normal interaction becomes plastic when the 'limiting contact pressure' reaches the center of the contact region. Vu-Quoc et al. (2000) provided a precise method for the normal force–displacement relation for interacting spherical particles by considering plastic deformation. Since the dynamic response of the rock shed impacted by rock blocks is related to the mechanical features of the rock shed as well as the rockfall characteristic, many researchers combined the Hertz contact theory with rock shed dynamic components to develop the dynamic model for the rock shed. Olsson (2003) developed a Hertz contact theory-based analytical method for delamination initiation and growth under the small mass impact on orthotropic laminated composite plates. Zheng and Binienda (2007) analysed the permanent indentation and central displacement effect on the laminated composite plate under small mass impact loading using the elastoplastic contact theory and also proposed closed-form solutions for the contact force. Wang et al. (2020) established a theoretical computation technique for the rockfall penetration depth and impact force by taking into account the gravel soil strengthening coefficient.

9.4.1.3 Embankments

The embankments are typically designed with simplistic approaches. These include (a) the *Pseudo-Static Approach* which considers a force that is statically equivalent to the dynamic impact force (Jaecklin 2006; Kister and Fontana 2011; Brandl and Adam 2000); (b) *Penetration Criteria-Based Approach* that calculates the rock block penetration into the embankment, and evaluates the minimum embankment thickness by multiplying it with a factor of 2–3 (Brunet et al. 2009); and (c) *Energy Balance Approach* which evaluates the blocking incident translational kinetic energy dissipated in the embankment during the impact. In the *Pseudo-Static Approach,* a safety factor is taken into account for representing the uncertainties related to the theory of a statically equivalent loading. The static stability of the embankment is checked by considering this force combined with the gravity forces. In *Energy Balance Approach,* the friction along shear planes is the first energy dissipation mechanism, assuming that a portion of the embankment deforms like a rigid body (Tissières 1999; Brandl and Adam 2000). Numerous shear planes might be taken into account, particularly along the reinforcement layers (Ronco et al. 2009). The dissipation of energy due to soil compaction is also taken into account (Ronco et al. 2009). The design determines the structural deformation needed to dissipate the kinetic energy of rockfall is compatible with the size of the embankment. For this purpose, the impact force can be used to calculate the upstream deformation due to the block penetration (Ronco et al. 2009). All these approaches typically include finding out the impact force or the block penetration. For this purpose, various formulas or methods have been used. Kar (1978) and Paronuzzi (1989) developed an expression for evaluating the penetration that can be modified for consideration of reinforcement layers. The expressions provided by Mayne and Jones (1983), Labiouse et al. (1996), or Montani (1998) can be used to estimate the impact force (Jaecklin 2006; Peila et al. 2007; Ronco et al. 2009). The soil parameters taken into account in these expressions were acquired through static testing and mostly related to the elastic response of soils. In addition, the impact force can also be used to determine the block penetration, δ, (Carotti et al. 2004; Peila et al. 2007; Ronco et al. 2009), as shown in Eq. 9.3.

$$\delta = \frac{mv^2}{\mathrm{F}_{max}} \tag{9.3}$$

where F_{max} is the maximum impact force, m is the mass of the rock block, v is the block velocity just before impact, and δ is the block penetration in the embankment. This relation shows that for a given velocity, the higher the penetration, the lower the impact force.

9.4.1.4 Catch Ditch

Based on slope inclination and height, Ritchie (1963) proposed tables and design charts for catch ditches for calculating the minimum width and depth of the ditch and determining the rockfall impact position as a function of the slope steepness and height. Ritchie (1963) also found out the rockfall motion characteristics and suggested a depth up to 2 m and variable width flat-bottomed ditch connected to the road by a constant slope of 1.25H/1V. The given design chart and the FHWA (1989) modification of it represent a significant advancement in the design of roads and rail lines protection. However, Ritchie´s model have some drawbacks: (a) it does not provide cost criteria permitting for the selection of appropriate rock retention capacity for each slope segment; (b) it only provides outcomes for a particular shape ditch (i.e., trapezoidal ditch); and (c) this steep-sloped, deep ditch design makes it challenging for vehicles to return safely to the road and tough to maintain the road margins.

9.4.2 Experimental Approach

Experimental studies help comprehensively analyse the dynamic impact mechanism of falling rocks. Over time, numerous researchers have performed laboratory and field experiments on prototype, small-scale, or real-scale models of the rockfall protection structures to analyse rockfall impacts. These experimental studies have been performed not only to develop an understanding of the rockfall impact but also to calibrate interaction models among the falling rock and protection structures for parameters such as the impact force, maximum impact energy, impact height, energy dissipation, and maximum structural deformation. But the drawback of these experimental studies is that they only allow the study of a limited number of variations for both the geometries and impact energies due to their complexity.

9.4.2.1 Flexible Barrier

For the testing of flexible barriers, two distinct arrangements are mainly possible depending on how the falling rock is accelerated, namely, vertical drops and inclined guidance of test blocks (Gerber 2001). A summary of experimental testing of flexible barriers to withstand rockfall up to 2008 can be found in Thommen (2008), and the experimental procedures have not greatly changed since then. Tajima et al. (2009) performed real-scale experiments on the flexible barrier with energy-dissipating devices and revealed that energy-dissipating devices could effectively diminish the tension in the net as well as the impact on the steel post and make it stable. Also, the rock vertical drop experiment on the flexible barrier conducted by Gottardi and Govoni (2010) revealed that runout length data of the energy-dissipating devices on the cables help show the distribution of forces between the nets. Besides, Liu et al. (2014, 2016) performed real-scale experiments on flexible barriers subjected to rockfall impact and evaluated the total deformation of the barrier after the impact. The authors also analysed the energy dissipation and destruction mechanism of the ring-type brake energy dissipation devices and the steel column posts. The outcomes show that the steel wire net is a highly significant energy-absorbing element, and optimizing the elements is crucial for future research. Along with this, they observed that initial force in the ring-type brake energy dissipators upsurged with an increase in the thickness of the steel pipe and length of an aluminium skirt, which also improved the flexibility of the barrier systems.

Additionally, researchers also conducted a force and displacement study. Peila et al. (1998) carried out real-scale experiments to analyse the impact energy of rockfall and its influence over the flexible barrier displacement and evaluate the parameters such as the dissipated kinetic energy of rocks and the maximum probable deformation of the barrier. Tajima et al. (2010) conducted rockfall impact experiments on a single module (single span net) made from polyethylene to study the performance of the net and assess its capacity to dissipate energy using the ring-type brake and U-shaped energy dissipators. Bertrand et al. (2012), proposed the 'curtain effect,' which considers the spatial heterogeneity of stiffness and strength as well as the failure rate of the flexible barrier due to rockfall impact. Giacomini et al. (2012) observed that the steel nets in flexible barriers efficiently dissipate the energy of impacts between the falling rock and flexible barrier, resulting in a 60% reduction in the length of the impact area. Thompson et al. (2013) conducted experimental investigations on a single-span net wherein the impact force was imparted on two types of nets with hinged or fixed boundaries. In addition, a prediction of future studies was put forward about the response behavior of various types of nets. Buzzi et al. (2015) performed three small-impact tests to evaluate the effects of stiffness on force transfer in flexible nets and revealed that the higher the structure conforms to the regulation, the lesser force is transmitted to the net and the column post. Moreover, the 'bullet effect' of rockfall is investigated, and a better grid geometry has been suggested after a few experiments are carried out to examine the effect of rock block size, cable diameter, and net size on the performance of the flexible barrier.

9.4.2.2 Attenuator System

Over the past few decades, the studies are concentrated more on the testing of the attenuator systems. Here, the oblique impact is required; hence, vertical testing is not feasible, as the aim is not to stop the falling rock but to diverge or regulate its fall path or trajectory. Arndt et al. (2009) studied the mechanical behaviors and durability of the net and support cables by performing a real-scale impact test using an attenuator or hybrid flexible protection system. Giacomini et al. (2012) conducted an in-situ impact test of an attenuator system to analyse the rockfall velocity and energy distribution of the system. Some of the reported studies (Glover et al. 2012; Wyllie et al. 2017) investigated the entire process of energy dissipation and diversion of the falling path of rocks by enhancing the interface friction between rock blocks and slope surfaces during the experiments. These studies also analysed the interaction between nets and detached blocks, and the transmission of the impact force, energy dissipation, and net deformation.

9.4.2.3 Embankments

Several reported studies (Burroughs et al. 1993; Tissières 1999; Yoshida 1999; Peila et al. 2007; Lambert et al. 2014) have considered experimental approaches to understand the performance of rockfall protection reinforced embankments under rock block impact. While some studies examined the behavior of granular materials through real-scale impact tests on in-situ soil layers (Pichler et al. 2005), as well as on embankments (Burroughs et al. 1993; Peila et al. 2002). Other studies (Peila et al. 2007; Sung et al. 2008) assessed the deformation behavior of reinforced embankments under the impact. However, only a few relevant design parameters and the safe values of the energy absorption level of the embankment could be assessed. This is due to the high energy values of rock impacts in the field experiment, the limited size and shape of falling rocks, and the limited number of impacts. Small-scale or prototype experiments with kinetic energies <1,000 kJ are also reported for the embankments (Lambert and Kister 2018; Lu et al. 2021). These small-scale experiments are not only cost-saving, but the results are of great qualitative value. The kinetic energy of rocks is mostly >1,000 kJ. While the rockfall protection embankments may withstand multiple impacts of energy low to medium, small-scale experiments usually focus on determining the ultimate capacity of the embankments to withstand the block impact. Some of the reported studies also investigated the post-impact residual features to ensure the effective intercept of the subsequent rockfall (Durville et al. 2011). Though limited in number, some studies have also been carried out on geosynthetics-reinforced embankments. Burroughs et al. (1993) used rock blocks of varying shapes, masses, and sizes, and rolled them down on an actual slope before hitting the embankments. In such cases, the propagation of the rock blocks is uncertain and could fragment; thus, it is difficult to effectively address a falling rock at a target on an embankment. It is challenging to extrapolate these results for various structural configurations and materials; since the mechanical properties, impacted material thickness, and boundary conditions significantly affect the embankment response (Calvetti 1998; Montani 1998).

9.4.2.4 Rock Shed

Several studies have reported the laboratory and field experiments for the analysis of rock sheds. Pichler et al. (2005) carried out rockfall tests to analyse the relationship in the rock mass, fall height, impact force, impact duration, penetration depth, and the rock shed deformation resistance. Calvetti (2011) performed real-scale experiments to estimate the impacting force of falling rock, its transfer to the soil cushion layer at the interface, and the dynamic response of the rock shed. Calvetti and di Prisco (2012) carried out systematic rockfall experiments on a rock shed, with a reinforced-concrete sphere of diameter 0.9 m and mass 850 kg dropped from heights varying between 5 and 45 m. The force of impact and the deformation of the rock shed are analysed. Zhao et al. (2021) performed a series of experiments to analyse the capacity of two types of composite cushion layers in a rock shed subjected to multiple rock block impacts. The outcomes illustrated that the composite cushion layer made of sand-expandable polyethylene is highly durable and effective against multiple impacts than sand-expandable polystyrene. The studies conducted for the analysis of the dynamic response of the rock shed can be categorised into three phases: elastic compression phase, which occurs just after the block impact; plastic deformation phase, in which the stresses induced by impacting rock on the rock shed surpasses its yield strength; and elastic resilience phase occurs after reaching the maximum compression deformation. While Zheng and Binienda (2007) performed a study based on these three phases, the study considered the constant rock shed elastic modulus in the second phase. It is expected that when plastic deformation increases, the elastic modulus will decrease. The other limitation of this study is that it only analyses the rock shed impact force variation with time, not the impact force variation with the rock shed deformation (Olsson 2003; Zheng and Binienda 2007). Therefore, it is impossible to find the permanent deformation of the rock shed due to rockfall, making it difficult to evaluate the rock shed's safety in the future.

9.4.2.5 Catch Ditch

The Oregon Department of Transportation (ODOT) conducted real-scale experiments between 1992 and 1994, collecting results from three types of catch ditches with varying inclinations (1H/1V, 4H/1V, and 6H/1V). Rock blocks are dropped from varying heights but along a constant gradient (0.25H/1V) (Pierson et al. 1994). The likelihood of the blocks hitting the road, the frequency of rockfall, and the retention capacity of the catch ditch are estimated. In 2001, the FHWA and the ODOT examined various configurations of the catch ditches. About 11,250 rocks of varying sizes are rolled over four different slopes (0.25H/1V, 0.5H/1V, 0.75H/1V, and 1H/1V) and at various heights. In this case, the efficacy of three different types of triangular catch ditches (1H/0V, 6H/1V, and 4H/1V) is assessed. The outcomes enabled the generation of new design charts (Pierson et al. 2001).

9.4.3 Numerical Approach

Conducting large-scale experiments is very expensive and time-consuming. Therefore, at the design phase, it is necessary to limit their number and use their findings to develop numerical models capable of estimating the behavior of structures at various energy level impacts and to study the influence of block kinematics. Numerous numerical models have been established to consider rock impact dynamics. The widely-used models are either continuum-based models like the finite difference method (FDM) and the finite element method (FEM), or the discrete element method (DEM) based on discontinuous mechanics. The discrete element method (DEM) was first proposed by Cundall and Strack (1979) and has become more widely used. This method uses Newton's equation of motion and generally allows the modeling of large deformation. Discrete element methods (DEM) have been considered by several researchers (Nicot et al. 2007; Plassiard and Donzé 2009; Lorentz et al. 2010; Bourrier et al. 2011) to study the rockfall impact responses of the structures. DEM takes the discrete nature of granular material into account through the clustering of particles that interact with each other at contact points. The macroscopic mechanical nature of the granular particle clustering is influenced by the grading and shape of particles, the porosity of the granular assembly, and the contact characteristics. On the other hand, finite element method (FEM) based techniques involve a re-meshing algorithm and an explicit method to model large distortions and rockfall dynamics (Burroughs et al. 1993; Peila et al. 2007; Sung et al. 2008). Jarrin and Meignan (2010) used the finite difference method (FDM) to model rockfall protection bunds. In order to combine the benefits of the discrete element method in the impact region and of the finite element method in the far field, Breugnot et al. (2016) proposed a composite discrete-continuum method. The effect of the impact position, the shape of block, and the mass to velocity ratio for the same kinetic energy have been examined.

9.4.3.1 Flexible Barrier

The performance of rockfall flexible barriers has been significantly improved using numerical modeling-based studies (Volkwein 2005; Dhakal et al. 2012; Albaba et al.

2017). The nonlinear material behavior, geometrical nonlinearity caused by large deformations, and short-time simulation period have been successfully modeled using explicit finite element analysis strategies such as the Central Differences Method (Bathe 2001). This approach provides a detailed dynamic response to the system. It can also deliver information on the loading and degree of utilisation of any system configuration. The literature has suggested several approaches for simulating steel wire nets in the numerical model, with the most popular being the finite element method (FEM). The FEM has been used to model the impact of falling rocks against a flexible barrier in which the wire nets have been modeled using beam elements, truss elements, shell elements, and special purpose finite elements. For continuum problems, the FEM is well developed for dynamic modeling of nonlinear geometries with complicated contact and mechanical behavior, but for discontinuous problems, computing time becomes a major concern, particularly if the failure of the wire net needs to be taken into account. Therefore, the discrete element method (DEM) is a useful substitute since it is mainly effective for problems requiring dynamic impact and failure. The DEM has special features for analysing the motions and interactions of individual particles (Yu et al. 2018). Bertrand et al. (2008) and Dugelas et al. (2019) suggested a DEM technique for simulating twisted-pair hexagonal nets and a multi-node sliding cable model for the rockfall dynamic analysis. The modeling outcomes are contrasted with the tensile strength experiments performed on the net. Lisjak et al. (2020) use the coupled DEM—FEM to examine the interaction of rock blocks with the slope.

9.4.3.2 Rock Shed

To examine the interaction among the soil cushion and slab of the rock shed, 3D FEM models enable a coupled simulation of the rock shed with all its elements (Khasraghy et al. 2011). The peak impact force can be accurately simulated, though it is challenging to simulate a waveform of the second wave of the impact force. Since the impact resistance nature of the sand cushion layer is mainly discrete, the discrete element method (DEM) can be used to understand this nature. The DEM is considered to numerically analyse the materials (such as sand) cushioning mechanism. The DEM can monitor various deformation patterns, from elastic to plastic deformations, and post-fracture deformations (Matsushima and Chang 2011; Naito et al. 2020).

9.4.3.3 Embankments

Ronco et al. (2009) and Peila et al. (2007) performed finite element method (FEM)-based modeling of rock block impact on geosynthetic reinforced rockfall protection embankment by using explicit FEM code Abaqus. The local deformation of the reinforced embankment to stop a rock block is also modeled, and the total dissipation of kinetic energy by both the plastic deformation and frictional effect is estimated. Cuomo et al. (2020) investigated the performance of geosynthetics-reinforced embankments through the FEM code Plaxis. Other contributions are provided by Plassiard and Donzé (2009), Wang and Tonon (2011), and Zhao et al. (2017) in simulating the falling rock fragmentation and its impact on the embankment through the DEM approach.

9.4.3.4 Catch Ditch

Pfeiffer and Bowen (1989), Pantelidis (2010), and Nishikawa et al. (2012) employed the numerical approach to develop rockfall propagation expressions and simulate the interaction between the propagating rocks and the ground. Pantelidis (2010) proposed a design chart for catch ditches based on the Ritchie ditch model. The results of this analysis are based on the modeling of the 100 rocks rolling over the slope of hard rock with a catch ditch at the toe of the slope.

9.5 Design Guidelines and Design Considerations

The design guidelines aim to codify/organize a validated general design procedure that is easy to apply while considering the uncertainties in the geotechnical domain and the dynamic propagation models. Presently, limited recommendations or guidelines are available for the design of rockfall protection structures. Since the design methodologies are either fairly new or under development, understanding these structures is constantly developing. The design guidance and recommendations presented here are based on currently accessible methodologies established by researchers and engineers. As the knowledge of the behavior and performance of these structures grow, the design methodologies are being updated. Most of these rockfall protection structures discussed previously are exclusive systems designed and tested at certified testing centers employing standard testing techniques. The designer must select an appropriate methodology for their site, taking into account the structure and associated risks. Thus, employing numerous methods and comparing the outcomes may be beneficial.

9.5.1 Flexible Barriers

Flexible barriers, or fences, are the most well-developed than the other rockfall protection structures, with recently released design guidelines by the Italian Standards Institute (UNI 2012) and the Austrian Standards Institute (ONR 2012). These standards will probably undergo further development when more information concerning the effectiveness of designed flexible barriers becomes available. The following are some of rockfall flexible barriers' most important design considerations.

Design Energy. The designer must first determine whether to design according to service energy level (SEL) or maximum energy level (MEL) load conditions based on ETAG 027 testing standard. Their applications in design are given by Peila and Ronco (2009). In MEL design, the flexible barriers are intended to resist a single impact of design energy. However, it will most likely need to be repaired or replaced after the block impact. This method could be used in instances when the frequency of rockfall incidents is expected to be minimal. While in SEL design, the flexible barriers are intended to resist several impacts of design energy, and it is envisaged that after impact, it will require little to no maintenance. This may be appropriate in regions where frequent rockfall occurrences are expected, or vehicles are easily accessible for repair and maintenance. Manufacturers' energy values are based on their MEL design load. For a flexible barrier with an energy value of 3,000 kJ, the design block would have allowable energy of 3,000 kJ in a MEL design and allowable energy of 1,000 kJ in an SEL design.

Size of Flexible Barrier. ONR (2012) and UNI (2012) suggested a broad approach in which partial safety factors are applied to input and output parameters in rockfall modeling. The partial safety factors are considered for uncertainty in the assumptions in input as well as the fact that ETAG 027 certification of the barrier was carried out under ideal conditions and assumptions (Grimod and Giacchetti 2014). The results of rockfall modeling should be combined with observations obtained during the site assessment when sizing the barrier for both bounce height and energy capacity. The majority of the literature discusses the difficulties of calculating bounce height as well as the limits of rockfall models in this regard. It is critical to evaluate bounce heights in the modeling process through model calibration and sensitivity assessments. If data from recent rockfall events are available, the evaluation of the heights of bounce from the rockfall-prone slope region is also required.

Deflection of flexible barrier. Rockfall protection flexible barriers may significantly deflect when subjected to falling rock impacts. The location of the particular infrastructure to be safeguarded against rockfall must be compared to the potential deflection of the barrier net. According to the Italian standard (UNI 2012), a safety factor of 1.0 to 1.5 should be applied to the maximum deflection of the barrier, based on design approaches (SEL or MEL) and the number of functional modules of flexible barrier or fence (measured during the ETAG 027 testing).

Anchor and Post Foundation Design. The primary component for transferring force to the ground is the anchors, which connect the barrier cables and posts to the ground. Typically, a foundation plate and concrete plinth are used to install the anchors. The manufacturer specifies anchor force based on the forces observed through the ETAG 027 testing of a specific system. In general, a safety factor is applied to the anchor forces, and proof tests should be done to check the functioning of an anchor. Sub-surface surveys may be essential to check the nature of rock and the bedrock depth, as well as the pull-out tests on test anchors, to verify the bond strength of design grout–ground. Whether the foundations or anchors are set in rock, discontinuity alignments should be investigated to see if there's a chance of possible formation of unstable blocks that could shift under anchor loads. Depending on the anchor spacing, group effects also need to be considered. The design safety factors can be determined from the possible variability of field situations (quality and type of rock, bedrock thickness, etc.) and past knowledge of the site conditions.

Protection against Corrosion. Besides foundation construction and block impacts, the barrier design life will be influenced by the corrosion of its components. The barrier and its components must be treated with corrosion protection at the installation site.

9.5.2 Embankment

In current practice, reinforced rockfall protection embankments are the most widely employed technique of rockfall protection. Lambert and Bourrier (2013) discussed various approaches to embankment design that have been employed in the past. Some of these approaches focus on calculating the block penetration depth in the embankment. Generally, in an embankment, the kinetic impact energy of falling rock is dissipated (Grimod and Giacchetti 2013) via plastic deformation in the form of crater formation (80–85% of the impact energy), friction loss (15–20%), and elastic deformation (1% of the impact energy). The UNI (2012) and ONR (2012) have provided design recommendations for rockfall protection embankment design. The embankment design comprises an evaluation of the embankment geometry based on design rock size, impact height, and energy. These evaluated parameters are considered for calculating the block penetration depth with the help of a series of design charts developed from the physical tests and numerical modeling. The embankment design is either based on the serviceability limit state or the ultimate limit state (Grimod and Giacchetti 2013). The ultimate limit state corresponds to the maximum resistance capacity of the embankment without collapse (deformation >50% of embankment thickness at impact height). The serviceability limit state corresponds to the maximum deformation of the embankment that allows it to be repaired easily (deformation <20% of embankment thickness at impact height). Also, it is typically not more than 30 to 40 cm on the downward side and not more than 50 to 70 cm on the upstream side.

Further, the energy balance approach is adopted for the efficient design and construction of rockfall embankments. This design approach is best described in Ronco et al. (2009) and further updated to encounter the standards of the Technical Guideline provided by Christchurch City Council (CCC) for rockfall protection. The design approach includes two phases: (a) Evaluation of the energy levels of the rockfall and (b) Design of the rockfall protection embankment. The ETAG 27 requirements are considered while calculating the design energy level parameters. The design of the embankment is based on the factored energy values. The factors used comprise MEL (maximum energy level) in the order of 1.3 times the design energy level for low-frequency rockfall events and SEL (service energy level) in the order of 0.3 times the design energy level for multiple rockfall impacts (Ronco et al. 2009). Following are some considerations particular to each site that may dictate embankment design, including construction sequencing, product limits, and contractor needs, based on experience with rockfall protection embankments.

Embankment Inclination. The hillside face inclination should be as steep as feasible to minimize the chances of blocks rolling up and over the structure. At an inclination of 70°, the probability of rocks passing over the embankment is less as compared to shallower angles because there is less rotational energy (Ronco et al. 2009).

Embankment Fill. To help drainage through the embankment, coarse-grained materials are typically used in the bottom layer of the embankment. The locally available fill material may be used with adequate measures for erosions, stabilization, or soil improvement to reduce the cost of construction.

Embankment Width. The width of the embankment must be adequate for the operation of compaction machinery. According to Lambert and Bourrier (2013), the top crest width should be greater than 1.0 m, and the minimum width of the embankment at the top should be 2 m, although Ronco et al. (2009) suggested embankments with a top crest width of about 0.9 m. Additionally, the embankment width at the block impact position should be greater than two times the penetration depth.

Embankment Height. The embankment height should be sufficient so that the falling block does not overpass. The embankment design must consider a freeboard above the impact height. A normal force is applied at this freeboard height above the impact position and produces shearing resistance against this impact force (Wyllie 2014).

Durability and Reparability. The facing components of the embankment must be durable to endure exposure to the environment. These components should be easy to repair under the SLS conditions; or replaceable under the ULS conditions.

9.5.3 Attenuator System

The primary goal of rockfall attenuator systems is to reduce the intensity of rockfall so that the rocks can pass through the attenuator system, reducing the energy, which is then manageable at a downslope catchment area. Such a catchment area can be a catch ditch, a rockfall barrier, or an additional attenuator in sequence. The major sources of energy losses are achieved through the three interactions, including (a) Net and impacting rock frictional contact; (b) Rock and slope surface frictional contact; and (c) Net and slope surface frictional contact.

The attenuator systems have been used for several decades and subjected to several field testing (Arndt et al. 2009). The Swiss Federal Institute for Forest and Landscape Research (WSL), in collaboration with Geobrugg AG, Switzerland, established the first standard for rockfall attenuator testing. This led to the Swiss standard for rockfall attenuator testing (Gerber 2001), which was later adapted to fulfill a European standard, the ETAG 027 (EOTA 2008). The Geobrugg company carried out the primary experimental program of attenuator system protection against rockfall in 2017. The testing procedure involves an impact of a rock into a rockfall attenuator generated from a rock in free fall. During the experiment, the accelerometer was mounted in the mid of experimental objects and continuously collected data, including angular velocities and accelerations. Since it is difficult to identify the precise alignment of the block during impact, only general trends rather than exact values are used to compare these data. Numerical approaches are considered for getting a better understanding of the interaction between highly flexible protection structures and impacting rock blocks. To date, although rockfall attenuator systems have been widely applied as a rockfall mitigation solution, their design has been based on much engineering judgment and past experience of a trial-and-error approach. There are no established design guidelines for attenuators as of yet. Up to now, designs have been carried out utilising a theoretical approach based on limited field experiments and observations (Arndt et al. 2009; Glover et al. 2012). The general design recommendations for this kind of rockfall protection structure are given below.

Materials. The attenuator systems are generally designed with the help of ETAG 027 flexible barrier with modifications consisting of the wire net arrangement to make a tail that may be placed across the slope downstream of the system.

Energy capacity. The MEL design approach is used the same as followed for flexible barriers. The dynamic force and energy in the attenuator system are reduced since the system does not retain the rock block.

Drape Net Design. For the design of draped net, the material type, weight and durability, and the length of the required net are considered. The slope (slope angle, roughness) over which the net will rest is considered, along with the potential slicing forces resulting due to the bouncing and rotation of the rock. The purpose of the drape is to provide extra frictional contact between the block and the slope surface. If the drape is not appropriately designed, the rock block may be retained underneath the drape (affect future performance), or it may depart with a slight decrease in its energy.

Anchors and Posts. The force acting on an anchor in attenuator systems will generally be less as compared to a flexible barrier or fence. The forces exerted by the weight of the draped net may be taken into account for the post-spacing design.

Corrosion Protection. The design life of the system may be influenced by the frequency of rockfall captured by the system and the environmental situations. Same as considered for rockfall flexible barriers or fences.

9.5.4 Rock Shed

Based on real impact experiments, the first Swiss design guideline for rockfall protection sheds was issued in 1998. The effect of the cushion layer on the force of the impact was the main focus of the test experiments. The guideline applicability is limited to penetration depths that are smaller than half of the depth of the cushion layer. The impact load used in the latest version of the guideline (FEDRO 2008) is a function of the properties of the cushion layer (i.e., thickness, soil modulus, and internal friction angle) and the impacting block (i.e., size, mass, and velocity). A coefficient C accounts for the structural behavior due to the dynamic load (brittle: C = 1.2, ductile: C = 0.4). Since the design approach uses a quasi-static equivalent force, it does not take into account whether forces are applied as acting on the cushion layer or acting on the slab, or as reactions from the slabs at the supports after the impact. The manual comprising recommendations for various protective measures is the handbook published in Japan (Masuya 2007). Here, the impact force acting on a shed depends on the mass and falling height of the block as well as on an amplification factor for the cushion thickness and Lamé's constants. The important design considerations for rock sheds are given below:

Foundation. The footing would need to be rested on a rock to provide the necessary bearing capacity. Since traffic operations would not provide enough time to construct the foundation on rock, bedrock-drilled rock socketed piers are used to support the foundation (Wyllie 2014). The force on the foundation includes the live load of rock fall impacts, the dead weight of the shed, and the force exerted horizontally on the crash wall.

Crash Wall. The crash wall is a wall that connects the columns holding the slab with a connector. The connector prevents the transfer of moments from the wall into the columns. The crash wall and foundation together would be cast-in-place concrete.

Mountain-side Wall. The mountain-side wall is a continuous wall that serves as both a support for the roof beams and a retainer for the fill. To withstand the weight of retained fill and water pressure that builds up behind the wall, the wall has incorporated tie-backs through the wall and rock anchors embedded in the rock face.

Columns. The columns are pre-cast structures with longitudinal spacing that corresponds to the width of roof beams. A layer of synthetic rubber is embedded in the concrete to give flexibility to the hinge. Pre-stressing cables are incorporated into the crest of all beams to form a rigid connection between the roof beams and the columns.

Roof Slab Beams. The roof slab beams are pre-cast structures. Holes for the post-stressing cables in the columns are included in the outer ends of the beams. The tops of the valley side columns are rigidly connected to the beams. Groups of post-tensioned cables connect the roof slab beams themselves.

Cushion Layer. The layer of loose sand is placed on top of the roof or slab of the rock shed to protect it from falling rocks. The sand is contained on the valley sides and sides of the shed by concrete blocks that are fastened to the outer edge of the slab.

9.6 Summary

Rockfall is a type of dangerous hazard in mountainous regions that is difficult to treat due to its unpredictability, rapidity, and widespread dispersion. The degree of damage caused by rockfall to the roads, rail lines, and infrastructures is highly severe. It is incredibly important to summarize rockfall mitigation strategies systematically. Various types of strategies can be used to mitigate rockfall hazards in mountainous regions, some of which are employed to prevent the detachment of rocks from the rock-cut slope (active mitigation), while others are designed to protect the infrastructures down the slope by intercepting and stopping the falling rocks during downslope propagation (passive mitigation). To choose the most suitable rockfall mitigation measures in hilly areas, some major active measures to prevent rockfall and passive measures to protect the infrastructures are summarized in this chapter. The implementation of appropriate mitigation measures depends on a detailed investigation of the environmental factors that contribute to the occurrence of the rockfall hazard. According to past studies, passive measures have received more attention compared to active measures owing to the uncertainties associated with rockfall events. Flexible and semi-rigid passive mitigation measures (i.e., fences, attenuators, and embankments) are preferred over rigid, passive mitigation measures (i.e., stiff structural walls). The effectiveness of active measures depends on the precise identification of unstable and dangerous rocks, accurate assessment of failure modes, and thorough study of rock failure mechanisms. The effectiveness of passive measures heavily relies on the accurate assessment of rockfall trajectories, velocities, energies, and bounce heights. Selection of an appropriate mitigation strategy is a crucial and challenging task for various topographical and geological conditions, and this chapter intends to ease this task by presenting a comprehensive review of the mitigation measures.

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