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THE USE OF FLEXIBLE PROTECTION SYSTEMS FOR NATURAL HAZARD MITIGATION

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Abstract

One common approach to providing protection against natural hazards such as unstable slopes, rockfall, debris flow, and avalanche is the construction of large, rigid structures. The effectiveness of these designs is typically solely dependent upon the strength of the materials being employed. In order to achieve the strength required to protect against natural hazards, designs tend to consist of very large constructions. These designs are often expensive to construct, especially in difficult access conditions. Additionally, they are ineffective in many situations and often lack durability. An alternative approach to hazard mitigation is the use of high strength, flexible protection systems. The effectiveness of flexible systems is a result of their ability to move and shift with the hazard in question, allowing them to absorb energy instead of just resisting it. As a result, these systems can be of lighter weight construction, resulting in lower material costs and greatly simplified erection.

Résumé

La façon la plus fréquente pour prendre des précautions contre les risques naturels comme les pentes instables, les chutes de rochets, l'écoulement de debris, et les avalanches est de construire des bâtiments d'une grande dimension. L'efficacité de ces édifices dépendrais strictement sur la solidité et la résistance des materiaux de construction utilisés. En vue d'atteindre la solidité requise pour une protection contre les catastrophes naturelles, les plans doivent consister en bâtiments d'une grande envergure. Ces plans sont souvent très couteux à construire; surtout dans des conditions d'accès difficile. De plus, ces édifices sont souvent inefficaces et non durables. Une solution possible pour l'atténuation du danger est d'utiliser des systèmes de protection flexibles et solides. L'éfficacité de systèmes flexibles est due à leur capacité de mouvement et de changement, tenant à la nature du peril naturel tout en permettant un amortissement d'energie au lieu d'une résistance inutile. Ainsi, ces plans peuvent être d'une charge légère, peu couteux, et d'une erection simplifiée.

1. INTRODUCTION

As growth and development around the world continues to drive expansion into areas threatened by natural hazards, the need for strategies to protect against these threats continues to increase. Historically, many approaches have been employed to protect against such threats as avalanche, rockfall, debris flow, and unstable slopes. These efforts have varied widely in terms of their success, cost, and visual impact.

Efforts to provide protection against avalanche can be traced back as far as 1518. While history does not present much evidence of research into rockfall protection, it can be assumed that it first became of common importance with the advent of railway construction in 1834. With the railways passing through mountainous areas and carrying large numbers of passengers at high speeds, the potential for calamitous rockfall accidents increased greatly. Despite this fact, textbooks from the 1800's include little or no mention of rockfall protection. Until the 1950's efforts to mitigate rockfall hazard consisted mainly of rigid walls constructed with materials typically on hand in the railroad environment (steel rails, wooden beams). Within this same time period, the need to provide protection for mountainous roads also began to become apparent, yet little effort was made toward engineered and tested solutions.

Beginning in the early 1950's research was begun in Switzerland into the use of wire rope nets to provide protection against avalanches. Subsequent research and development has resulted in the application of various high strength, flexible materials in the mitigation of rockfall, debris flow, and unstable slopes.

2. AVALANCHE PREVENTION

Recent expansion in alpine areas is increasingly pushing development into previously untouched land that presents significant avalanche risk to structures and people. When building in the danger zone is unavoidable or desirable, there are a variety of measures that can be employed to mitigate the risk:

- Drift Fences – Typically of light construction and intended to influence wind and snow movement to prevent the formation of cornices.
- Diversion and Retarding Structures – Massive dams and walls designed to divert or slow down a moving avalanche. These structures need to withstand very large forces and are accordingly expensive.
- Supporting Structures – Structures erected in the avalanche starting zone in order to prevent slab avalanches from beginning.

Supporting structures can be constructed of lighter-weight materials because they don't have to accommodate the large dynamic forces of moving avalanches. This leads to lower material costs, and reduced installation costs. Many designs for these types of structures consist of timber, steel, or concrete. These structures are rigid, however, and often sustain damage while retaining the large static loads imposed on them by a creeping snow pack.

An alternative approach is to use flexible wire rope nets. The first wire rope nets designed for avalanche protection consisted of nets woven with an 8” x 8” mesh size. Early designs utilized timber posts to support the retaining nets, with steel posts eventually replacing the timber posts (Figure 1).

Figure 1. Wire rope net supported by steel posts

The first installation of a wire rope net supporting structure was in 1951 on the Schafberg at Pontresina in the Engadine Valley of Switzerland. Early installations consisted of nets erected individually. Beginning in 1954, research was conducted to determine the most effective design of such structures. That research has resulted in the current approach which utilizes modular structures erected in a series of lines (Figure 2), with standardized design guidelines published by the WSL in Davos, Switzerland.

Figure 2. Series lay-out of avalanche netting structures

The first wire rope net avalanche supporting structure installed in North America was constructed in the Alpental Valley, east of Seattle, WA in 2000. It is erected in a series of rows each with a height of 4.5 meters. After having been in place for three full winters, it has successfully prevented the initiation of any avalanches.

The effectiveness of wire rope netting systems is a result of the flexibility of the various components. The steel support posts have a ball and socket joint at the base to allow the posts to move under load. All anchors and anchor ropes consist of wire rope. As a result, the system components are loaded in tension as much as possible. This allows the use of relatively light-weight materials, keeping the system cost lower; and allowing relatively easy installation in difficult access conditions through the use of helicopter placement of pre-assembled sections.

Structures consisting of wire rope nets are more durable then rigid approaches to retaining structures as a result of their flexibility. When compared to massive diversion and retarding structures, they also offer a tremendous cost advantage. Studies have also shown that the open nature of the wire rope nets results in a greatly reduced disturbance to the aesthetics of the surrounding area.

3. ROCKFALL PROTECTION

The earliest attempts at providing rockfall protection for roads and railroads consisted mainly of the construction of galleries or rock sheds. This approach is still employed today, and is very effective. For most situations, however, these large structures are cost prohibitive.

A wide variety of other approaches have been attempted over the years, typically consisting of some combination of steel or timber posts with wire mesh and steel cable, wood beams, earth walls, or tires (Figure 3). These systems typically lack the durability to stand up to multiple, high-energy impacts. These failures indicate the need for an approach relying on flexible materials. The use of flexible materials allows rocks to slow down over a longer period of time, imparting less force to the system infrastructure; and greatly increasing durability and repeatability of performance.

Figure 3. Rubber tire rockfall barrier.

3.1 Wire Rope Nets for Rockfall Protection

The first application of flexible wire rope nets to rockfall protection was a result of the observation that avalanche prevention structures were frequently subjected to rockfall during snow free periods. Field experience showed that these structures successfully withstood impacts from rocks, as evidenced by a 1961 impact of an avalanche structure near St. Gallen, Switzerland by a total of 3 cubic meters of rocks without damage (Figure 4).

Figure 4. Rock impact to avalanche prevention structure

Observations such as these prompted the design of wire rope net structures specifically for rockfall protection. The first such installation occurred in 1958 at Brusio, Switzerland. This structure consisted of a 5 meter high net supported by steel girders on top of a retaining wall. Similar installations followed soon after, and met with success.

Despite their success in the field, the energy which these designs could withstand was not conclusively known. The dynamic nature of a rockfall impact differed greatly from the static loads imposed upon an avalanche structure. As a result, the dimensioning models which had been used to design avalanche structures did not apply to rockfall; and similar models were not available for rockfall systems. This resulted in the first scientific rockfall tests in 1962 at Brunnen, Switzerland. These tests provided proof of the nets' ability to withstand rock impacts of up to 23 kJ.

3.2 Braking Elements

Subsequent testing indicated that significant improvement in barrier design energy could only be achieved by adding flexibility to the system beyond that of the elongation of the wire ropes. This discovery led to the development of braking elements. Braking elements act as mechanical fuses within the barrier, and are incorporated into the support and anchor ropes of the system. They allow the supporting infrastructure of the system to continue to move with a large impact, while providing resistance in order to absorb energy.

In 1991 the pipe brake ring was developed in Switzerland (Figure 5). This design consists of a length of steel pipe bent into a ring with the support rope running through the pipe. Where the two ends of the pipe meet, they are clamped with a compressed aluminum sleeve. This clamp prevents the brake from activating under minor impacts, and restricts its use to events in the range of the barrier's design energy. When the brake is activated, the ends of the pipe slide through the clamp. This allows for displacement of the system, while a slowing force is applied through the friction of the pipe sliding through the clamp and the resistance of the pipe to deformation. If activated, the braking element will only displace as much as is necessary in order to absorb the impact. As a result, it does not need to be reset before subsequent impacts; and only needs to be replaced after it is fully activated (Figure 6).

Figure 5. Pipe braking element

Figure 6. Fully activated pipe braking element

3.3 Ring Net Rockfall Barriers

The introduction of braking elements to rockfall barriers provided the ability to absorb much larger impacts. The next step in development was to find a netting material that could provide better performance then the wire rope nets that had been used to date. Wire rope nets provided the flexibility necessary to stand up to repeated rock impacts, but they did not absorb any of the resulting energy. They simply transmitted the forces to the system infrastructure.

The first ring nets used for rockfall barriers were World War II surplus submarine nets. These nets consisted of spliced rings and had been used to protect harbors from submarine attacks. The submarine nets proved to be effective when used in rockfall barriers, but they did not represent an effective long-term solution. The supply of surplus stocks was finite, and reproduction of the hand-made nets was cost-prohibitive.

A solution was found in 1996 with the development of a fully automated process to produce ring net panels consisting of bundled 3mm high tensile strength steel wire. Each ring in the net panel (Figure 7) is connected to four neighboring rings by looping through them, allowing rings to move independently of those surrounding them. The production process allows for the number of wires bundled in each ring to be varied depending upon the intended design energy of the barrier.

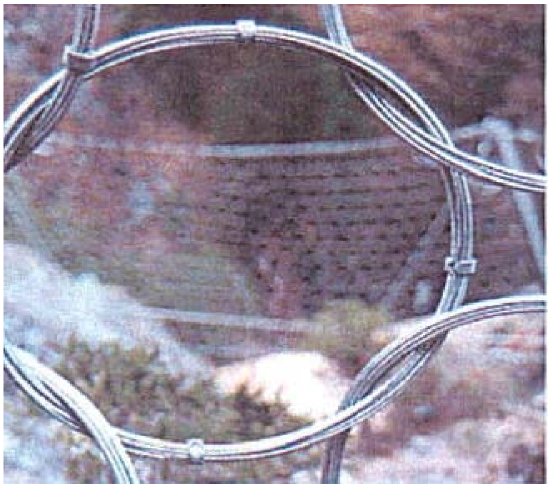

Figure 7. Bundled Steel Wire Ring Net

The development of the bundled wire ring nets represents a dramatic improvement in the efficiency with which rockfall barriers absorb impacts. The wire rope nets that had been used previously had a very limited ability to dissipate the energy of an impact. They primarily acted to catch the rock and transmit the majority of the energy to the system infrastructure. The ring nets, however, act in an elastic fashion when impacted, deforming as necessary to absorb a significant percentage of the energy imparted by a rock (Figure 8). This results in a high level of internal energy absorption within the net itself, greatly increasing the energy that the overall system can withstand. With the exception of very large impacts beyond the barrier design energy, the rings will return to their original shape after the load is removed. This allows the barrier to withstand repeated design load events without requiring maintenance.

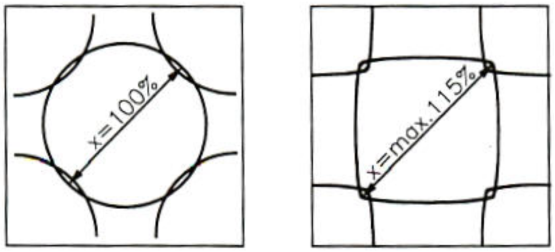

Figure 8. Elastic deformation of ring during impact

3.4 Testing

Since the first rockfall barrier tests in the 1960's, hundreds of tests have been carried out in Switzerland, California, Japan, and other areas around the world. The earliest tests consisted of dropping rocks into individual net panels. Later tests became more comprehensive, including rolling rocks down a hill into test barriers and launching rocks at barriers with an inclined cable-way. The latest test facility in Walenstadt, Switzerland consists of a vertical drop from a crane into a rockfall barrier mounted horizontally to a vertical cliff face. This test arrangement allows for highly repeatable results, and has enabled very detailed study of barrier performance. This latest research has resulted in rockfall barrier designs that are capable of withstanding impacts of up to 3000 kJ (equivalent to a 10 ton block moving 55 miles per hour).

An uncompromising testing program is vital to successful design of rockfall barriers. All barrier designs must be subjected to full scale 1:1 field testing before use in the field. Rigorous testing leads to effective barrier designs that can be trusted to protect roads, railroads, structures, and people from the danger of rockfall (Figure 9).

Figure 9. Rockfall Barrier impacted by rock slide

3.5 Advantages of Flexible Rockfall Barriers

Flexible rockfall barriers are not appropriate for all situations. Some of these situations include:

- Insufficient catchment area at toe of slope
- Bounce heights too high to make barrier feasible
- Any rock movement on slope is undesirable
- Impact energy is too high for current barrier designs

In situations where rockfall barriers are appropriate, however, they are nearly always the ideal solution:

- Better ability to withstand repeated, high-energy impacts then rigid barriers results in better performance and lower need for maintenance
- Lightweight materials enable installation in difficult access conditions
- Less expensive and less invasive then large scale excavation of slope, or construction of berms or catchment ditches.
- Open, lightweight construction has a minimal aesthetic impact on the surrounding environment

4. DEBRIS FLOW BARRIERS

The initial application of flexible barriers to debris flow mitigation was largely accidental. Small snow avalanches as well as debris and mud flows would occasionally impact rockfall barriers installed in the field. Investigation of these occurrences illustrated that flexible barriers could effectively retain significant amounts of debris material. Rockfall barrier designs are optimized to withstand the highly dynamic impacts of rocks. This type of impact is significantly different from the loading characteristics of a debris flow. This observation prompted further testing into how flexible barriers behave when impacted by debris flows.

4.1 Testing

The first test of a flexible barrier specifically for debris flow was in Oregon, USA in 1996 (Figure 10). This series of tests comprised a variety of barrier designs all based upon standard rockfall barriers. Wire rope nets and ring nets were both tested as well as a variety of anchoring arrangements and several different secondary mesh coverings for the net panels. The results of this testing illustrated that flexible barriers could reliably retain moderately sized mud and debris flows. The final tests allowed only 0.05% of the released material to pass through the barrier.

As a result of the testing, the following details were discovered:

- Ring nets are more effective then wire rope nets
- 1” square chain link material should be included on the nets to retain the fine material
- The infrastructure and anchors need to be higher strength then standard rockfall barrier designs in order to accommodate the mass loading characteristics of the debris flows

Figure 10. Flexible debris barrier testing at the USGS test flume in Oregon, USA

Further research was carried out in 2001 in Germany to examine the behavior of a ring net system used for woody debris entrapment in a torrent. The test set-up (Figure 11) consisted of a ring net panel rigidly anchored to a steel test frame along with load cells to measure the forces being transmitted into the support ropes. The results (Figure 12) illustrated that flexible barriers are capable of entrapping woody debris within small watersheds. This testing also allowed comparison of actual results to modeled results and will aid in the development of a design concept for flexible debris barriers.

Figure 11. Woody debris test site in Germany

Figure 12. Successful test with woody debris

4.2 Advantages of flexible debris flow barriers

Testing and field experience have shown that flexible barriers are effective at retaining smaller debris and mud flows consisting of up to approximately 700 cubic meters of material (Figure 13). Further research and development will likely expand their use to even bigger flows. Other mitigation measures used for these types of flows include dams, diversion and retaining walls, and catchment basins. Flexible barriers offer a significant cost advantage over these approaches as well as a much less invasive installation process which is often a key issue within fragile ecosystems.

Figure 13. Debris flow of approx. 720 m^3 stopped by flexible barrier in Japan

5. SLOPE STABILIZATION WITH HIGH STRENGTH STEEL WIRE MESH

Anywhere a highway, railroad, or structure encroaches upon a slope, instability is bound to be a significant and recurring problem. Limited right of way frequently mandates the creation of over-steepened or truncated slopes. Other contributing factors to slope instability can include groundwater conditions, the structural geology of the slope, or environmental factors such as heavy rainfall or erosion. These factors lead to two main types of instability: surficial degradation of the slope, and deeper instability along discontinuities.

Before selecting what type of mitigation is most appropriate for a particular slope, it is necessary to distinguish between surficial problems and deeper instability. Surface instability is characterized by material moving down the slope under the influence of gravity. Depending upon the site conditions, this material can include soil, mud and debris, or rocks and boulders. Deeper instability consists of the movement of a mass of material along planes of weakness.

A wide variety of mitigation measures are available to address stability concerns. Surficial problems can be addressed by use of a slope matting material (jute mesh, wire mesh, wire rope nets, etc), shotcrete facing, catchment barriers, re-vegetation of the slope, and other methods. Deeper instability typically necessitates more extensive mitigation measures such as pattern anchoring both with and without a facing material (meshes, shotcrete, concrete panels, etc.), retaining walls, or excavation of the unstable material.

5.1 Shotcrete

Pattern anchoring is an approach commonly selected to address stability issues. Because of its high strength, shotcrete is often used as a facing material in these designs. Unfortunately, shotcrete has a number of drawbacks:

- Requires drains to allow for de-watering
- Visually unappealing - does not allow slope to be re-vegetated (Figure 14)
- Lacks durability and tends to crack, particularly at anchor points (Figure 15).

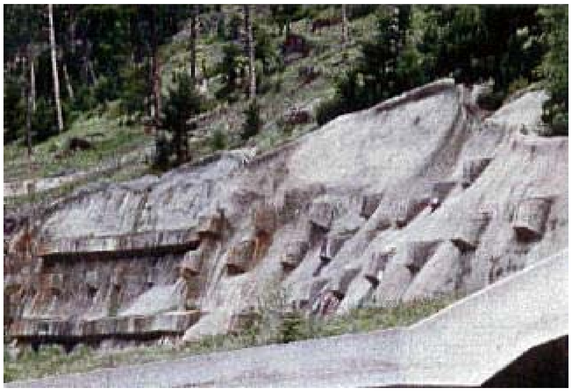

Figure 14. Shotcrete protected slope

Figure 15. Shotcrete cracked at anchor point

5.2 High Strength Steel Wire Mesh

As an alternative to shotcrete, high strength steel wire mesh can be used as the facing material. Recently developed steel wire mesh with a strength of 150 kN/m has the strength to be used in a manner similar to shotcrete while retaining the advantages of flexible materials. The open nature of the mesh construction makes de-watering unnecessary and the flexibility of the mesh provides much improved durability. The mesh strength allows it to be used on fractured rock slopes in addition to soil and colluvial slopes.

The anchors and mesh act together as a system to provide stability to the slope, preventing deformations in the top layers and restricting movement along planes of weakness. As a result of the high strength of the mesh, it is possible to pre-tension the system against the slope. This pre-tensioning enables the mesh to provide active pressure against the slope, preventing break-outs between the nails; and enabling wider anchor spacing which results in a lower overall installed cost.

In many areas aesthetics are of great importance. One advantage of high strength mesh as a facing material is that it allows re-vegetation of a slope. After the mesh is installed (Figure 16), the slope can be hydro-seeded or planted. If erosion is a concern, jute mesh or geo-fabric can be installed underneath the mesh to provide protection against surficial run-off. With time, the finished product is a permanently stabilized slope with a natural appearance (Figure 17).

Figure 16. High strength mesh anchored to slope

Figure 17. Re-vegetated slope after mesh installation

5.3 Advantages of High Strength Mesh for Slope Stabilization

Compared to other alternatives (particularly hard facings such as shotcrete or large retaining structures), stabilization with high strength mesh offers the following advantages:

- Cost effective
- No need to provide drainage behind the facing
- Allows greening of the slope – resulting in a natural, aesthetically pleasing appearance
- Longer useful life

6. CONCLUSIONS

The use of flexible materials in the mitigation of natural hazards has become more and more common over the last 50 years. This trend is a result of the proven ability of these systems to provide effective, economically feasible, long lasting protection. When compared to other solutions using rigid materials, systems comprised of flexible materials have a variety of advantages:

- Lower material cost
- Easier installation and lower construction cost
- Less invasive construction
- More durable and longer lasting
- Better performance in many instances
- Less aesthetic impact on the surrounding area

Protection systems comprised of flexible materials will continue to play an increasingly important role in protecting against avalanche, rockfall, debris flow, and unstable slopes. Continuing research and development will serve to further their use in these fields and expand their use into other fields.

7. References

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