7th International Conference on Debris-Flow Hazards Mitigation

Flexible debris-flow nets for post wildfire debris mitigation in the western United States

William F. Kane[a*], Mallory A. Jones[b]

[a,b]*KANE GeoTech, Inc., 7400 Shoreline Drive, Suite 6, Stockton, California 95219 USA*

Abstract

Wildfires are a continual threat in the western United States. Post-fire debris flows annually cause millions of dollars in damage and often result in loss of life. Rapid post-fire response is essential to prevent additional hazards in terms of debris-flow damages. Flexible systems utilizing high-strength steel ring nets have proven to be reliable and cost effective. These systems can be installed rapidly to minimize or eliminate the dangers caused by post-fire debris flows. Wildfires in the western United States generally occur during the dry season in late summer and fall. Although monsoonal storms can cause debris flows in the summer months, seasonal rain storm events occur in fall and winter, often resulting in devastating debris flows. In the Rocky Mountain states debris flows occur during the summer monsoon season. In both areas, storm cells can remain stationary over mountain peaks for hours dropping large amounts of rain in a very short time. The resulting runoff and erosion can cause damaging debris flows miles away from the rain event. Debris impacts differ significantly from rockfall impacts. The debris nets must withstand both a surge in pressure on impact, and a static load once the flow has dissipated. Tested and engineered, flexible nets can be rapidly deployed in strategic locations to lessen or eliminate the threat. Compared to large, rigid structures and debris basins, these nets are cost-effective, rapidly constructed, environmentally friendly, and approval by regulatory agencies can relatively quick. This study focuses on current mitigation and protection practices using flexible debris-flow nets as developed in Switzerland and used in the United States. Case studies of projects in Colorado, New Mexico, and California detailing site investigations, engineering, and construction of flexible debris-flow nets are described. Of special interest are the steps and protocols taken as a result of debris flows following the Thomas Fire in California.

Keywords: debris flow; ring nets; protection; wild fire

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1. Introduction

Each year, across the globe debris flows cause substantial damage and loss of life. Torrential rains from typhoons and hurricanes, or post-wildfire rain events can trigger large masses of vegetation, soil, and rock to flow catastrophically from mountain valleys and canyons out into inhabited areas. To date, the majority developmental work on debris-flow nets has been conducted by the Swiss government in conjunction with the Swiss company Geobrugg, AG, Romanshorn, Switzerland. This paper describes design and projects using the Swiss/Geobrugg debris mitigation products. Other manufacturers also provide debris nets. These nets were not used in the projects described.

The principle behind debris nets is to catch debris flows close to the source, usually in mountain canyons, stop the massive flow, and then, if desired, allow the material to be placed back in the channel to allow natural process to return to normal sediment transport conditions.

Flexible debris nets have been installed in hundreds of locations around the world to protect people and infrastructure in a low-impact, environmentally sound way.

The basic debris-flow protection system consists of a custom ring net engineered to resist the velocities and dynamic and static pressures unique to debris flows. Support ropes are installed into channel banks and transfer debris impact and pressure loads from ring nets to the ground. Excessive energy is absorbed by net braking elements in the support ropes. In addition, the rings in the system allow the passage of water and fine sediment beneath and through the net.

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[*] Corresponding author e-mail address: william.kane@kanegeotech.com

1.1 Development from rockfall barriers

European countries pioneered the development of rockfall protection barriers in the mid 20th Century. Rockfall barriers were the logical extension of snownets already installed in mountainous regions. Early snownets were composed of wire rope nets which held snowfall until spring melting thereby preventing avalanche formation. Post-thaw inspection of the nets showed them to have caught boulders which had fallen from above. This led to research and development of rockfall barriers on a full scale by Brugg Cable (now Geobrugg), Maccaferri, and other wire and wire rope manufacturers.

The California Department of Transportation (Caltrans), an early American adopter of rockfall barriers, observed that the barriers were effective in stopping small debris flows. This led to increased interest and research in the use of flexible nets to stop debris events.

2. Research

2.1 Theory

Existing methods for determining debris-flow protection were meant for large watersheds and large-scale structures such as basins and check dams (Bradley, et al., 2005). Early research on debris nets, including the use of anti-submarine ring nets, was conducted by the California Department of Transportation (Caltrans) and the United States Geological Survey (USGS). They installed a flexible ring net at the base a small flume (De Natale, et al., 1996). Other researchers were also conducting research on flexible nets in Japan, Europe and other countries. Conventional debris-flow net design is based on field observations and full-scale testing in controlled situations (Muraishi and Sano, 1997). Other publications related to the design of debris-flow protection systems includes Mitzuyama, et al. (1992), Rickenmann (1999, 2001), and PWRI (1988).

2.2 Illgraben research

After catastrophic debris flows in Switzerland in 2005, the Swiss government partnered with Geobrugg to conduct a major research program to determine if the nets could be used as lightweight, low-cost, environmentally sound replacements for concrete check dams and debris basins. The goal was to develop a standardized approach to debris-flow mitigation using flexible high-strength steel ring nets (Wendeler, 2017)

The main focus of the Swiss research was a full-scale test site on the Illgraben near Leuk, Switzerland. The Illgraben usually produces five to six debris-flow events per year. A fully instrumented debris net was installed, Fig 1. Geophones installed upstream signaled the instrumentation at the net site to begin collecting data. They also turned on floodlights for nighttime events. Instruments monitored flow height, net rope forces, flow velocity, and weight. The channel dimensions were well known so volume and density could be determined.

2.3 Mechanics of debris flow impacting flexible barrier

Geobrugg examined the forces involved in the impact of debris material into a flexible net. They found that flows occur in pulses or waves. The first pulse was stopped at the base of the net. Subsequent pulses flow up and over the previous pulses. Nets were designed using this information with the maximum forces at the base of the net. In addition, the flexing and deformation of the net and net ropes will also absorb the dynamic impact pressures. Once the debris material is stopped the net must then support the static load of the material.

It should be noted that debris flows tend to be sequential events so that after an initial dynamic impact, additional surges add only a quasi-static load to the net, instead of a fully dynamic load. In addition, the debris material already impacted and de-watered on the net serves to absorb some of the energy of the subsequent surges. The result is that much of the debris-flow material is not against the net, resulting in decreased energy absorption and height requirements, Fig 2.

2.4 Design concept

As a result of its research, Geobrugg (2003) developed a methodology suitable for the design of its debris-flow net systems. Existing research results allow a peak discharge to be calculated and the flow velocity estimated. Once the mass and velocity are known, the design pressures can be determined. Finally, the design height is calculated.

Fig 1. Instrumented test net in the Illbraben, Leuk, Switzerland.

2.4.1 DEBFLOW software

This methodology is incorporated into the software program, DEBFLOW, which determines the appropriate Geobrugg debris-flow system as a function of the characteristics of a given debris-flow basin and channel. The DEBFLOW program is based on the full scale testing in controlled situations at Illgraben, solutions of the rope equation, and finite element modeling.

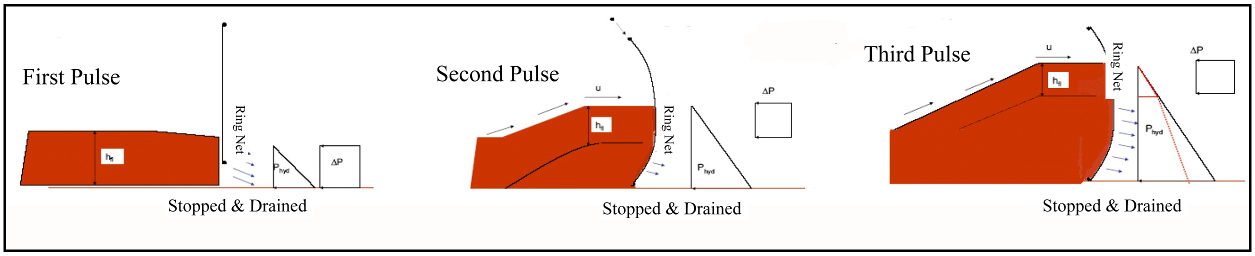


Fig 2. Schematic showing successive impact pressures from a debris flow being applied to a net. The net and its anchorages must be designed to withstand dynamic and static (Rankine) pressures. Note that successive debris impacts after the first flow lose energy by having to go up the previous flow and also stop debris material back up in the channel.

Given input parameters such as debris material, channel dimensions, number of pulses, etc. DEBFLOW provides the user with recommended Geobrugg nets. The type of net specified depends on the width of the channel and the calculated dynamic and static pressures.

There are two basic versions of the Geobrugg debris net systems. The VX net is intended for relatively narrow channels up to 40-ft (15-m) wide, Fig 3. The UX net is installed in wider channels up to 90-ft (25-m) wide and has posts to keep the top net support rope from sagging, Fig 4.

2.4.2 Debris-flow Volumes

In the United States, initial volumes can be estimated following debris flows using WERT and BAER Reports. However, these estimated total debris-flow volumes will frequently exceed the one-event capacity of the available flexible net designs. Therefore, for design purposes, nets can be assumed to fill completely.

Debris-flow volume storage area can be based on field observations, previous flow volumes, and measurements of channel geometry (Gartner, et al., 2008, and others,). For DEBFLOW analyses, the calculated volume of sediment detained by each net is based primarily on a uniform

Fig 3. Post-fire VX net installed above running stream in Nambé Pueblo, New Mexico. Note basal opening allowing water and fish passage beneath. Animals can pass either underneath or through rings.

geometry of each net and channel gradient. This assumes the storage area is a trapezoidal prism extending upstream from the net. This volume estimate does not take into account changes in channel shape upstream from each net location. However, sites are chosen to maximize storage area, so the volume estimates should be considered minimum values of sediment retained. Optimum locations are where channel geometry is constricted and upstream geometry widens to provide maximum storage capacity.

Fig 4. UX net with posts for wider channels Camarillo, California.

3. Design and Construction

In order to produce installation plans for the nets, it is necessary to consider strength of the anchoring rock and, if required, the design of foundations for the posts. Design loads are supplied to the engineer by the manufacturer as a result of their testing and modeling. Rock and soil properties are determined during the field investigation at each installation site.

Flexible debris nets can be constructed rapidly with minimal environmental impact and can be combined with the existing debris basins to maximize material storage in the canyons. They have a small construction footprint and do not change channel flow unless a debris-flow event occurs.

3.1 Anchor Design and Testing

Anchor design for UX and VX nets consists of determining the depth required to support the loads on the wire ropes. Previous work by the Post Tension Institute (PTI) (2014) gives a methodology for anchor design that is used for soil walls, tie-back walls, slope post-tensioning, slope stabilization system design, and rockfall and debris net anchor design. The PTI provides design charts with a recommended shear, or bond, strength for a particular rock/grout combination as determined by the geologist. The data comes from thousands of actual installations.

For example, from PTI tabulated data, a weathered and fractured sandstone will have a bond strength of 100-psi to 120-psi. The maximum test load, as provided by Geobrugg, for a debris net anchor is about 80,000-lbs. Using the PTI criteria and assuming a 4-in drill hole and minimum bond strength of 100-psi, the necessary depth to hold the anchor in the fractured sandstone is 10.6-ft. This is well within the capability of a small rock drill.

Rather than using estimates of bond strength material type, it is preferable when possible to perform actual field pull-out tests on anchors to determine the site-specific bond-strength characteristics. Verification anchors are sacrificial anchors installed in typical sections of colluvium or rock. The anchors are drilled to various depths and tested. The load at pullout can then be back-calculated to determine the actual bond strength for the particular rock in the field. Tabulated data is often very conservative and time and money can be saved by performing verification tests prior to net installation.

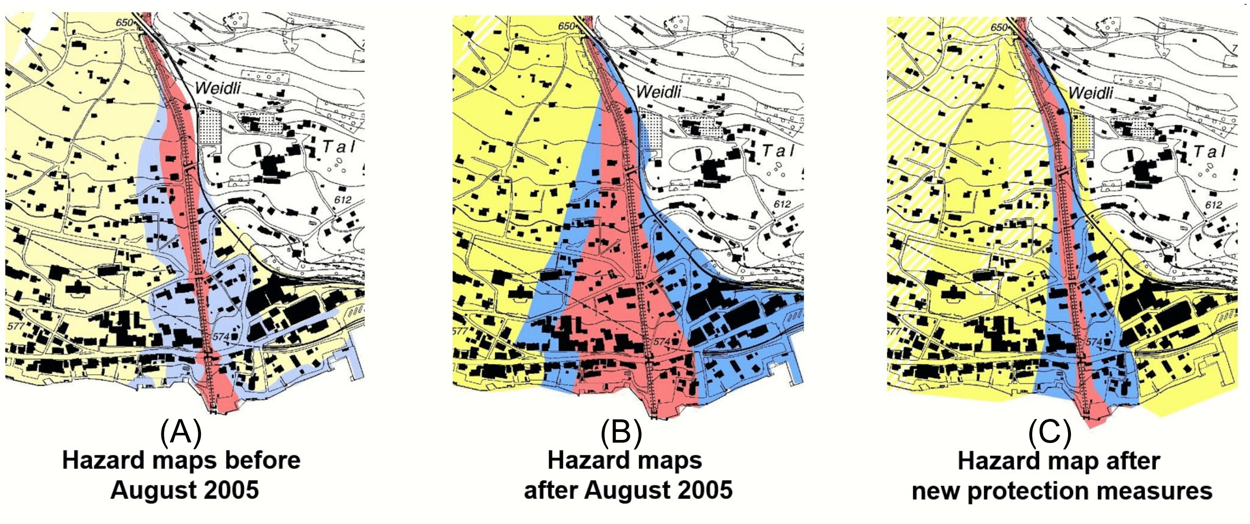
3.2 Foundation Design

UX nets require the construction of post foundations. Early practice involved using a large block of reinforced concrete about 1-m x 1-m. These blocks were not engineered and consisted of reinforced threaded bars inserted in the concrete to anchor the post base plate. Although easy and inexpensive to construct, they were prone to large foundation displacements and cracking on impact.

Subsequently, engineered shallow foundations were used. These foundations are designed using concrete and building codes for steel reinforcement. In general they are designed to use the passive pressure of the soil as the soil resistance. Since lateral loading on post foundations can exceed 80,000-lbs, foundation dimensions can become quite large and introduce additional complications during construction.

Because of the high loads and large foundation blocks, cast-in-drilled-hole (CDIH) foundations are considered economical alternatives to large concrete blocks. These foundations resist the loads by deformation and changing soil resistance. The design approach was developed by Reese & O'Neill (1988). Developed for laterally loaded pile foundations, the method utilizes the finite difference method and p-y curves (Reese & O'Neill, 1988). These curves model the soil or rock as systems of springs which push back on the foundation as it deforms from the bending of the foundation. Design consists of comparing the maximum moment developed in foundation with foundation strength. Displacement of various depths on the foundation can be calculated. Controlling factors in design are foundation size and displacement. The approach involves significant computational effort. Generally, lateral foundation loads are too great to use shallow foundations.

4. Construction



(A) Hazard maps before August 2005

(B) Hazard maps after August 2005

(C) Hazard map after new protection measures

Fig 5. Changes in risk in the town of Brienz, Switzerland before (A), after the catastrophic debris flows of 2005 (B), and after the installation of a system of Geobrugg debris nets in the Alpine drainages above the town (Geobrugg, 2017).

Debris net construction initially consists of drilling anchor holes and grouting wire rope anchors. Drilling equipment varies but in general downhole hammers are used. Sometimes these are hand operated but can be equipment mounted. Specialized equipment that can negotiate narrow canyons like the Kaiser SL2 are versatile and can drill quickly.

For UX nets and SLBs, foundations are constructed and posts erected. Because debris channels often contain loose sand and rock, foundation usually require an excavation. A reinforcing bar cage is fabricated and placed in the hole, concrete is then poured into the excavation. If the excavation is large, a sonotube or form is necessary. Backfill around the form must be compacted to perform as the material used in the design. Alternatively, a controlled density fill (CDF) or soilcrete can be used.

Support ropes are installed between the anchors. Then the ring nets are hung and secured with shackles. If a backing mesh is used, it is installed at this time. Finally, the overtopping plates are installed to the top rope.

5. Risk Reduction

After the flooding of August 2005 in Switzerland, the Swiss government and Geobrugg worked to reduce the debris risk to residents living in high risk zones by using environmentally sound debris nets. Fig 5 shows the changes in risk in the town of Brienz, Switzerland along the Trachtbach River after two catastrophic debris flows in summer 2005.

6. Case Studies

6.1 Glen Eyrie Conference Center, Colorado Springs, Colorado

In the summer of 2012, the Waldo Canyon Fire destroyed 11-mi^2 of mountainous land above the city. Debris flows following the fire created substantial damage. Glen Eyrie Conference Center at the base of Queen's Canyon installed three flexible debris nets. To protect the structures, a VX net was installed in the channel near the Center with a UX net directly above it. These nets were meant to be cleaned out. Further up the Canyon, a UX net was installed to protect a small water supply dam. It was not intended for clean out.

The lower UX net was a unique design. The channel was too wide to install a stock UX net. In addition, the Center required access to the back of the net. An engineered fill embankment was designed and constructed to allow the support ropes to pass through the embankment and be anchored directly in the bedrock, Fig 6. This design allowed the net to deform as intended since none of the actual debris net was embedded in the embankment.

6.2 Santa Clara Pueblo, New Mexico

The Jemez Mountains portion of the New Mexico lands of the Santa Clara Band of Pueblo Indians was devastated by the Las Conchas Fire in the summer of 2011. Initially nine sites were selected for flexible debris nets. Funding delays led to further degradation of the channels resulting in the construction of only five nets in the fall of 2014.

Equipment to construct the CIDH foundations for the UX nets could not be obtained so the contractor excavated the foundations and formed the shafts using sonotube tubes. A mixture of colluvium and cement was used to backfill around the tubes, resulting in higher strength than the native material originally there.

The following summer the nets experienced an impact. The resulting cost savings to the Pueblo from not having the material impact their road was significant, Fig 7.

6.3 Nambé Pueblo, New Mexico

The Pacheco Fire of 2011 burned Sangre de Cristo mountains above the Nambé Pueblo. Subsequent debris flows impacted the Nambé Rio and Nambé Reservoir. The Pueblo installed three debris nets along the water to prevent further degradation of the reservoir. The nets were designed with a relatively large basal opening to allow wildlife and small debris to pass beneath, Fig 3.

6.4 Camarillo Springs, California

The Springs Fire of May 2013 burned a large swath of the Santa Monica Mountains. A debris-flow event consisting of mostly ash occurred in October 2014. During cleanup, a second debris flow occurred in December 2014 doing significant damage to a number of homes in the community, Fig 8.

Several types of debris mitigation structures were constructed including shallow landslide barriers, UX and VX debris nets and berms to conduct surface runoff into the channels. The short time frame in which to construct the mitigation led to the use of soilcrete as backfill around excavations. Instead of a sonotube, a corrugated metal pipe was used for the foundation form. This added stiffness also enabled the shafts to be shortened, which in turn, allowed the construction time to be reduced.

Two days after construction was completed, the first major rainfall of the season occurred filling several of the nets, Fig 9.

Fig 6. VX net (below) and UX net (above) with armored access abutment, Glen Eyrie Conference Center, Colorado Springs, Colorado.

6.5 Montecito, California

In December and January, 2018, the Thomas Fire became the largest fire in California history. In early January 2018, torrential rains pounded the Santa Ynez Mountains above the coastal community of Montecito. The ensuing debris flows killed 23 people, destroyed 10% of the housing in the community, blocked the U.S. Highway 101 Freeway interrupting commerce, Fig 10.

A preliminary risk assessment of the mountain canyons and the community was made to determine the need for debris-flow mitigation prior to the upcoming rainy season (BGC, 2018). BGC concluded that a large supply of fine-grained sediment, boulders, tree-trunks, and branches remain in the canyons and is readily available for future debris-flow events in the coming rainy season. They also pointed out that the existing sediment basins in Montecito are inadequate to catch and store the volume of debris likely to be mobilized during a debris-flow event similar to the January 9, 2018 event.

BGC recommended that immediate mitigation action be taken and that an instrumentation and warning system be installed. They recommended that flexible debris nets be placed in the canyons to help protect against large-scale debris-flow events.

Seventy-one sites in the five canyons that drain into Montecito were identified as potential flexible debris net sites. Of those, 16 were to be constructed the first summer. However, delays caused by environmental permitting issues resulted in construction being scaled back to 12 debris nets. Another outcome of the environmental community concern was that no foundation construction could occur in the channels. This eliminated the consideration of UX nets. A “Super VX” net has been engineered to span the larger sites that conventional VX nets cannot span.

Fig 7. Filled Geobrugg UX debris net in Santa Clara Pueblo, New Mexico.

6.6 Conclusions

Flexible debris nets have been shown to be effective measures in the protection of people and property in post-fire debris events. Among the advantages are:

- Lightweight - easily deployed
- Rapid construction
- Economical
- Significant risk reduction
- Environmentally sound

With the size and frequency of wildfires in the American southwest increasing, the use of these nets has demonstrated that it is a proven technology for protecting people and infrastructure.

Fig 8. Aftermath of post-fire debris flow in Camarillo Springs, California.

Fig 9. Filled VX debris net in Camarillo, California.

Fig 10. Aerial view of debris-flow damage in Montecito, California, January 13, 2018.

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