RESPONSE OF FLEXIBLE WIRE ROPE BARRIERS TO DEBRIS-FLOW LOADING

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ABSTRACT

In June 1996, an experimental study at the U.S. Geological Survey Debris-Flow Flume established the degree to which flexible wire rope barriers could contain rapidly-moving, staged debris flows consisting of water-saturated, poorly-graded gravelly sand. Six tests were conducted with four different barrier designs. All debris flows had volumes of about 10 cubic meters, masses of about 20 metric tons, and impact velocities of 5 to 9 meters per second. The study demonstrated that flexible wire rope barriers can effectively mitigate or even completely contain small debris flows.

BACKGROUND

During the winter of 1994-95, a flexible wire rope rock net installed along California State Route 41 in San Luis Obispo County stopped and contained several rainfall-induced debris flows having a combined volume of approximately 60 cubic meters (Duffy and DeNatale 1996). In June 1996, a limited experimental study was undertaken to establish, in a more quantitative fashion, the response of such flexible systems to debris-flow loading.

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EXPERIMENT DESIGN

Field testing was performed at the U. S. Geological Survey Debris-Flow Flume located within the H. J. Andrews Experimental Forest near Blue River, Oregon. The flume is a reinforced concrete channel 95 meters long, 2 meters wide and 1.2 meters deep. The uppermost 88 meters of the flume bed lie at an angle of 31 degrees, while the lowermost 7 meters gradually flatten to a run-out slope of 3 degrees. A concrete run-out pad at this same 3 degree slope extends 25 meters beyond the mouth of the flume. Up to 20 cubic meters of water-saturated sediment can be discharged from the mouth of the flume at velocities of approximately 10 meters per second (Iverson et al. 1992). A view of the facility taken from the end of the concrete run-out pad is shown in Figure 1.

Figure 1: The USGS Flume

Massive 1.22 meter wide concrete panels can be placed on the run-out pad to confine the flow beyond the mouth of the flume. In the June 1996 experiments, eight confinement panels were placed to provide an additional 5 meters of channelized flow. This arrangement ensured that the flow would not spread laterally prior to its impact with the flexible barrier. A schematic plan view of the experiment configuration is shown in Figure 2.

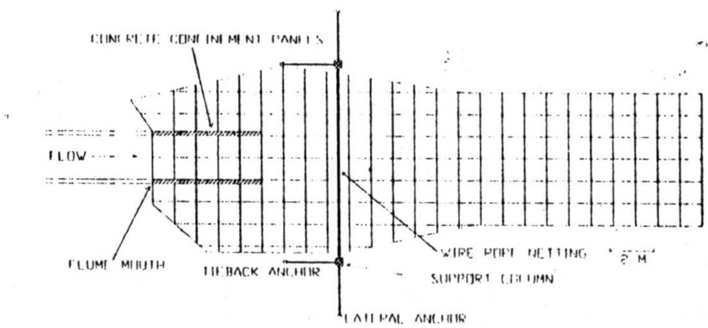

Figure 2: Schematic Plan View of the Experiment Configuration

In the June 1996 experiments, a load cell and two piezometers were placed within the run-out pad (1 meter behind the flexible barrier) to record the vertical total stress and pore fluid stress that developed at the base of the deposit. An ultrasonic flow depth sensor was attached to a support beam that crossed this same section. An extensometer was attached to the front of the net to record the time history of net deformation in the direction of flow. Load cells were installed in two of the four barrier anchor cables to measure the time history of tensile force sustained by these key structural elements. The kinematics of the flow and barrier response were documented through still and video camera surveillance during each event. In addition, a topographic survey of the deposit was performed at the conclusion of each event. A high-frequency digital data acquisition system permitted continuous, synchronous recording of all instrument signals.

THE DEBRIS

The selection of appropriate materials is an important step in any parametric study involving physical modeling. In the present study, an attempt was made to select a soil that was (1) reasonably similar in composition and properties to materials that typically comprise real debris flows, (2) reasonably pervious, so that 10 cubic meters of material could be placed behind the flume gate and saturated with water in under twelve hours, (3) readily available in large amounts, so that multiple flows could be released without having to transport and reuse any of the already-deposited material, and (4) readily available at a modest cost.

Initial laboratory investigations focused on three possible soils: (1) a poorly-graded, gravelly-sand mixture that had been used in previous USGS debris-flow experiments (hereafter referred to as the USGS mix), (2) a poorly-graded, gravelly-sand that had been deposited along California State Route 41 in San Luis Obispo County during the debris flows of 1994-95, and (3) a poorly-graded, medium-to-fine sand that is routinely deposited along California State Route 1 (the Pacific Coast Highway) near the community of Malibu during heavy winter storms. Bulk samples of the three soils were brought to California Polytechnic State University for geotechnical laboratory testing. All testing was performed in accordance with American Society for Testing and Materials (ASTM) standards.

Grain size distribution data are compared in Figure 3 and Table 1. The gradation characteristics of the USGS mix are remarkably similar to those of the Highway 41 soil. The hydraulic and mechanical properties of the USGS mix are quite similar to soil. The hydraulic and mechanical properties of the USGS mix are quite similar to those of many natural debris flow materials (Major et al. 1997). Previous testing has shown that 10 cubic meters of this mix can be saturated in less than six hours. Approximately 50 cubic meters of the mix were already stockpiled at the flume facility, and additional amounts were readily available from a nearby quarry at a modest cost. Since the USGS mix met each of the four selection criteria defined above, it was used in the current study.

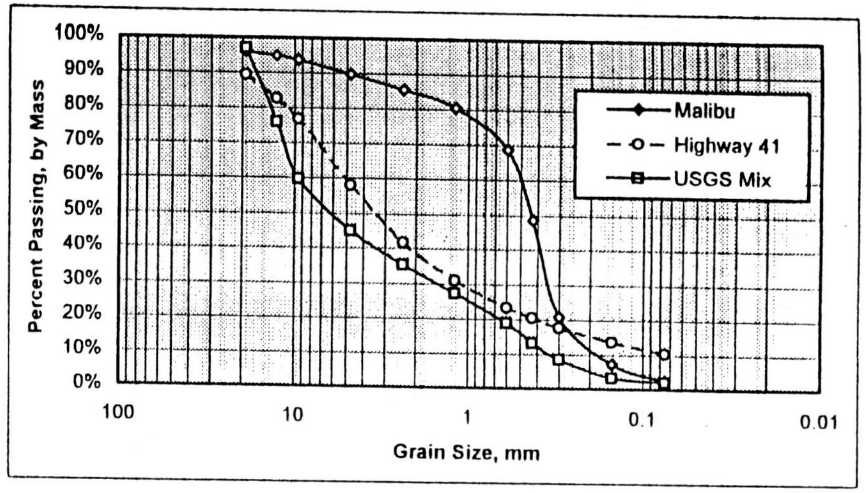

Figure 3: Grain Size Distribution Curves

Table 1: Comparison of Key Gradation Characteristics

SYMBOL	PROPERTY	PROPERTY VALUE		
		MALIBU	RTE 41	USGS
% G	Percentage Gravel	10.4	42.1	24.1
% S	Percentage Sand	87.1	47.6	73.9
% F	Percentage Fines (Silt + Clay)	2.5	10.3	2.0
D_{50}	Mean Grain Diameter (mm)	0.43	3.4	6.2
D_{10}	Effective Grain Diameter (mm)	0.19	0.07	0.35
C_u	Coefficient of Uniformity	2.63	74.3	27.3
C_c	Coefficient of Concavity	1.29	3.96	0.77
USCS	Unified Soil Classification System Symbol	SP	SP-SM	SP

THE FLEXIBLE BARRIERS

Six tests were conducted with four different barriers. All barriers had a height of 2.44 m (8 feet) and a length of 9.14 m (30 feet), sufficient to completely span the flume's concrete run out pad, as shown in Figure 2.

The first barrier system (Test #1) employed 30 cm by 30 cm (12 inch by 12 inch) wire rope netting overlaid with a 5 cm (2 inch) chain link liner to reduce the size of the largest clear opening. The net panel was supported by an infrastructure consisting of 1.90 cm (0.75 inch) diameter perimeter and anchor cables and two W 4 x 13 structural steel columns. W 4 x 13 is the American Institute for Steel Construction (AISC) designation for a wide-flange section having a nominal depth of 4 inches and a self-weight of 13 pounds/foot.

The second barrier system (Tests #2 and #3) employed 20 cm by 20 cm (8 inch by 8 inch) wire rope netting overlaid with a 5 cm (2 inch) chain link liner. A second chicken wire liner was attached to the middle third of the net to further reduce the size of the largest clear opening. The net panel was supported by an infrastructure consisting of 1.90 cm (0.75 inch) diameter perimeter and anchor cables and hinged-base columns. The barrier was subjected to two consecutive debris flows.

The third barrier system (Tests #4 and #5) employed 15 cm by 15 cm (6 inch by 6 inch) wire rope netting overlaid with full-width chain link and chicken wire liners. The net panel was supported by an infrastructure consisting of 1.90 cm (0.75 inch) diameter perimeter and anchor cables and W 8 x 48 fixed-base columns. The barrier was subjected to two consecutive debris flows. Oblique and close-up views of the unloaded barrier are shown in Figures 4 and 5, respectively.

The fourth barrier system (Test #6) employed 30 cm (12 inch) diameter interlocking rings overlaid with full-width chain link and silt screen liners. The net panel was supported by an infrastructure consisting of 1.90 cm (0.75 inch) diameter perimeter and anchor cables and W 8 x 48 fixed-base columns. Frontal and close-up views of the unloaded barrier are shown in Figures 6 and 7, respectively.

DEBRIS VOLUME, FLOW VELOCITY, ANCHOR CABLE FORCES, and BARRIER DEFLECTION

Debris volume, flow velocity, and net deflection data acquired during the six experiments are compared in Table 2. Flow velocities were derived from the time-stamped videotape records acquired with an overhead boom camera. The concrete run-out pad is marked with a set of one meter square grid-lines. Velocities were obtained by noting the time required for certain readily identifiable debris (such as the gravel spray, chunks of foam sealant, and/or wave fronts) to pass from one grid line to another.

Barrier deflection in the direction of flow was recorded by a cable extensometer that was attached to the net at mid-span, at a point 50 cm (20 inches) above the run-out pad. The time-histories of deflection are compared in Figure 8. The three successful barrier systems experienced comparable degrees of outward deflection during virgin loading (Tests #2, #4, and #6). In all three cases, the maximum deflection was between 1.5 and 2.0 meters. A second release of debris into an already-loaded net (Tests #3 and #5) produced less than one-half meter of additional outward movement.

Elementary mechanics tells us that the anchor force in a cable-stayed column can be reduced by increasing the flexural rigidity (EI) of the column or by increasing the moment resistance of the base plate assembly. The experimental anchor force data shown in Figure 9 are entirely consistent with elementary theory. The largest tie-back forces occurred during Test #1 (which employed fixed-base but relatively flexible

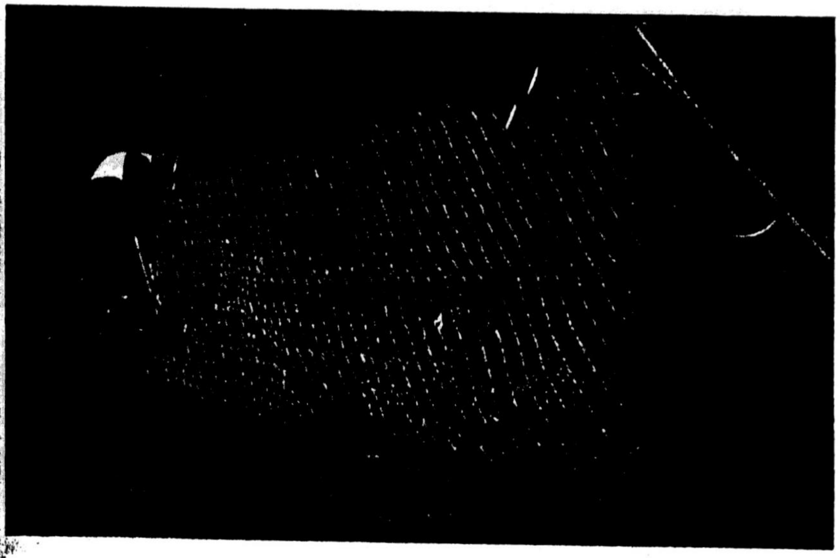

Figure 4: Oblique View of Barrier #3 (Test #4)

Figure 5: Detail of Chain Link and Chicken Wire Liners (Barrier #3)

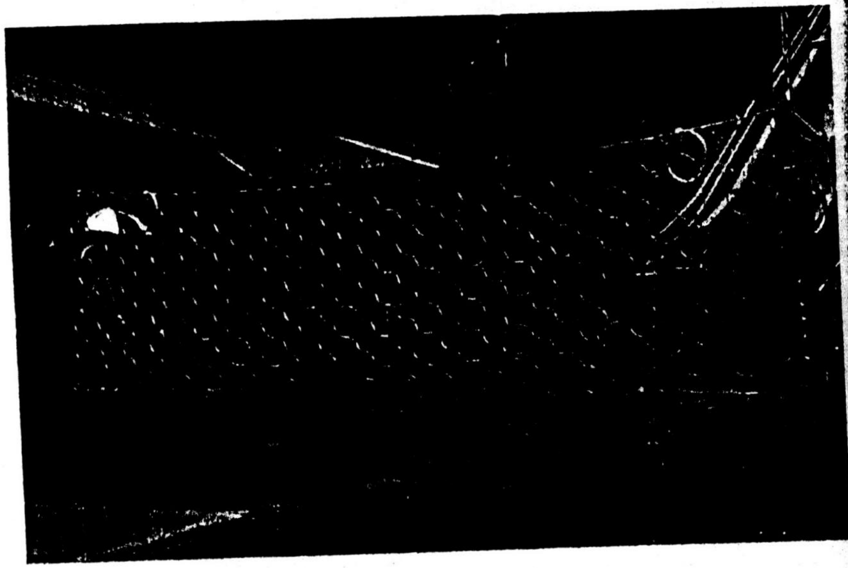

Figure 6: Frontal View of Barrier #4 (Test #6)

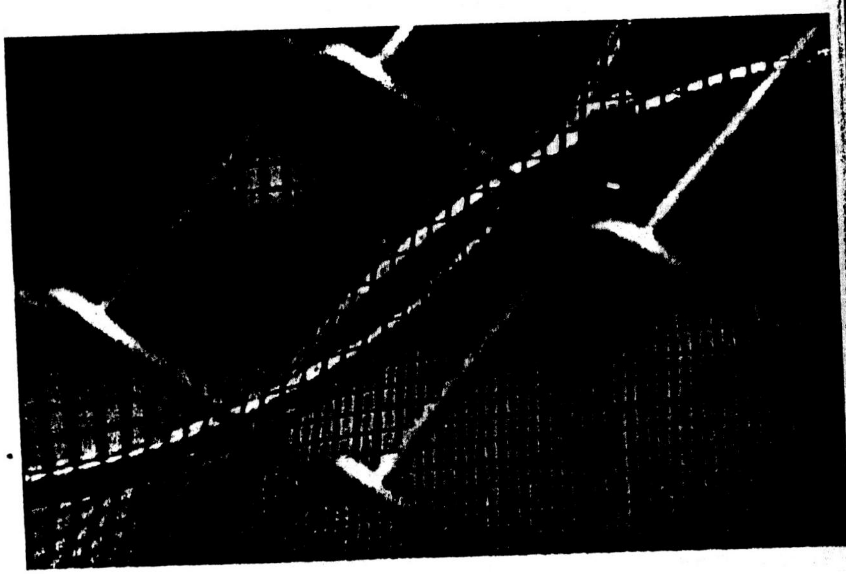

Figure 7: Detail of Interlocking Rings with Chain Link and Silt Screen Liners

W 4 x 13 columns) and Tests #2 and #3 (which employed hinged-base columns). The smallest tie-back forces occurred during Tests #4, #5 and #6 (which used fixed-base and relatively stiff W 8 x 48 wide-flange columns).

Table 2: Comparison of Debris Volume, Flow Velocity, and Net Deflection Data

Characteristic	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
Debris Volume (m^3)	9.8	9.6	10.3	10.4	10.4	10.1
Impact Velocity of Gravel Spray (m/sec)	SM	12.5	---	10.0	---	10.0
Impact Velocity of Debris (m/sec)	SM	9.0	6.5	8.0	6.0	5.0
Outward Deflection of Net Panel (m)	SM	1.46	0.30	1.93	0.40	1.50
SM = Data Acquisition System Malfunctioned						

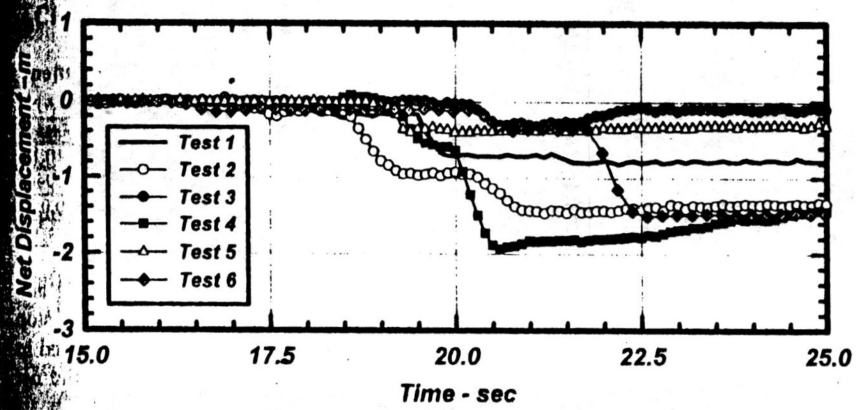

Figure 8: Time Histories of Net Deflection

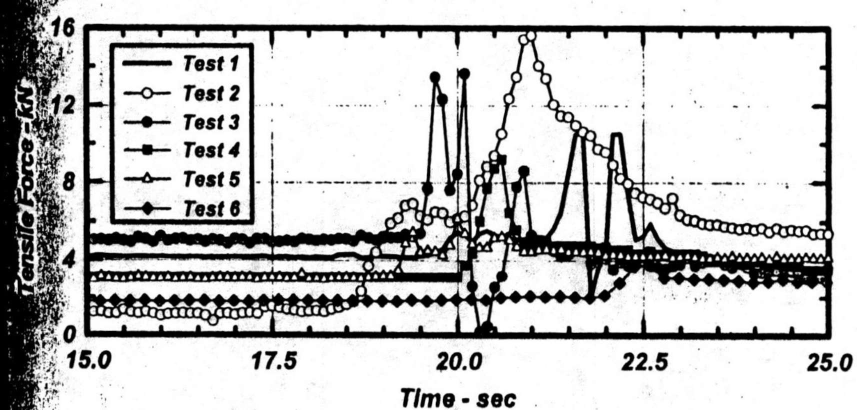

Figure 9: Time-Histories of Force in Right Tie-Back Anchor Cable

CONTAINMENT

The primary objective of the June 1996 field testing program was to establish the degree to which relatively open and porous flexible barriers could stop and contain rapidly-moving, staged debris flows. Hence, measurements were made of the volume and spatial distribution of the material that passed beneath or through each net.

A comparison of barrier effectiveness in terms of debris containment is presented in Table 3. The first two barrier systems incorporated full-width chain link net panel liners to reduce the size of the largest net opening. The first barrier system (Test #1) experienced a support column failure and collapsed during the flow event. The second barrier system performed well during the initial debris flow (Test #2) but experienced an anchor cable connection failure and partially collapsed during the subsequent debris flow (Test #3).

Table 3: Comparison of Barrier Effectiveness in Terms of Debris Containment

Characteristic	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
Initial Debris Volume (m^3)	9.8	9.6	10.3	10.4	10.4	10.1
Volume Passing Through Net (m^3)	SC	0.46	SC	0.12	.046	.0046
Percentage Passing (%)	SC	4.8	SC	1.2	0.44	0.05
Note: SC = System Collapsed						

The last two barrier systems incorporated full-width chicken wire (Tests #4 and #5) or silt screen (Test #6) liners. As shown in Table 3, each barrier was able to stop and contain the vast majority of the flowing debris. Full containment was realized in Test #6, where less than 0.05% of the sediment passed beneath or through the net (Figure 10).

Figure 10: Full Containment of Debris by the Ring-Net Barrier (Test #6)

SUMMARY

The experimental study described herein permitted the evaluation of four flexible debris-flow mitigation systems. The moderate variety of infrastructure options studied and the inherent variability of even a well-controlled, staged debris-flow make it difficult to isolate the effect of any single parameter during a six-test study. Nevertheless, the testing program did provide much useful data. Both the 15 cm (6 inch) wire rope barrier and the 30 cm (12 inch) interlocking ring net barrier stopped and contained the rapidly flowing sediment. Full containment was realized in Test #6, where less than 0.05% of the sediment passed beneath or through the net. These final two barrier systems may have the energy absorption and retention characteristics to effectively mitigate many small, natural debris flows.

ACKNOWLEDGMENT

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APPENDIX I: REFERENCES

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