# DEBRIS-FLOW INITIATION EXPERIMENTS USING DIVERSE HYDROLOGIC TRIGGERS

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## ABSTRACT

Controlled debris-flow initiation experiments focused on three hydrologic conditions that can trigger slope failure: localized ground-water inflow; prolonged moderate-intensity rainfall; and high-intensity rainfall. Detailed monitoring of slope hydrology and deformation provided exceptionally complete data on conditions preceding and accompanying slope failure and debris-flow mobilization. Ground-water inflow and high-intensity sprinkling led to abrupt, complete failure whereas moderate-intensity sprinkling led to retrogressive, block-by-block failure. Failure during ground-water inflow and during moderate-intensity sprinkling occurred with a rising water table and positive pore pressures. Failure during high-intensity sprinkling occurred without widespread positive pore pressures. In all three cases, pore pressures in most locations increased dramatically (within 2-3 seconds) during failure. In some places, pressures in unsaturated materials rapidly "flashed" from zero to elevated positive values. Transiently elevated pore pressures and partially liquefied soil enhanced debris-flow mobilization.

## INTRODUCTION

Most subaerial debris flows mobilize from landslides triggered by shallow ground-water flow in hillslopes. Several field investigations have attempted to record the shallow ground-water conditions that initiate debris flows (e.g. Harp et al. 1990; Johnson and Sitar 1990; Montgomery et al. 1990); however, no study has yet obtained high-resolution hydrologic data for the relatively infrequent, atypical hydrologic conditions that trigger debris flows. As an alternative, we created artificial slope failures under carefully controlled experimental conditions with intensive monitoring of hydrologic and deformation responses. Comparable control in the field would be difficult to achieve. Our experiments focused on monitoring soil moisture and pore-water pressure responses under three hydrologic conditions believed to trigger debris flows: localized ground-water inflow from adjacent bedrock or soil (e.g. Mathewson et al. 1990); prolonged moderate-intensity rainfall (e.g. Cannon and Ellen 1988); and bursts of high-intensity rainfall (e.g. Campbell 1975).

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We present complete data sets for hydrologic responses measured in three experiments, all of which resulted in slope failure and debris-flow mobilization. On the basis of these data, we discuss critical differences in the hydrologic behavior leading to slope failure and remarkable similarities in the pore-water pressure response during failure. Iverson et al. (1997) described mechanical analyses of slope stability and debris-flow mobilization for the first two experiments. Hydrologic response patterns for the third experiment (intense rainfall) produced new, illuminating results that differ from conventional ideas regarding slope instability.

## EXPERIMENTAL CONFIGURATIONS

Our three experiments (hereafter designated I, II, and III) were conducted in the USGS debris-flow flume (Iverson et al., 1992). In each experiment, we constructed a tabular prism of 5.3 to 6.4 $m^3$ of soil behind a 0.65-m high retaining wall installed near the head of the 2-m wide, 95-m long flume (Fig. 1). Here, the flume contains channels on the bed for simulating ground-water inflow, an overhead sprinkler system for simulating rainfall, and a drain near the retaining wall for controlling water outflow.

All experiments used relatively homogeneous, isotropic granular soils, which were placed behind the retaining wall using a front end loader and hand shovels. Although no attempt was made to systematically densify the resulting loose soil, no obvious layering or macropores were observed in the soil prisms. For experiments I and II, we used a mix of poorly sorted sand and fine (<10 mm) gravel having a porosity of 0.41-0.48 and a saturated hydraulic conductivity of about $10^{-3}$ m/s (Iverson et al., 1997). For the high-intensity sprinkling experiment III, we used a mix of poorly sorted silty sand having a porosity of about 0.5 and a hydraulic conductivity less than the high-intensity sprinkling rate. Also in experiment III, we placed a thin layer of gravel on the soil surface to retard surface erosion. Sprinkling intensities in experiments II and III ranged from about 50 to 200 mm/hr. Although these intensities are high for temperate rainfall, experimental soil hydraulic conductivities were large, and it is the ratio of rainfall intensity to hydraulic conductivity that controls hydrologic behavior. We define high intensity as greater than the saturated hydraulic conductivity.

Subsurface monitoring instruments were arranged in nests at several locations within the soil prisms to measure infiltrating water or a rising water table (Fig. 1). Each nest typically included deep (within 10 cm of the bed), intermediate, and shallow sensors. We measured unsaturated soil water tension (negative pressure) as well as positive pore pressures preceding failure in each experiment with 9 or 10 tensiometers equipped with bi-directional pressure transducers (Baum and Reid, 1995). We determined volumetric soil moisture content with either a 6 probe time domain reflectometry (TDR) system designed by Herkelrath et al. (1991) or a 9 probe commercially available TDR system. Immediately prior to and during failure, we measured positive pore pressures using 6 or 9 sensors designed for optimal dynamic response (Iverson and LaHusen, 1989). Surface displacement was measured with two extensometers and recorded on sequences of still photographs and videotape. Iverson et al. (1997) provides examples of still photographs taken during failure in experiments I and II. Data from all sensors, except the TDR probes, were logged digitally using personal computers equipped with hardware and software for high-speed, high-volume data acquisition. Data for experiments I and II were collected at 1 Hz prior to failure and at 1000 Hz during failure.

For experiment III, data were collected at 10 Hz. TDR probes were sampled every 3-4 minutes by a separate data-acquisition system.

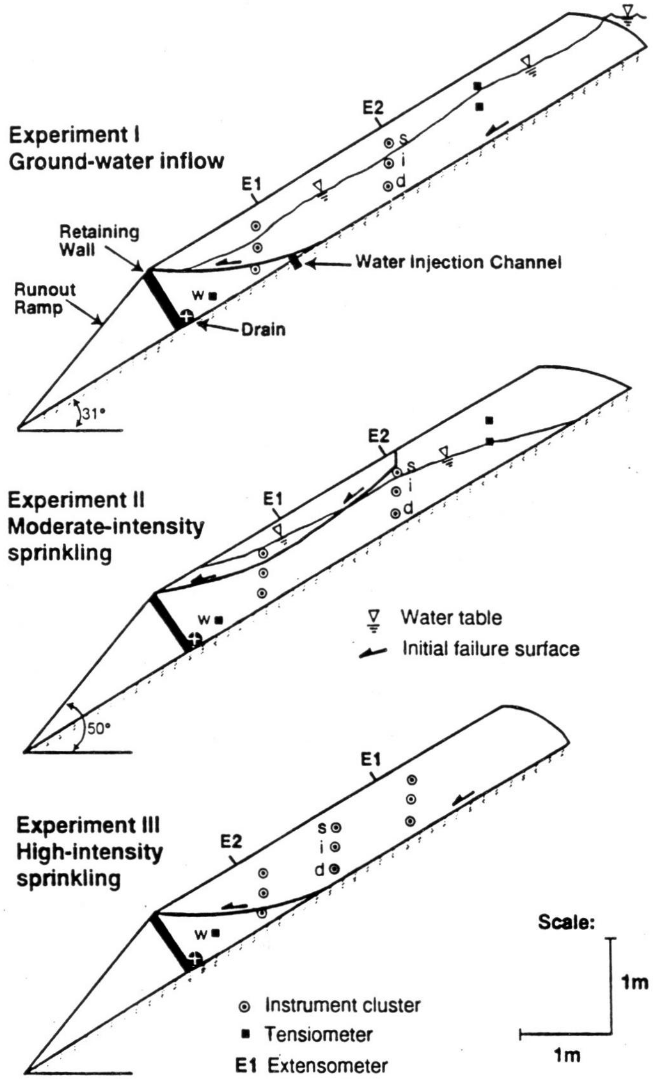

Figure 1. Schematic vertical cross sections of soil prism configurations for three experiments showing water-table profiles immediately prior to failure and inferred initial failure surfaces . Most instrument nests have a deep (d), intermediate (i), and shallow (s) cluster contain a tensiometer tip, TDR probe, and dynamic pore-pressure sensor. Tensiometer (w) is near the retaining wall.

## HYDROLOGIC CONDITIONS LEADING TO FAILURE

The three modes of water application (ground-water inflow, moderate-intensity rainfall, and high-intensity rainfall) lead to differing hydrologic behaviors preceding slope failure. In all three experiments, details of the sensor responses correlate well with the water application history and with directions of water movement (downward infiltration or a rising water table). Moreover, data from the different types of sensors corroborate each other.

### Experiment I (Ground-water inflow)

Figure 2 depicts the hydrologic response to water applied exclusively by subsurface inflow via an injection channel and an upslope infiltration pond.

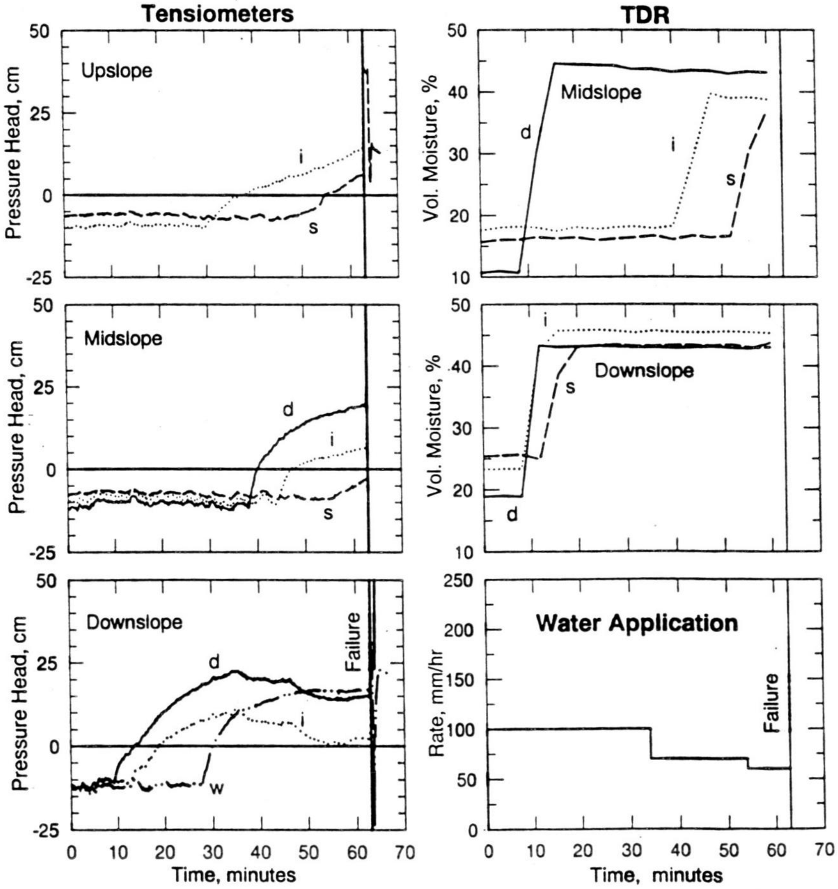

Figure 2. Hydrologic responses during experiment I (ground-water inflow).

The water application rate is the volumetric influx per horizontal surface area. During this experiment, we adjusted the inflow rate and the drain outflow rate to create a nearly slope-parallel water table with negligible ground-water exfiltration at the slope toe. Initially, most of the tensiometers measured negative pressures and the TDR probes registered low moisture contents (10-25%), indicating that the soil was unsaturated. The deeper tensiometers downslope of the injection channel responded first to ground-water inflow. All nests of both tensiometers and TDR probes showed a consistent response pattern over time with the deeper sensor responding first (solid lines in Figure 2), then the intermediate sensor (dotted lines), and finally the shallow sensor (dashed lines). After pore pressures became positive, most continued to rise, with the highest pressures measured by the deepest tensiometers. Pressure decreases in two downslope tensiometers were caused by reducing the water injection rate from the injection channel immediately upslope. Once TDR probes registered responses, volumetric moisture contents increased relatively quickly to around 40% (similar to the porosity) indicating saturation. These responses are consistent with a rising water table. Failure occurred while most of the sensors showed increasing positive pore pressures.

### Experiment II (Moderate-intensity sprinkling)

The hydrologic response to moderate sprinkling (Fig. 3) differed from that in experiment I. During initial sprinkling at about 50 mm/hr, both TDR nests showed that a wetting front moved slowly downward from the surface, but that the soil remained unsaturated behind the front with moisture contents of 20-25%. The slope remained unsaturated for more than one hour. Then positive pressures developed in the two deep tensiometers downslope and moisture content determined from the deep TDR probe in the downslope nest increased to above 40%. These measurements indicated the formation of a small saturated wedge and water table near the retaining wall, caused by transient perching on the impermeable flume bed. For more than two hours with the drain open, the saturated zone was confined to this small wedge and failure appeared unlikely with this sprinkling intensity. We then doubled the sprinkling intensity to about 100 mm/hr. Conspicuous exfiltration of ground-water near the slope toe, surface runoff, and gullying ensued. Pore pressures recorded by the midslope and downslope tensiometer nests increased rapidly and became positive. Moisture contents determined from the other TDR probes increased as well. Pore pressures in the upslope tensiometer nest, however, remained negative. Thus, a saturated wedge (with a rising water table) rapidly grew in the downslope part of the slope.

In this experiment, failure also occurred after most of the sensors indicated increasing positive pore pressures. Many field studies have documented similar hydrologic behavior in soils involving transient perching of a water table on underlying lower permeability materials (e.g. Weyman 1973; Reid et al. 1988), and this mechanism forms the basis for most analyses of debris flow triggering by rainfall (e.g. Campbell, 1975). Interestingly, pore pressures in two shallow sensors declined before failure (Fig. 3), apparently due to soil dilation coincident with measured downslope soil creep and observed tension crack development. Iverson and LaHusen (1989) and Harp et al. (1990) reported similar evidence of pore pressure declines before slope failure.

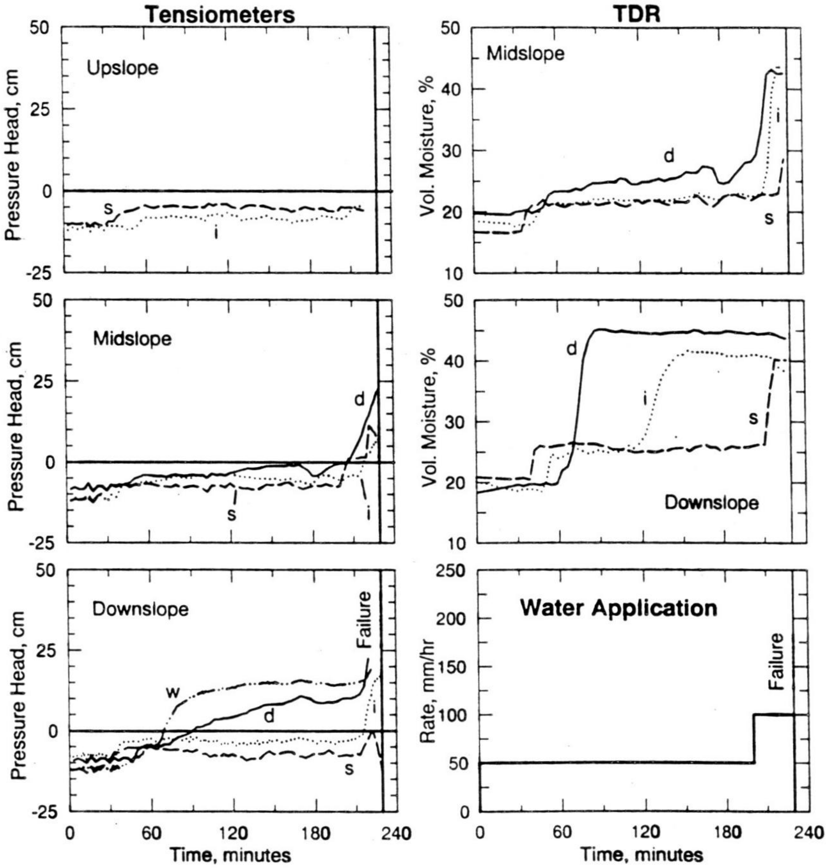

Figure 3. Hydrologic responses during experiment II (moderate-intensity sprinkling).

## Experiment III (High-intensity sprinkling)

High-intensity sprinkling produced precursory hydrologic behavior more enigmatic than in the previous experiments (Fig. 4). Our water application strategy was to initially wet the soil and then to apply a high-intensity burst of sprinkling. During the initial wetting period, we applied moderate (about 100 mm/hr) sprinkling. All the tensiometer and TDR nests showed similar response patterns, with shallow sensors responding first, intermediate next, and deep last, indicating the downward movement of an unsaturated wetting front. Rapid perturbation and slow re-equilibration of tensiometer pressures during the first 10 minutes of sprinkling is probably due to thermal effects of the applied cold water (local air temperatures were higher during this experiment) . During this phase of water application, however, most soil tensions approached and remained near zero, and the shallow and intermediate moisture contents increased to about 35%. The difference between these moisture contents and the porosity is probably due to entrapped air. Thus, most of the soil became wet and nearly saturated or "tension saturated." We discontinued this moderate sprinkling before any positive pore pressures developed and then applied high-intensity (about 200 mm/hr) sprinkling. After 8 minutes, shallow gullying and surface slumping occurred at midslope and downslope locations, exhuming several of the shallow sensors. Failure occurred after 11 minutes of high-intensity sprinkling. During this high-intensity sprinkling period, the tensiometers showed small responses to thermal and unloading effects, and some of the TDR probes showed small increases in moisture content. Only one sensor, the deep upslope tensiometer, showed steadily increasing small positive pore pressures prior to failure (some of the other sensors increased early in this period, but were level during the few minutes preceding failure). This failure was not induced by a large region of positive pore pressure.

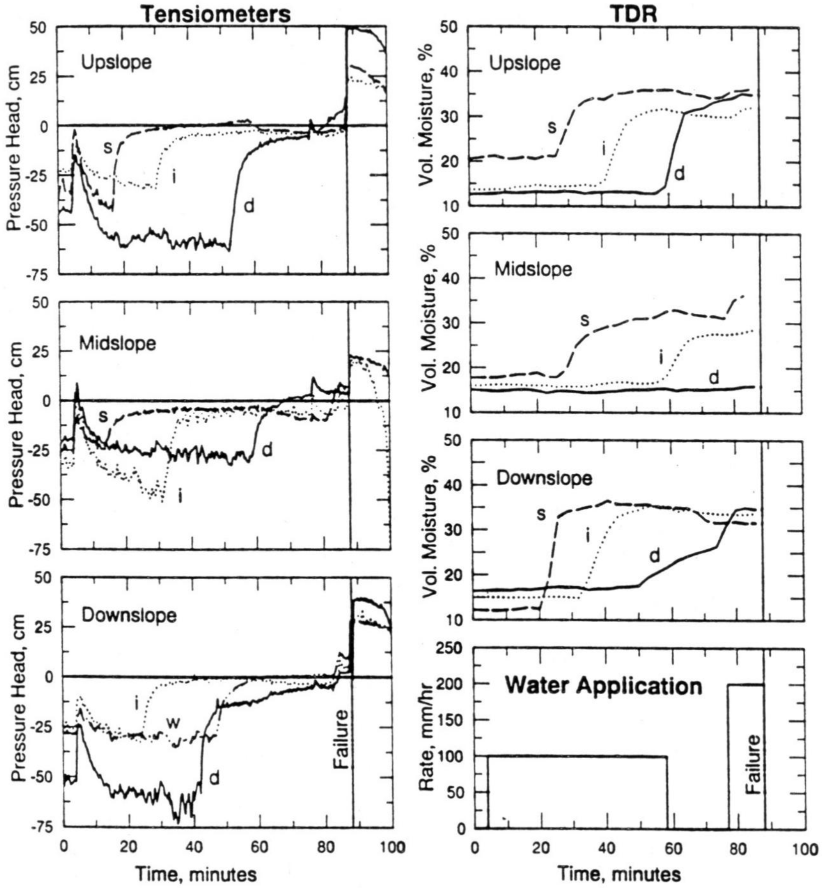

Figure 4. Hydrologic responses during experiment III (high-intensity sprinkling).

## DIVERSE HYDROLOGIC CONDITIONS AT FAILURE

Immediately prior to failure the pore-pressure distributions and resulting water table configurations within the soil were very different in the three experiments (Fig. 1). Nevertheless, all three configurations led to slope failure and subsequent debris-flow mobilization. In experiment I, the water table nearly paralleled the slope and growing positive pore pressures were present in over half the soil. Video and photographic records indicate that the failure surface intersected the flume bed and that failure involved most of the soil mass. In experiment II, the water table formed a wedge against the downslope retaining wall. The initial failure was relatively thin and involved only part of the downslope region. Within one second of the initial failure, slope rupture retrogressed upslope and eventually involved about one third of the soil in a process of block-by-block failure. Failure did not, however, retrogress to the head of the prism, nor did it appear to penetrate to the flume bed. In experiment III, the water table was minimal or nonexistent. In this experiment, the initial failure surface extended along the flume bed and failure involved most of the soil mass, similar to experiment I.

Conventional limit-equilibrium stability analyses that account for changes in effective stress caused by positive pore pressures appear capable of explaining the failures in experiments I and II, where large domains of positive pore pressure existed prior to failure (Iverson et al., 1997). In experiment III, lack of widespread positive pore pressures prior to failure makes failure more difficult to explain. Anderson and Sitar (1995) proposed that undrained loading caused by high-intensity rainfall without sufficient drainage can trigger failure. In our experiment, failure caused by added weight (overcoming cohesional strength) or by the reduction of soil water tension appears unlikely because the soil was wet and developed nearly zero tensions long before failure. Undrained unloading caused by shallow surface slumping may have triggered failure, but lack of significant positive pore pressures reduces the efficacy of this mechanism. We favor a mechanism wherein high-intensity sprinkling produced a small pressure perturbation that traveled downward from the surface through tension-saturated materials. When this perturbation arrived at the flume bed, positive pore pressure developed immediately at the bed and propagated upward, triggering failure. Such rapid response in tension-saturated materials is analogous to the rapid and large responses to rainfall observed in a capillary fringe (Gillham, 1984).

## PORE-PRESSURE RESPONSE DURING FAILURE

Although the hydrologic conditions leading to failure differed greatly between the three experiments, dynamic pore pressures measured during failures were remarkably similar (Fig. 5). In all experiments, positive pore pressures increased dramatically contemporaneous with rapid downslope soil displacement. This increase is probably a response to soil contraction and agitation (Iverson et al., 1997). During failure the soils partially liquefied, aiding in debris-flow mobilization. Most pore pressures more than doubled during failure, similar to behavior measured by Iverson and LaHusen (1989) and by Eckersley (1990). In general, pore pressures were greatest in the deep sensors, creating large upward or outward pore-pressure gradients (Fig. 5). Pressure decreases seen in Fig. 5 were due to sensors pulling out of the moving soil.

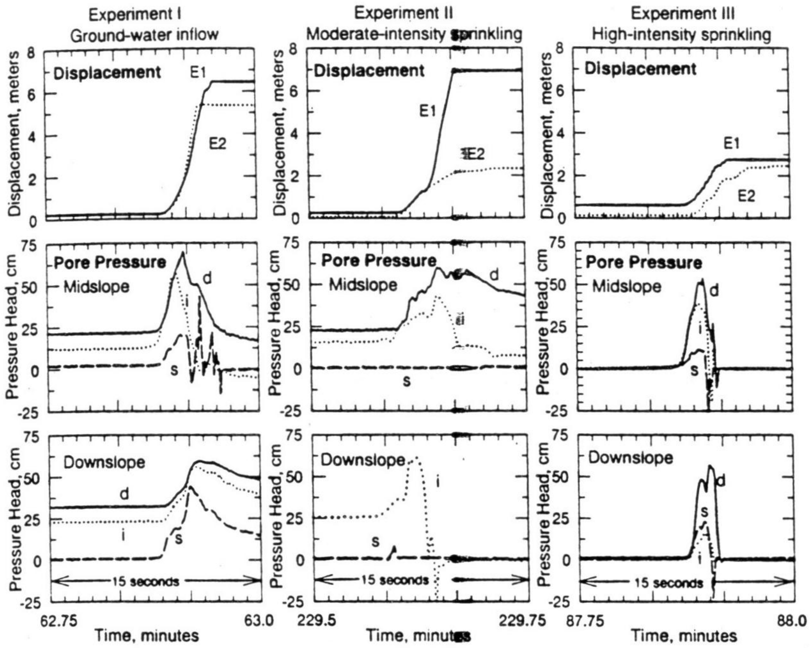

Figure 5. Surface displacement and pore pressure response during failure for the three experiments.

Responses measured in the three experiments differ in several ways. In experiments I and III, pore-pressure change was very rapid (about 2 seconds to peak), and all sensors responded. In experiment I, the two shallow sensors above the water table recorded zero pore pressure prior to failure, and in experiment III, all but one of the sensors recorded zero pressure. Nevertheless, all these sensors responded with large increases in positive pore pressure during failure. This "flashing" to elevated positive pore pressures throughout a nearly saturated soil mass was probably caused by contracting soil (Iverson et al., 1997). Widespread elevated pressures account for the highly liquefied appearance and almost complete mobilization of these two failures. In contrast, during experiment II pressure response was slightly slower and longer (about 3-4 seconds to peak). The two shallow sensors above the water table remained near zero and did not "flash" to elevated positive pressures. This failure did not completely liquefy, and instead failed in a slower block-by-block mode.

## CONCLUSIONS

1) Three experimental hydrologic conditions (ground-water inflow, moderate-intensity sprinkling, and high-intensity sprinkling) triggered slope failure and subsequent mobilization of poorly sorted granular debris. Ground-water inflow and high-intensity sprinkling led to abrupt, complete failure whereas moderate-intensity sprinkling led to retrogressive, partial failure.

2) Failure during ground-water inflow and during moderate-intensity sprinkling occurred under conditions of a rising water table and a large region of increasing positive pore pressures. Failure during high-intensity sprinkling occurred without a widespread region of positive pore pressures; failure mechanics in this mode are more enigmatic.

3) During all failures, pore pressures in most locations increased rapidly. In some places, pressures in unsaturated domains "flashed" from zero to elevated positive values. Partial liquefaction of the soil and large upward pore-pressure gradients enhanced debris-flow mobilization.

## ACKNOWLEDGMENTS

We thank Susan Cannon and Jon Major of the U.S. Geological Survey and two anonymous reviewers for their helpful reviews of this paper. We thank Tony Bequette, Sarah Christian, Kevin Hadley, and Winston Stokes for assistance with experiments.

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**Hyatt Regency San Francisco**
**San Francisco, California**
**August 7-9, 1997**

**Edited by Cheng-lung Chen**

Published by the
**ASCE** **American Society of Civil Engineers**
345 East 47th Street
New York, New York 10017-2398

Abstract:
This proceedings, *Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment*, contains papers presented at the First International Conference held in San Francisco, California, August 7-9, 1997. The papers covered a variety of topics ranging from debris-flow mechanics to debris-flow hazards prediction and assessment. In addition to the peer-reviewed papers, this volume includes two invited papers. One presents an overview on the geoscience and geotechnical engineering aspects of debris flow while the other provides an overview of hydroscience and hydrotechnical engineering aspects.

Library of Congress Cataloging-in-Publication Data

Debris-flow hazards mitigation : proceedings of first international conference : sponsored by the Technical Committee on Hydromechanics, Subcommittee on Mechanics of Non-Newtonian Fluids Applied to Debris Flows and Mudflows and the Technical Committee on Sedimentation of the Water Resources Engineering Division of the American Society of Civil Engineers, in cooperation with the Federal Emergency Management Agency, International Association for Hydraulic Research, and the U.S. Geological Survey : Hyatt Regency San Francisco, San Francisco, California, August 7-9, 1997 / edited by Cheng-lung Chen.
p. cm.
ISBN 0-7844-0268-X
1. Debris avalanches--Congresses. 2. Debris avalanches--Safety measures--Congresses. I. Chen, Cheng Lung, 1931- . II. International Conference on "Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment" (1st : 1997 : San Francisco, Calif.) III. American Society of Civil Engineers. Subcommittee on Mechanics of Non-Newtonian Fluids Applied to Debris Flows and Mudflows. IV. American Society of Civil Engineers. Sedimentation Committee.
QE599.A1D43 1997 97-24995
551.3'09--dc21 CIP

Library of Congress Catalog Card No: 97-24995
ISBN 0-7844-0268-X
Manufactured in the United States of America.

Cover photos: Four photos of a debris flow over a dam at Kamikamihorizawa Creek of Mount Yakedake, Japan (photographed on August 3, 1976, in sequence of 2 seconds apart). Photos courtesy of Prof. Hiroshi Suwa of Kyoto University.