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GEOTECHNICAL PROPERTIES OF DEBRIS-FLOW SEDIMENTS AND SLURRIES

J.J. Major¹, R.M. Iverson¹, D.F. McTigue², S. Macias², and B.K. Fiedorowicz³

ABSTRACT

Measurements of geotechnical properties of various poorly sorted debris-flow sediments and slurries (≤ 32 mm diameter) emphasize their granular nature, and reveal that properties of slurries can differ significantly from those of compacted sediments. Measurements show that: (1) cohesion probably offers little resistance to shear in most debris flows under low confining stresses normally found in nature; (2) intrinsic hydraulic permeabilities of compacted debris-flow sediments vary from about 10^{-14} - 10^{-9} m²; permeabilities of "typical" debris-flow slurries fall toward the low end of the range; (3) debris-flow slurries are characterized by very large values of "elastic" compressibility ($C \sim 10^{-2}$ kPa⁻¹); and (4) hydraulic diffusivities of quasistatically consolidating slurries are $\sim 10^{-4}$ - 10^{-7} m²/s. Low hydraulic diffusivity of debris slurries permits excess fluid pressure and low effective strength to persist during sediment transport and deposition.

INTRODUCTION

Recent modeling and experimental data indicate that debris flows and their deposits are fundamentally granular media influenced by solid-fluid interactions (Iverson 1997a,b; Hutter et al. 1996; Major 1996; Martosudarmo and Johnson 1997). One important solid-fluid interaction that characterizes debris flows is modification of stresses by pore fluid in a deforming mass of frictional material. Iverson (1997a,b) hypothesizes that, under common conditions, debris-flow mobility is strongly affected by Coulomb resistance to shear. This hypothesis is motivated by studies of experimental debris flows (~ 10 m³) composed of gravel, sand, and mud that have documented nonuniformly distributed, nearly lithostatic

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pore-fluid pressure during debris mobilization (Iverson et al. 1997), transport (Iverson 1997a,b), and deposition (Major 1996). Those experiments demonstrate that elevated pore-fluid pressure persists for the tens-of-seconds duration of the experimental flows as well as during post-depositional sediment consolidation. Therefore, soil friction and pore-fluid hydraulics may play a key role in debris-flow behavior. Here, we present measurements of properties relating to the strength and hydraulic diffusivity of various poorly sorted debris-flow sediments ($\leq 32\text{mm}$ diameter). We present properties of both water-saturated sediments measured using standard geotechnical methods and liquefied debris slurries subject to geostatic load. We address three basic questions: (1) How is it possible for excess ($>$ hydrostatic) pore-fluid pressure to persist, rather than dissipate, during transport and deposition of the experimental debris flows? (2) Can fluid pressures of such magnitude persist for the duration of a typical natural debris flow? (3) How do Coulomb strength parameters of natural debris flows containing abundant fine debris compare with those of the experimental debris?

PROPERTIES RELATED TO COULOMB STRENGTH

Coulomb strength of granular debris is partitioned between cohesion and friction. Accordingly, we measured the apparent cohesion (c) and internal friction angles (ϕ) of a variety of debris. These properties describe the ability of static debris to resist shear; they also are relevant to a new hydraulic model of debris-flow motion (Iverson 1997b).

PROPERTIES RELATED TO PORE-FLUID HYDRAULICS

Dissipation of excess pore-fluid pressure in a granular medium is a diffusive process, characterized by a diffusivity coefficient (D). This coefficient depends on properties of both the granular skeleton and the intergranular fluid. For simple linear diffusion, the coefficient of diffusivity is approximated by (Major 1996)

$$D = \frac{kK}{\mu} \quad (1)$$

where k is the permeability of the granular skeleton (in m^2), K is the elastic bulk modulus (reciprocal of compressibility, C) of the skeleton (in Pa), and μ is the viscosity of the pore fluid (in Pa-s). Bulk modulus relates isotropic stress to volumetric strain in an elastic specimen; the larger the modulus, the less compressible the material. A kindred property that provides information regarding soil deformation is the compression index (C_c), a measure of compressibility commonly used in soils analyses. The compression index relates changes in void ratio (e) to changes in applied vertical effective stress (σ'_v) (Lambe and Whitman 1969).

MATERIALS

A diverse range of debris-flow sediments was used in this study. The sediments include mixtures of sand and gravel bearing a few percent mud used at the USGS debris-flow flume (Iverson 1997a; Major 1997); clay-bearing debris of the 1980 North Fork Toutle River debris flow from Mount St. Helens, Washington (Scott 1988); and clay-rich debris of the Osceola Mudflow from Mount Rainier, Washington (Vallance and Scott 1997). These sediments were selected because they encompasses a range of many debris flows (figure 1).

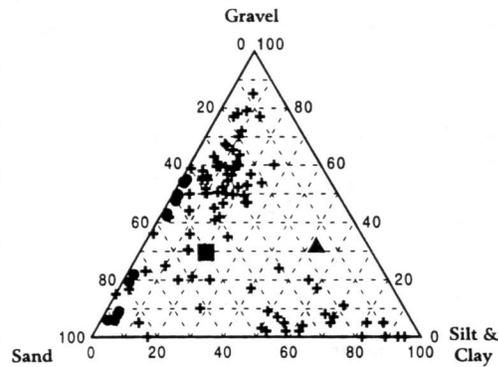


Figure 1. Sediment compositions (≤ 32 mm diameter) of debris flow deposits. Circles, USGS flume debris; square, Mount St. Helens debris; triangle, Osceola Mudflow; crosses, other debris-flow deposits. Most natural debris flows include many grains > 32 mm, which are excluded here.

METHODOLOGY

We obtained static Coulomb strength parameters and other properties related to deformation of compacted debris by compressing samples under low confining stresses in 4-, 6-, and 15-inch-diameter triaxial cells following ASTM standards (ASTM 1995). We used large-diameter cells to test the USGS flume debris, which contained particles up to 32 mm diameter. We used the smaller cell to analyze debris from Mount St. Helens and Mount Rainier; in these analyses particles larger than 10 mm were removed.

Several properties that describe soil deformation are based on the assumption that granular debris behaves elastically. We acknowledge, however, that soils behave elastically only under very small strains (e.g., Hicher 1996). Even at small strains, soil behavior may be nonlinearly elastic, with properties dependent on mean effective stress; void ratio; shape, size and size-distribution of grains; and loading history (Hicher 1996). We limit our estimates of elastic properties to initial behavior under relatively small strain ($\epsilon \sim 0.03$ -3%).

Preparation, saturation, and loading of compacted samples simulated natural conditions. Preparation included incrementally adding debris to a cell mold and tamping each debris layer to achieve dry bulk densities of 1500-2000 kg/m³, comparable to natural bulk densities (Ellen 1988; Iverson 1997a; Major 1997). Following specimen saturation, confining stresses and pore-fluid pressure (in the 4" cell) were adjusted to achieve effective-confining-stress magnitudes typical of debris flows (about 10-200 kPa). Effective confining stresses were held constant during standard triaxial tests. Tests conducted in the larger two cells were not subject to back-pressured pore fluid. In those drained tests, pore-fluid pressure was assumed to be zero. Specimens were compressed at constant rates of strain during a test, but rates

varied among tests. Strain rates varied from 0.01% to 0.13% per minute in the larger two cells to about 0.2% per minute in the small cell. Detailed test conditions are reported in Major (1996).

Triaxial tests performed under low stresses are sometimes influenced by stiffness of the latex membrane that surrounds the specimen. Following ASTM (1995) procedures, we measured Young's modulus ($\bar{E} = 750$ kPa) for a 0.3mm-thick latex membrane. Under the stress magnitudes employed in these analyses (Major 1996), deviatoric stresses apparently were affected by no more than a few percent by membrane stiffness. Therefore, results presented here are not corrected for stiffness of the latex membrane.

We evaluated permeabilities of compacted sediments and a few slurries, measured under constant-head conditions, for a range of porosities (n). Test details (Major 1996) are briefly summarized here. We made 48 measurements using a compaction permeameter modified to permit upward, rather than downward, flow, and 20 measurements during isotropic compression tests in the 4" triaxial cell. Several procedures achieved variable porosities in the compaction permeameter. In some tests, we poured sediment loosely into the mold; in others, sediment was tamped with varying degrees of vigor. For comparative purposes a few specimens were slurried and poured into the mold. Triaxial specimen preparation is described above. During tests, hydraulic gradients were ≤ 0.38 in the compaction permeameter. In the 4" cell, we applied a 7-14 kPa differential pressure to each specimen to drive water from bottom to top. In these tests, hydraulic gradients were large (3.2-9.6), but applied confining stress prevented specimen liquefaction. Permeability was determined from Darcy's law.

We compared estimates of compressibility and hydraulic diffusivity (equation 1) obtained from deformation of compacted sediments with values obtained independently from gravity-driven consolidation of debris-flow slurries. This comparison sought to establish whether standard geotechnical tests provide accurate estimates of some properties of liquefied debris-flow slurries. We poured approximately 50 liters of liquefied sediment into a smooth-walled cylindrical aluminum tank supporting suspended, screened pressure transducers, and measured pore-fluid pressure and surface displacement in meter-deep slurries for several days to weeks (Major 1996). We fit a linear, constant-coefficient pressure-diffusion model to these data. The estimated diffusivity coefficient represents the value that minimizes the difference between predicted and measured values of excess pore-fluid pressure. Estimates of slurry compressibility are obtained by inserting the optimal D value into an expression that predicts surface displacement (Major 1996) and adjusting the value of the bulk modulus to minimize differences between predicted and measured surface displacement.

RESULTS

Stress-strain relations obtained during triaxial tests reveal that stresses in debris-flow sediments compacted to natural densities achieve a plateau, rather than a discrete peak value, as axial strain increases (figure 2). Further straining causes little stress change. This is typical behavior of a "loose" soil that has an initial void ratio that exceeds a critical-state

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Triaxial and isotropic compression results yield estimates of bulk modulus and compression index. Bulk modulus, obtained from relations between isotropically applied stress and volume strain, ranged from 10^3 - 10^4 kPa (table 1). Compression indices, of (figure 4), ranged from

Permeabilities of compacted sediments varied from about 10^{-9} - 10^{-14} m² (figure 5); permeabilities of slurries were about 10^{-12} - 10^{-13} m². Note that sediment types fall into distinctly different fields on figure 5, with clay content increasing to the

Figure 5: Shear stress, in kPa vs. Deviator stress, in kPa for compacted sediments. The plot shows distinct fields for different sediment types based on clay content. The y-axis ranges from 0 to 16 kPa, and the x-axis ranges from 0 to 16 kPa. The plot is labeled 'Fig. 5' and 'sedt'.

value (Lambe and Whitman 1969). The stress states at failure are represented by the "highest" points of the stress-strain curves. Envelopes bounding Mohr circles that define the stress state at failure yield static internal friction angles and cohesion (figure 3). Internal friction angles of the debris-flow sediments ranged from 29°-39°; cohesion coefficients were small (4-9 kPa) (figure 3; table 1).

Triaxial and isotropic compression results yield estimates of bulk modulus and compression index. Bulk modulus, obtained from relations between isotropically applied stress and volume strain, ranged from 10^3 - 10^4 kPa (table 1).

Compression indices, obtained from relations between void ratio and vertical effective stress (figure 4), ranged from 0.05-0.7 (table 1).

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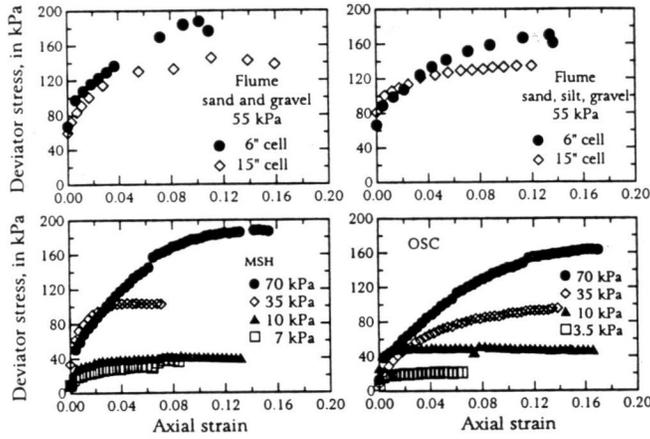


Figure 2. Stress-strain relations for samples of debris-flow sediments. Confining stresses shown.

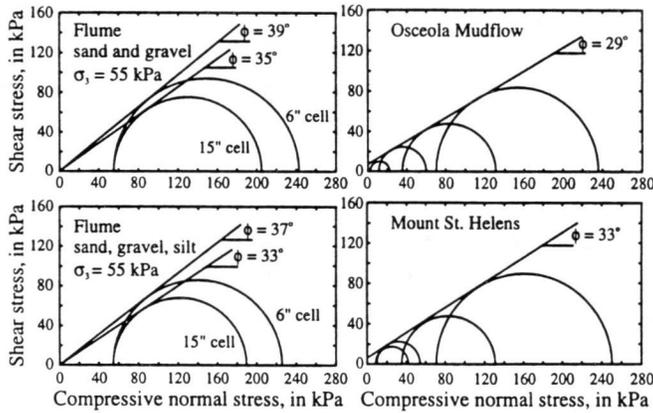


Figure 3. Mohr-circle diagrams illustrating Coulomb failure envelopes of debris-flow sediments. Stress-circle data are obtained from figure 2.

right. These data show that fines content greatly affects permeability. Measurements of fluid pressure in experimental debris-flow deposits reveal that even a few percent fines greatly affects permeability (Major 1996). Sediments having different size gradations and vastly different porosities can have similar permeabilities. Test results further indicate that permeability varies more-or-less exponentially with porosity ($k=k_0e^{an}$) (figure 5). Because a typically ranges from about 10 to 30 (Iverson 1997a; Major 1996), small changes in porosity (resulting from changes in effective stress) can yield large changes in permeability. Changes in porosity of as little as a few percent can cause more than 10-fold changes in permeability.

Table 1. Geotechnical properties of experimental material

[Flume debris data based on sediments ≤ 32 mm diameter tested in 6-inch and 15-inch diameter triaxial cells. Mount St. Helens and Osceola Mudflow debris data based on material ≤ 10 mm diameter tested in a 4-inch diameter triaxial cell. 6", 6-inch cell; 15", 15-inch cell; S, consolidation test; T, triaxial test; c, cohesion; permeability values are minimum and maximum values obtained from modified compaction permeameter and triaxial tests; --, no reliable data]

Property	Flume debris		MSH	Osceola
	sand/gravel	sand/silt/gravel		
Grain properties				
median diameter	3.9-7.4 mm	0.3-0.4 mm	0.5 mm	0.05 mm
mean diameter	2.6-3.7 mm	0.4-0.6 mm	0.5 mm	0.03 mm
ratio gravel:sand:mud	62: 37: 1	16: 80: 4	30: 50: 20	31: 16: 53
ratio sand:silt:clay	96:4: 0	95:4: 1	71: 26: 3	23: 52: 25
Bulk properties				
Folk sorting coefficient	2.3-2.4 phi units	1.5-2.1 phi units	3.8 phi units	7.3 phi units
porosity	0.27-0.29 [†]	0.33-0.38 [†] ; 0.33 [‡]	0.33 [‡]	0.44 [‡]
permeability m ² (porosity)	2x10 ⁻¹² (0.26)	4x10 ⁻¹² (0.34)	2x10 ⁻¹⁴ (0.33)	5x10 ⁻¹⁵ (0.44)
min/max	5x10 ⁻¹⁰ (0.37)	4x10 ⁻¹¹ (0.41)	3x10 ⁻¹¹ (0.50)	2x10 ⁻¹¹ (0.60)
friction angle, cohesion	39°, 35°, c = 0	37°, 33°, c = 0	33°, c = 4 kPa	29°, c = 9 kPa
bulk modulus	--	100 S	100 S	50 S
kPa	--	--	6000-30,000 T	3000-20,000 T
hydraulic diffusivity	10 ⁻⁴ S	10 ⁻⁶ S	10 ⁻⁶ S	10 ⁻⁷ S
m ² /s	--	--	10 ⁻⁵ - 10 ⁻¹ T	10 ⁻⁵ - 10 ⁻¹ T
compression index	0.05 (6")	0.09 (6")	0.10-0.11	0.10-0.70
(cell size)	0.05 (15")	--		

[†] Near-surface porosity of experimental deposit at USGS flume (Iverson 1997a; Major 1997).

[‡] Mean initial porosity value of slurries computed from initial fluid pressures in consolidation tests.

Consolidation tests of debris-flow slurries represent quasistatic, gravity-driven settling of liquefied masses of sediment. Consolidation is driven by debris weight rather than by an

externally imposed surface load. Transient changes in pore-fluid pressure and surface displacement reveal consolidation progress. Figure 6 illustrates pore-fluid-pressure evolution in three slurries. The abscissa represents the value of excess pore-fluid pressure (P_e) normalized by the initial value of basal excess pore-fluid pressure in the slurry (P_{e0}). The ordinate represents sensor depth (z) normalized by initial slurry depth (H). Profiles in each plot represent predicted evolution of normalized excess pore-fluid pressure across slurry depth (times (t_*) are nondimensional as discussed below). In each test, the estimated value of D represents the value that provides the best overall correspondence between predicted and measured excess pore-fluid pressure.

Values of D for the consolidating slurries ranged from about 10^{-6} - 10^{-7} m^2/s , a remarkably narrow range given the variation in sediment composition (table 1). Consolidating deposits of gravelly sand at the USGS flume had somewhat larger diffusivity values, $\sim 10^{-4}$ m^2/s (Major 1996). Optimal values of the diffusivity coefficient determined in these experiments are several orders of magnitude smaller than values common for most un lithified granular sediments; they are similar to values reported for clays, shales, and till (e.g., Roeloffs 1996).

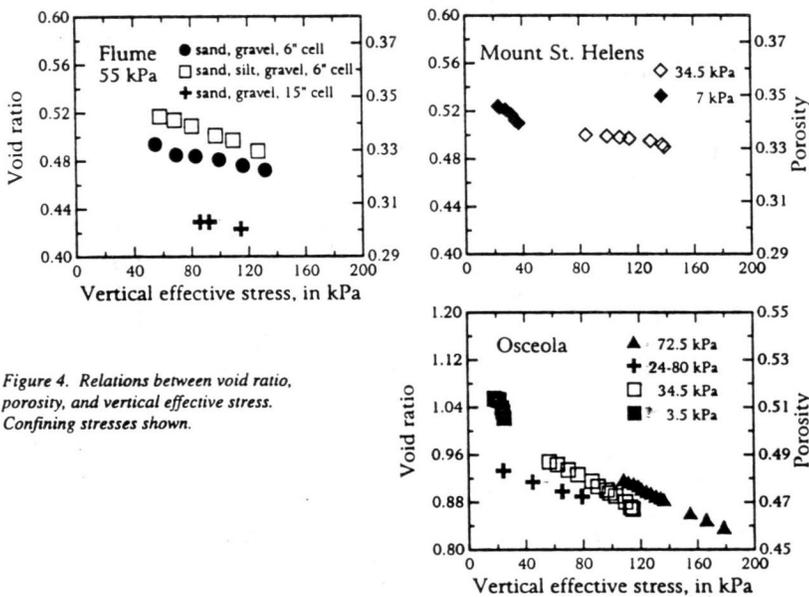


Figure 4. Relations between void ratio, porosity, and vertical effective stress. Confining stresses shown.

Figure 7 shows evolution of slurry surface displacement. Here, the ordinate represents the amount of surface displacement (d) normalized by initial slurry depth (H). Profiles in each plot represent predicted evolution of surface displacement for different values of bulk

modulus, K . Calculations of predicted profiles incorporate optimal values of D (Major 1996). These data suggest that $K \sim 50\text{-}100\text{ kPa}$ ($C \sim 0.01\text{-}0.02\text{ kPa}^{-1}$) for gravitationally consolidating slurries.

DISCUSSION

Triaxial compression tests on a broad range of debris, from clay-poor to clay-rich, demonstrate that resistance to quasistatic motion is dominated by grain friction. Cohesion contributed negligibly to shear resistance under confining stresses common in natural debris flows, even in so-called "cohesive mudflows" (Scott, 1988; Scott et al. 1995), such as the clay-rich Osceola Mudflow. These data show that cohesion offers little shear resistance in a wide variety of debris and need not be considered as a parameter affecting stress development in a Coulomb-strength based debris-flow model (cf. Iverson 1997a,b).

Compacted debris-flow sediments and liquefied slurries examined in this study are characterized by void ratios that are larger than critical-state values under common confining stresses and bulk densities. As a result they preferentially contract, or consolidate, in reaction to deviatoric stresses having magnitudes common in natural flows. Flattened stress-strain curves and large compression index values of compacted sediments attest that void ratios are larger than critical state. These results corroborate findings of Iverson et al. (1997) that demonstrate contraction of sediment masses following failure.

Quasistatically consolidating slurries are less hydraulically diffusive, and more compressible, than estimated from the results of standard geotechnical tests on compacted sediments. Estimates of D (eqn. 1) obtained from measured elastic and hydraulic properties of the compacted sediments (table 1), and assuming $\mu = 10^{-3}\text{ Pa}\cdot\text{s}$, range from 10^{-5} to $10\text{ m}^2/\text{s}$, values that are much larger than those estimated from a model of simple linear diffusion of excess fluid pressures in several quasistatically consolidating slurries. For slurry permeabilities of order $10^{-12}\text{-}10^{-13}\text{ m}^2$, measured and estimated hydraulic diffusivity values coincide only if the slurries are more compressible than estimated from compression of saturated compacted sediments. Good agreement between predicted and measured surface displacement of a consolidating slurry is achieved only if its apparent compressibility is approximately 1 to 2 orders of magnitude larger than that estimated from standard geotechnical tests of compacted sediments. Predicted surface displacements of consolidating

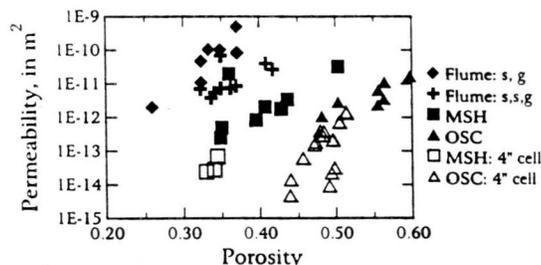


Figure 5. Relations between permeability and porosity. Solid symbols, compaction permeameter. Open symbols, 4" triaxial cell. s.g=sand and gravel; s,s,g=sand, silt, gravel.

slurries based on measured values of compacted-sediment compressibilities substantially underestimate measured displacements.

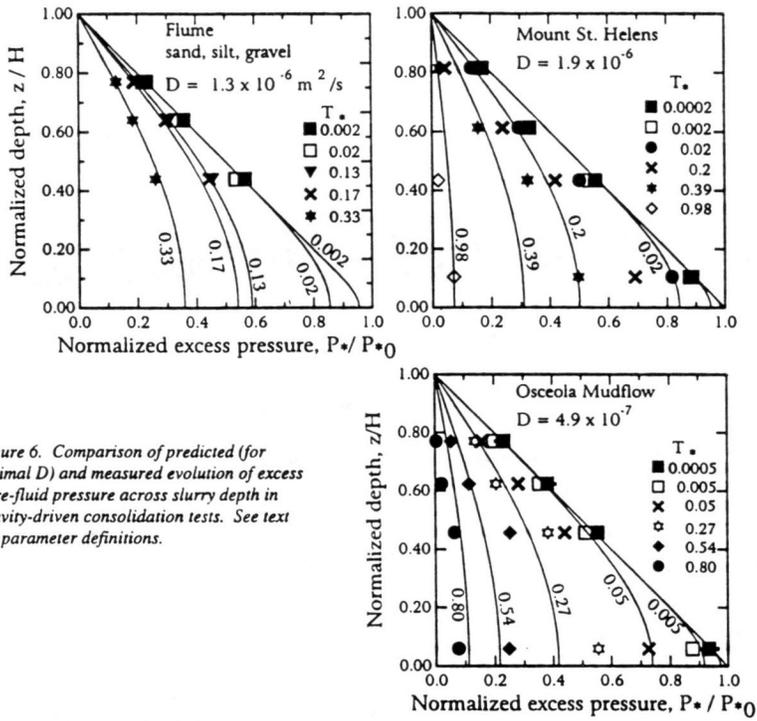


Figure 6. Comparison of predicted (for optimal D) and measured evolution of excess pore-fluid pressure across slurry depth in gravity-driven consolidation tests. See text for parameter definitions.

These disparities possibly result from variable response to stress distributions in compacted sediments and liquified slurries. The triaxially compressed compacted sediments and consolidating slurries had generally similar initial void ratios. Although the compacted sediments are looser than critical state, they have an existing well-established grain-contact network that rapidly bears significant effective stresses and inhibits compression via pore-space closure. In contrast the slurries are making a transition from full liquefaction (grain weight fully supported by fluid pressure) and establishing grain contacts that bear effective stresses. The low permeabilities of the slurries enable delayed transfer of stress from interstitial fluid to solid grains throughout the sediment depth (e.g., figure 6). Changes in permeability caused by small changes in porosity apparently transcend changes in compressibility that result from pore closure. These combined effects lead to the low hydraulic diffusivity of slurries.

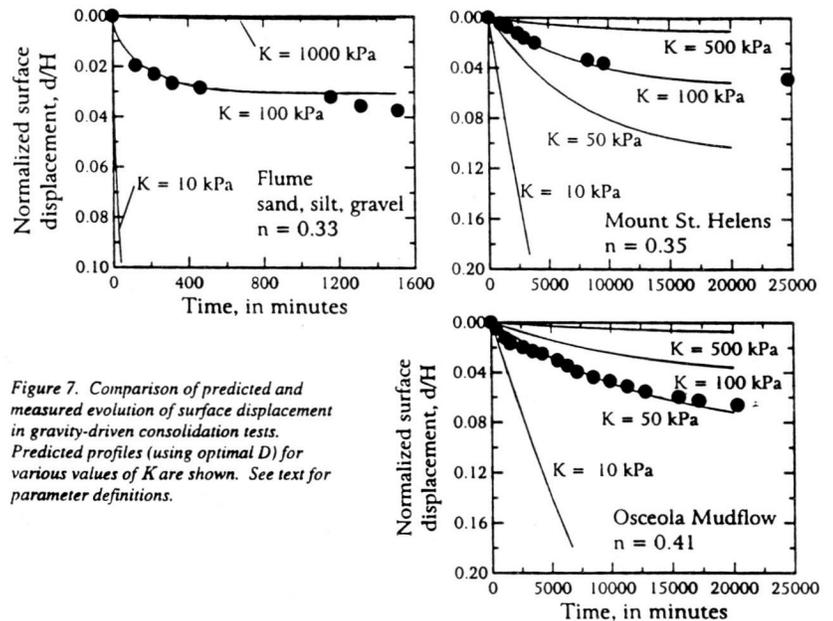


Figure 7. Comparison of predicted and measured evolution of surface displacement in gravity-driven consolidation tests. Predicted profiles (using optimal D) for various values of K are shown. See text for parameter definitions.

Low hydraulic diffusivities of debris-flow slurries estimated from consolidation experiments provide insight into the persistence of excess pore-fluid pressures measured during experiments at the USGS flume. The characteristic time scale for diffusion of excess pore-fluid pressures (ℓ^2/D) is a function of the hydraulic diffusivity, D , and the characteristic length scale, ℓ , over which fluid migrates. The characteristic length of fluid migration in debris flows is the flow depth. For plausible depths of flowing debris of 1 to 10 meters and for D of order 10^{-6} m²/s, characteristic times for the diffusion of excess pore-fluid pressure range from hundreds of hours to hundreds of days, times that far exceed durations of debris flows. These inferences are obtained from the behavior of quasistatically consolidating slurries rather than dynamically deforming debris, but they place an upper bound on pressure-dissipation times that may be characteristic of debris-flow slurries. These inferences explain the apparently liquefied state that can persist for days to weeks in freshly deposited debris, and strongly suggest that viscoplastic yield strength does not account for sediment deposition. For dynamically deforming debris, hydraulic diffusivity values will be larger. Even if they are as much as 2 to 3 orders of magnitude larger, characteristic pressure-dissipation times remain on the order of tens of minutes to tens of hours. Hence the low permeabilities of slurries and their propensity to contract under geostatic loads promote persistence of excess pore-fluid pressures throughout the duration of a typical debris flow.

CONCLUSIONS

Geotechnical analyses of compacted sediments and liquefied slurries (≤ 32 mm diameter) from diverse debris flows demonstrate several properties of natural debris. Results show: (1) Cohesion contributes negligibly to shear resistance under confining stresses normally found in nature. (2) Debris-flow permeability is highly sensitive to porosity, and hence to effective stress; minor amounts of mud greatly reduce material permeability. (3) Debris slurries are characterized by larger values of "elastic" compressibility than are saturated compacted sediments. (4) Standard geotechnical tests of compacted sediments yield values of bulk "elastic" properties that poorly represent effective bulk properties of slurries. Pore-fluid hydraulics of slurries are poorly estimated from properties obtained from standard tests on compacted debris-flow sediments. (5) Hydraulic diffusivities of widely varying slurries are of order 10^{-6} - 10^{-7} m²/s. Low hydraulic diffusivity of slurries explains measurements of high pore-fluid pressures that persist throughout the duration of experimental debris flows at the USGS flume and appear to persist in fresh deposits and natural debris flows.

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Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment

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Technical Committee on Hydromechanics,
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Technical Committee on Sedimentation of the
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Federal Emergency Management Agency
International Association for Hydraulic Research
International Erosion Control Association

and the

U.S. Geological Survey

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

I. 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

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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.