Significance of transient pore pressures and local slope conditions in debris flow initiation

La signification des pressions interstitielles transitoires et des conditions locales des pentes pour l'initiation des coulées de débris

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SYNOPSIS: A potential debris flow source area in the San Francisco Bay Area, California, was instrumented over two rainy seasons with continuously recording tensiometers capable of measuring both positive and negative pore pressures. During the period of observation two storms generated debris flows in the immediate vicinity of the instrumented site and significant positive pore pressure pulses were measured at the site during the two storms. The data show that the pore pressure pulses are highly transient and exhibit significant spatial variation. Similarly, the results of slope stability analyses using site specific data also show that the factor of safety varies significantly along the slope.

INTRODUCTION

In the San Francisco Bay Area, California, debris flows in residual and colluvial soils overlying Mesozoic and Tertiary rocks have been identified as a significant hazard following a series of intense rainstorms in January, 1982. The storms caused extensive flooding, and mass movement throughout the region. Millions of dollars in property damage and 14 of the 26 storm related fatalities were attributed to landsliding (Smith et al., 1982).

A majority of the slope failures were of the kind typically associated with prolonged intense rainfall and have variously been described as debris flows, debris avalanches and mudflows. These failures are apparently initiated by relatively high, storm-induced pore pressures, as suggested by post-failure field observations of substantial water flow emanating from failure scars. The debris flow source areas are typically located in the upper parts of hillslopes above the convex-concave transistion, generally have moderate to high length to depth ratios, and can contribute from one to several hundred cubic meters of material.

To investigate the mechanisms of debris flow initiation and the role of pore pressures in particular, a potential debris flow source area was instrumented for two winter seasons with continuously recording tensiometers/piezometers. In addition, the investigation included an extensive program of laboratory and field testing aimed at determining the strength and hydraulic characteristics of soils at the instrumented site.

SITE DESCRIPTION

The field site for the study was located near the top of a ridge in the Briones Hills, approximately 15 km east of Berkeley, California. This site was selected based on ample evidence of previous debris flow failures, geologic setting, and a perceived potential for future failures (Figure 1).

Figure 1 Aerial Photograph of the Field Site with the Location of the Instrumented Section Given by AA'

The bedrock at this location consists of horizontally bedded Tertiary marine and non-marine siltstones, sandstones, and mudstones. The soils overlying the bedrock consist of residual and colluvial material derived from weathering of the bedrock and from continuous downhill transport by creep, slumping and surface runoff. The climate of the Briones hills can be characterized as temperate-mediterranean, with average daily temperatures between 10 and 24° C, and mean annual precipitation of 0.56 m (Rantz, 1971).

Figure 2 presents a cross section of the field site, showing the thin veneer of residual soil derived from the bedrock. The soil thickness varies along the profile with a minimum of 0.5 m at Nest 0, thickening to 1.5 m at Nest 2, and then thinning to an essentially uniform thickness of 1.2 m further downslope. Soil depths were determined by hand-driven auger borings and seismic refraction profiling.

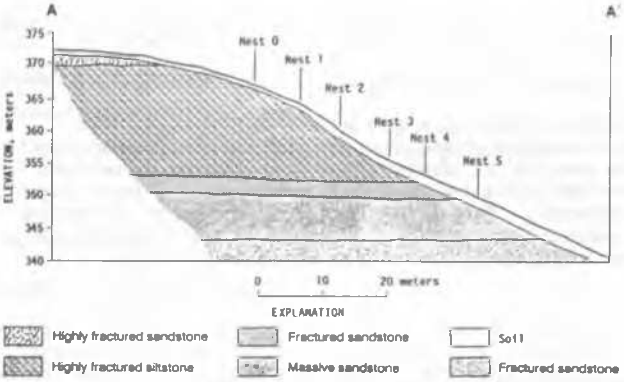

Figure 2 Schematic Cross Section of the Site Showing the Location of Tensiometer Nests

Field Instrumentation

Detailed information regarding pore pressures, precipitation, and temperature was collected during two winter seasons at the field site. Precipitation was measured in one millimeter increments using a tipping bucket rain gauge. Pore pressure measurements were made using tensiometers equipped with pressure transducers. Tensiometers are being increasingly used to measure both positive and negative pressures in studies of the hillslope hydrologic response to rainfall (Anderson and Burt, 1977; Johnson and Sitar, 1987; Pitts and Cy, 1987). In this study, transducers calibrated over both negative and positive gage pressures were used to measure the complete transition from unsaturated conditions (negative pore pressures) to essentially saturated conditions (positive pore pressures).

Tensiometers were installed in six "nests" located along a downslope profile as shown in Figure 2. Each nest consisted of three instruments installed at the top, middle and bottom of the soil profile. Particular attention was paid to placing the bottom tensiometer in each nest at the soil-bedrock interface in order to obtain information on pore pressure response in the weathered bedrock.

All instruments were connected to an automatic data acquisition device. Pore pressure measurements were made every hour between rainfall events and every millimeter of precipitation during rain. While the data acquisition system performed flawlessly, 44 percent of the pore pressure transducers failed at some point during the second season of monitoring.

Field Observations

During the two seasons of field monitoring eight significant storms occurred with total precipitation values ranging from 4.5 to 10.6 cm, and average rainfall intensities between 0.17 and 0.68 cm/hr (Table 1). Maximum rainfall intensities computed over 0.25 hr intervals are also shown in Table 1. These eight storms were distributed throughout the rainy seasons, consequently, the hillslope hydrologic response over a range of antecedent moisture conditions was recorded. Two of the storms, 16-17 February 1986 and 18 February 1986, generated numerous debris flows in the immediate vicinity of the instrumented site. Other storms with relatively high intensities did not generate debris flows, largely because antecedent moisture conditions were too dry to produce significant positive pore pressures (Johnson and Sitar, 1987).

TABLE 1

Characteristics of storms monitored during the winters of 1984-85 and 1985-86

Date	Precipitation Total (cm)	Maximum Intensity (cm/hr)	Average Intensity (cm/hr)
2/7-2/8/1985	7.8	1.75	0.53
3/26/1985	4.7	1.90	0.60
11/24/1985	4.5	0.53	0.23
1/29-1/31-1986*	10.6	--	--
2/16-2/17/1986	10.6	2.25	0.34
2/18/1986	4.9	3.00	0.68
3/07/1986	4.5	0.77	0.17
3/10/1986	4.5	1.75	0.25

*storm total from Berkeley station, field instruments disrupted by cattle.

Figure 3 shows the hourly rainfall intensity and pore pressure response of two of the nests recorded during the February 1986 storms, which generated debris flows on the slope immediately adjacent to the site. While relatively brief periods of high intensity rainfall occurred on 14 and 15 February, not until the latter half of 16 February were high rainfall intensities sustained sufficiently to generate positive pore pressures. The pore pressure plots show that the buildup and dissipation of positive pore pressures during periods of sustained intense rainfall can be very rapid, with the whole cycle lasting less than 24 hours.

Differences in the character and duration of the pore pressure response were also observed along the slope. The pore pressures at Nest 4 rose and dissipated slower than those observed at Nest 3, located approximately 8 m upslope. In addition, the positive pore pressure peaks observed at these nests were offset in time, with the peak at Nest 3 occurring approximately 2 hours before the peak at Nest 4. Thus, the data show that peak pore pressures occur at different times in different parts of a slope and suggest that the pore pressure pulses travel downslope during intense precipitation.

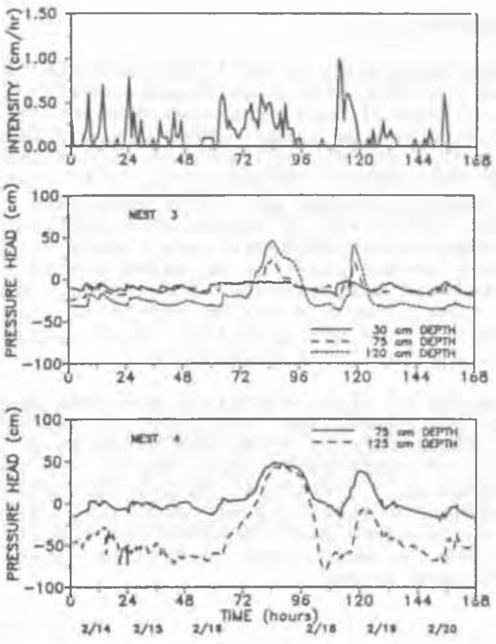

Figure 3 Rainfall Intensity and Pore Pressure Response at Nests 3 and 4 during the Storms of February, 1986

SLOPE STABILITY

Material Properties

The soil at the site is predominantly clayey silt (ML-CL) with liquid limits between 41 and 55 (average = 45), and plasticity index between 12 and 30 (average = 19). The clay minerals in the soil and in the bedrock are mainly smectites and as a result the soil is highly expansive. During the summer dry season the soil hardens and shrinkage cracks as wide as 5 cm are quite common. Therefore, undisturbed sampling can only be attempted during the winter rainy season when the soil is moist.

Two different sampling methods were used to collect samples for consolidation and triaxial tests: 1) Thin-walled 7.6 cm diameter by 30 cm long tubes were pushed by hand; and 2) a 0.027m^3 block sample was hand-trimmed from a small pit. The samples obtained using the thin-walled tubes were used in laboratory tests without trimming of the diameter and the block sample was trimmed to provide a 7.6 cm diameter specimen.

A series of 9 consolidation tests was performed on samples from different depths. The overconsolidation ratio (OCR) was found to be greater than 16 in samples from depths less than 0.65 m, while samples from greater depths had OCR values in the range from 3-4. This distribution and range of OCR values seems consistent with the observed pattern of seasonal wetting and drying.

The shear strength of the soil was obtained using four isotropically consolidated undrained (ICU) triaxial tests on samples from depths greater than 0.65 m. A constant rate of strain of 0.001 min^{-1} was used for the tests. All samples showed a tendency to contract during shear and stress-strain curves were rounded without pronounced peaks even at very low confining stresses. The effective stress paths and the effective strength envelope are plotted in Figure 4. The corresponding effective strength parameters are c' = 5.3 kPa and φ' = 32°.

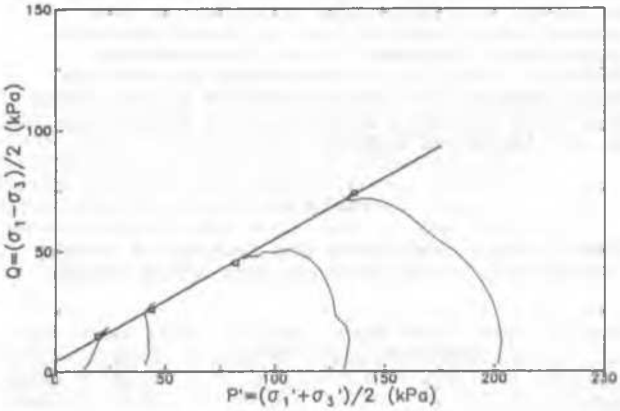

Figure 4 Effective Stress Paths from ICU Triaxial Tests

Method of Analysis

The potential for failure initiation was evaluated using the infinite slope stability method using effective strength parameters. The infinite slope method was selected because it allows a consistent means of comparing relative slope stability when slope angle, soil thickness, and pore pressures vary at different positions along the slope profile. Additionally, while this method does not precisely represent in-situ conditions, it can be reasonably accurate for analysis of failures having relatively large length to depth ratios, such as debris flows.

The stability of the slope in the vicinity of each instrument nest was assessed assuming seepage flow parallel to slope using the equation:

$$F.S. = [c' + (\gamma d \cos^2\alpha - u)\tan\phi'] / \gamma d \cos\alpha \sin\alpha \qquad (1)$$

where c' is cohesion, φ' is the effective angle of friction, α is the slope angle, d is the depth of the potential failure plane below the soil surface, u is the pore pressure, and γ is the total unit weight of the soil. For each nest the local slope angle, soil thickness and maximum pressure head observed during the 14-20 February storms were used in the calculation. Average shear strength and density parameters were used in the calculations because the available information was insufficient to justify a more complex treatment.

The results of the slope stability calculations are presented in Table 2, along with their associated local parameters. Calculated factors of safety for observed values of pressure head range from 1.31 at Nest 2 to 3.24 at Nest 0. Interestingly, the lowest computed factor of safety occurs along the steepest section of the profile, rather than at the location of the maximum observed pore pressure. Also it is important to note the large variation of the computed factor of safety along the slope profile. The computed factors of safety are quite high considering that several small debris flow failures occurred immediately adjacent to the instrumented section. Thus, it is necessary to consider which assumptions and procedures in the slope stability analysis might lead to overestimation of the factor of safety.

TABLE 2

Local slope conditions and factors of safety during the 14-20 February 1988 storm events.

Location	Local Slope Angle (degrees)	Max. u (kPa)	Soil Depth (m)	F.S.
Nest 0	19	2.0	0.50	3.24
Nest 1	24	0.0	0.70	2.50
Nest 2	34	0.5	1.50	1.31
Nest 3	29	4.6	1.20	1.39
Nest 4	24	5.0	1.20	1.67

For all calculations $\gamma = 18.6\ \mathrm{kN/m^3}$, $c' = 5.3\ \mathrm{kPa}$, $\phi' = 32°$.

Specifically, two potential contributing factors can be identified in this case:

1. In the slope stability analysis presented herein seepage was assumed to be parallel to the slope. However, significant pore pressures were observed at the bedrock-soil interface and it is possible that subhorizontal seepage gradients from the bedrock into the soil horizon were present, which would have caused the actual factor of safety to be lower than that computed in Table 2. In the scars of debris flows in the vicinity of the site and at other localities in the San Francisco Bay Area we observed water flowing from the bedrock for a significant period of time after failure suggesting that seepage from the bedrock into the soil horizon contributed to the failures. Unfortunately, the data from the instrumented site is insufficient to determine the actual seepage direction at the soil-bedrock interface.

2. The ICU triaxial tests used to obtain the strength parameters were performed at a relatively fast strain rate, whereas failures in the field occur as a result of relatively slow ($\approx$ 12 hrs) build up of pore pressures while the total stress remains essentially constant. Thus, creep tests with rising pore pressure might be more appropriate since they would more closely represent the actual process at the site as suggested by Brenner and others (1985). Shear strengths obtained from such tests would likely be lower than those obtained from the triaxial tests described herein.

CONCLUSIONS

The results of a detailed field instrumentation program indicate that significant positive rainfall-induced pore pressures develop in debris flow source areas. These pore pressures are highly transient and exhibit significant spatial variation. Consequently, sufficiently dense instrumentation and continuous pore pressure monitoring is needed when dealing with landslides initiated by intense rainfall. The currently common practice of using discrete pore pressure measurements at relatively widely spaced time intervals may be justified only in the case of slow moving slides which respond to long-term water table variations.

The results of slope stability analyses show that at any given time the factor of safety varies significantly along the slope as a function of slope angle, soil depth, and local pore pressure. Therefore, future attempts at evaluating the stability of potential debris flow source areas must consider the specific variations in local slope conditions rather than average values.

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ACKNOWLEDGMENT

This study was funded in part by P.Y.I. grant No. CEE-8352197 from the National Science Foundation and matching funds from the Environmental Activities Staff of the General Motors Corporation.