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SHAKING TABLE EXPERIMENT OF A MODEL SLOPE SUBJECTED TO A PAIR OF REPEATED GROUND MOTIONS

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ABSTRACT

This paper describes the third of a series of six shaking table experiments conducted as part of ongoing research to evaluate the accuracy and applicability of the Newmark (1965) procedure for computing seismically induced deformation in slopes. A cohesive model slope was shaken by two identical test motions in succession, mimicking a situation that commonly occurs when a preexisting landslide is subjected to strong earthquake shaking. Back analyses of the tests showed that the Newmark (1965) formulation provided moderately accurate estimates of the measured permanent deformations (within 40% to 85% of the maximum measured displacement). The accuracy of the Newmark (1965) formulation was greatest when displacement-dependent degrading yield acceleration was used to model the soil's transition from peak to residual shear strength. The Newmark analyses were most reliable for the second test that experienced relatively large deformations, and thus where the sliding resistance was controlled by post-peak to residual strength.

INTRODUCTION

In recent years, researchers at the University of California, Berkeley have studied dynamic response and seismically induced displacements of slopes, embankments, and solid-waste landfills [e.g., Augello (1997), Rathje (1997), Wartman (1999a)]. As part of these ongoing studies, a series of instrumented scale model slopes were constructed of soft clay, shaken in a 1-g environment, and later back analyzed to evaluate the accuracy and applicability of the Newmark (1965) sliding block procedure for computing seismically induced displacements in slopes. In this paper, the third in a series of six shaking table experiments is discussed. The first and second experiments of the test series are discussed by Wartman et al. (1998) and Wartman et al. (1999). Overviews of the Newmark (1965) procedure may be found elsewhere [e.g. Jibson (1993), Bray et al. (1995), and Kramer (1996)], and will not be repeated here.

The experiment is noteworthy because the model was shaken by two identical test motions in succession. The first test motion caused displacements that drove the soft model clay beyond its peak shear strength. The second test motion caused additional displacement and drove the model clay closer to its residual strength condition. The second motion experiment was similar to a situation that commonly occurs in seismically active regions when a preexisting landslide is subjected to strong earthquake shaking.

It is noted that the small-scale slope was not intended to precisely "model" a particular prototype-scale slope or embankment. Rather, the purposes of the test were to investigate the mechanisms of seismically induced deformations in slopes and to develop a small-scale, fully instrumented "case history" for evaluation and calibration of the Newmark (1965) procedure. For this reason, the test results will be presented at the model scale. It is important to note that although laws of similitude were not directly applied to the model tests, the static (shear strength) and dynamic (small strain shear modulus) properties of the model clay were adjusted and controlled so that they were reasonably proportioned to the scale of the model slopes (Wartman 1996). In addition, the frequency content of the input ground motions was adjusted to reflect the reduced-scale of the model tests.

TEST PROGRAM

Laboratory Facility

The experiment was conducted on a 1.2 m by 1.0 m single-degree-of-freedom shaking table at the University of California, Berkeley. The table consists of an aluminum plate and beams bolted to two parallel horizontal tracks defining the direction of table movement. The horizontal tracks are anchored to an independent foundation to isolate the table from machine-induced vibrations. The shaking table is driven by a 22,000 kg, 15.2 cm displacement hydraulic actuator ported by a 95 liter-per-minute servo valve. An *MTS 406* hydraulic control unit directs the servo valve based on a displacement feedback signal from the actuator and command signal.

The model slope was constructed in a 96 cm wide by 160 cm long stiffened Plexiglas container that was bolted to the shaking table. Stiffeners were attached to the outside of the container to minimize front and back wall deflections. The inside sidewalls were lubricated with canola oil to reduce friction along the sidewall-clay interface.

Model Slope Preparation

Figure 1 shows a profile of the model slope. The model was comprised of soft clay measuring 21.8 cm in height with a face slope of 1.8 horizontal: 1 vertical. The slope was underlain by a 6.4 cm stiff clay layer. The top of the slope was flat and extended 74.7 cm beyond the front slope crest. The back of the slope was comprised of stiff clay inclined about 1.4 horizontal: 1 vertical. The toe of the slope was located 20.8 cm from the front wall of the Plexiglas container. The model was constructed of laboratory mixed clay containing 3 parts kaolinite to 1 part bentonite. The liquid and plastic limits of the model clay were 133 and 27, respectively

The slope was instrumented with six accelerometers and seven displacement potentiometers at the locations shown in Figure 1. After the mechanical instrumentation was positioned, plastic was placed over the surface of the clay, and the model was securely wrapped in plastic to prevent moisture loss. The model was then "cured" for approximately one day to allow for thixotropic stiffening and strength gain before testing.

In addition to the mechanical instrumentation, uncooked pasta noodles were pushed vertically into the slope along three lengthwise profiles spaced approximately 20 cm apart. Once hydrated, the pasta strands became soft and pliable and served as slope inclinometers. Each of the inclinometer rows contained 24 to 26 roughly equally spaced strands of 2.5 mm diameter pasta. After placing the spaghetti, approximately 80 pushpins were positioned at various locations on the clay surface to serve as surface monuments.

Model Clay Properties

The pertinent material properties for the soft and stiff clays are summarized in Table 1. The shear wave velocity was computed before the experiment by measuring the time required for hammer generated shear waves to travel between the accelerometers.

Table 1 – Summary of Model Clay Material Properties

	Soft Model Clay	Stiff Model Clay
Cure Age (hours)	22.5	24
Water Content (Water Content Range)	127.7% (+/- 1.6% w.c.)	122.8% (+/- 0.3% w.c.)
Peak Undrained Shear Strength [kPa] (Range of Peak S_u)	2.34 (+/- 0.1 kPa)	4.30 (+/- 0.2 kPa)
Shear-Rate-Corrected Peak Undrained Shear Strength [kPa]	2.93	5.38
Residual Undrained Shear Strength [kPa] (Range of Residual Su)	1.55 (+/- 0.2 kPa)	2.72 (+/- 0.3 kPa)
Shear Wave Velocity (m/s)	6.5	19.0
Wet Density (g/cm^3)	1.4	1.4

Several in situ mechanized vane shear tests were performed immediately after the test using a 5.1 cm high, 2.5 cm diameter vane rotated at an angular velocity of 16 degrees per minute. After the peak shear strength had been measured, the vane was rotated 720 degrees and the residual shear strength was measured. The peak undrained shear strengths measured during the vane shear tests were corrected to account for shear rate effects. The correction was made by comparing the average sliding velocity during the test (determined from the displacement potentiometer recordings) to the circumferential

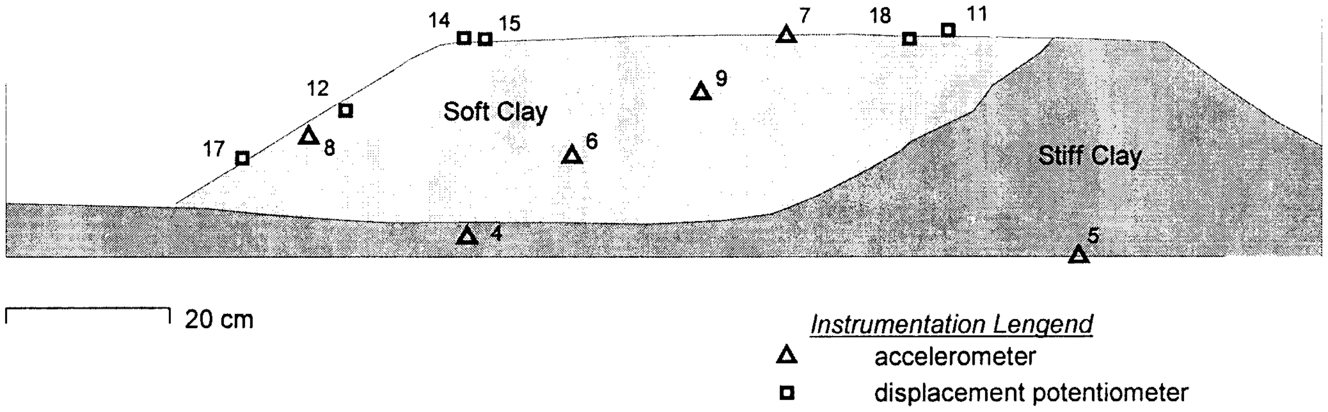


Figure 1 – Pre-test profile of model showing instrumentation locations

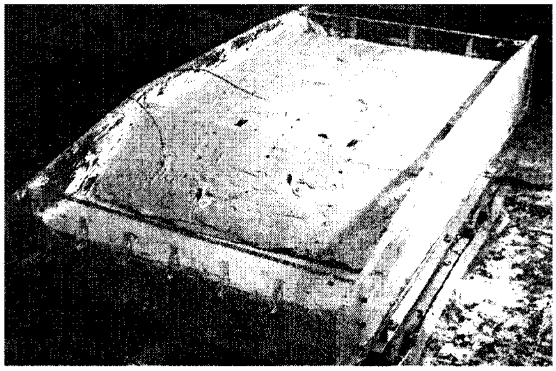
displacement rate of the vane shear tests. A strain rate factor was then applied to the measured peak strength based on a laboratory derived shear rate-undrained strength relationship developed by Wartman (1999a). The strain rate-corrected peak shear strengths were later used in the pseudostatic slope stability analyses. The residual strength of the model clay was generally insensitive to shear rates and therefore correction factors were not applied to the measured residual strengths (Wartman 1999a).

Input Motion

The input acceleration-time history was based on a strong motion recording from the Kobe Port Island Station (depth = 79 m) during the 1995 Hyogoken-Nanbu Earthquake. This original record was lengthened by roughly doubling the duration of strong shaking. This was done by copying and pasting a portion of the record, which effectively resulted in a repeating of the strong shaking. The test motion was further modified by reducing the magnitude of the original recording's forward-directivity displacement pulse. The time scale of the original motion was then reduced by a factor of 0.85 and the acceleration amplitude was multiplied by 4.3. The scaled motion had a maximum horizontal acceleration of 2.3 g and a mean frequency (Wartman 1999a) of about 21 Hz.

RESULTS

Figure 2 shows the model slope after the two full amplitude test motions. Observations made during the test and review of the test video indicates that the model oscillated considerably during the first test motion, and that displacement occurred at the toe. The model was inspected and photographed after the first test. The instrumentation brackets prevented a detailed survey of the surface, however, several key monuments were located using a measuring tape. About 15 minutes later, the motion was repeated, after which the instrumentation was removed and a formal survey was performed. The model again oscillated during the second test motion, but at a lower level then was observed for the first test. Offset was visible at the toe and near the back of the model where two grabens developed (Figure 3). The toe offset was generally uniform across the middle 78 cm of the model, suggesting that the effects of sidewall friction were minimal in this region.



ıure 2 – View of model after the two test motions

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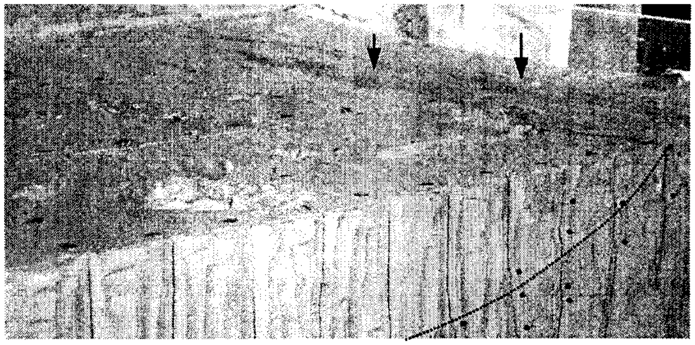

Figure 3 – Photograph taken during excavation of model. The arrows highlight the two grabens that formed along the back

Figure 3 – Photograph taken during excavation of model. The arrows highlight the two grabens that formed along the back surface of the model. The dashed line indicates the approximate location of the upper slide surface.

Figure 4 shows the developed post-test profile (after two test motions). The principal mode of permanent deformation was deep rotational/translational displacement along one or two shear surfaces. The deformed spaghetti strands suggested that some small-displacement (2 mm or less) secondary shears may have splayed from the principal shear surface, but this could not be confirmed. The deformed spaghetti strands suggest the shear surfaces may combine near the center of the model (shown as dashed in Figure 4), although this could not be confirmed. Information from the mid-length portion of other rows of spaghetti inclinometers was also inconclusive. Two shear surfaces were found near the back of the model, each of which was associated with a graben at the model surface. The maximum displacement at the toe of the slope (after two test motions) was 4.2 cm.

Figure 5 shows the pre-test geometry with vectors of surface displacement for the two test motions. The front of the slope generally moved horizontally with the back moving down along the stiff clay layer. Near the toe of the slope, total deformations are dominated by horizontal displacements. Vertical displacements increase near the middle and back, but horizontal movement continues to dominate the total deformations in this region. The large deformations near the toe are an indication of bulging that may have developed as a result of deviatoric straining. This deformation mechanism, described by Stewart et al. (1995), involves accumulation of seismically induced permanent shear deformations in regions of the embankment away from the distinct slip surfaces.

ANALYSES

Slope Stability

Based on the measured peak shear strength values, the slope had a static factor of safety of 9.2 at the time of the test (i.e., after a cure time of 22.5 hours). To maintain consistency with pseudostatic analyses, the static stability was assessed using the shear rate-corrected peak shear strength of the model clay.

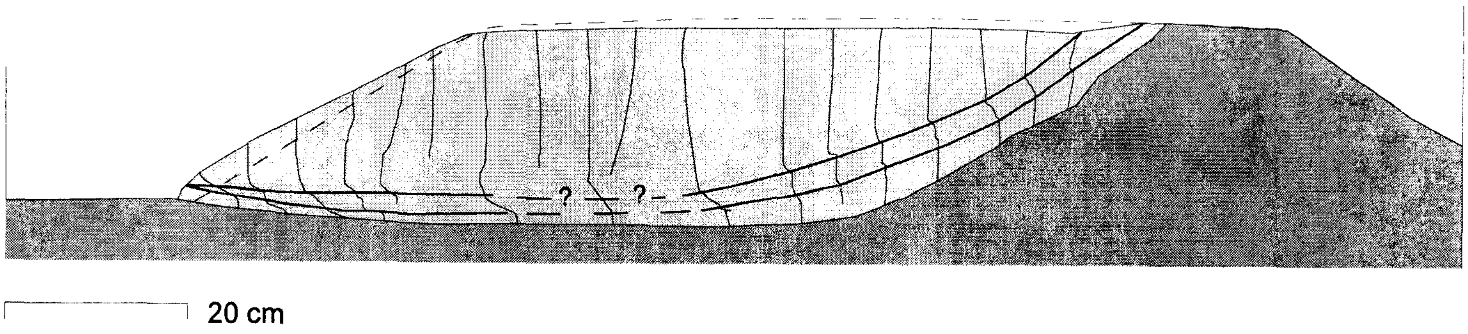

Figure 4 – Post-shaking profile of Slope 3 showing deformed clay surface and spaghetti stands (pre-shaking geometry shown with dashed line, shear displacement surfaces shown with dark solid lines [dashed where inferred]).

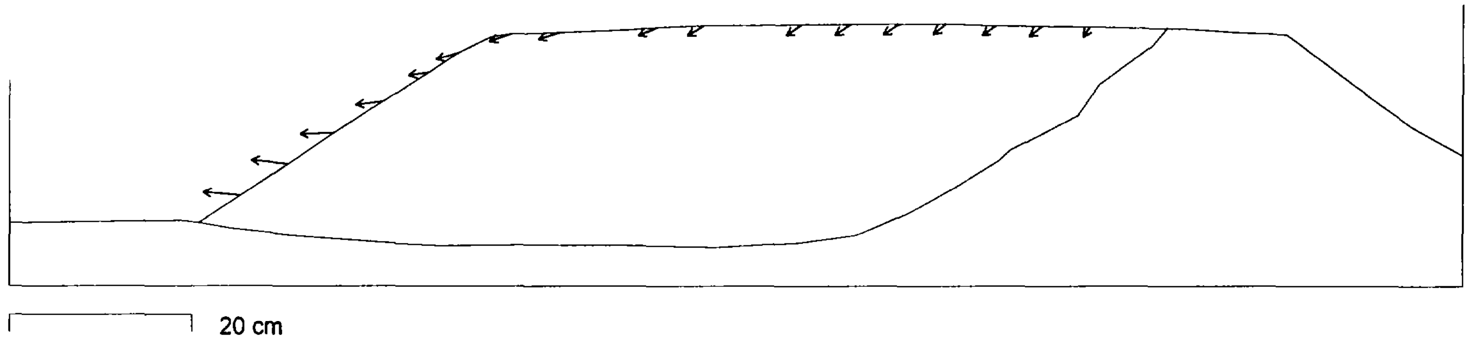

Figure 5 – Slope 3 pre-test geometry with vectors of surface displacement for the two test motions (vectors are shown to profile scale).

The yield accelerations for the principal deep rotational/translational shear surface based on strain rate-corrected peak and unadjusted residual soil strengths were 1.7 g and 0.87 g, respectively. The shape and location of the most critical dynamic surface slip surface predicted by the pseudostatic analyses was nearly identical to the lower principal shear surface shown in Figure 4.

Displacement Analyses

The program YSLIP_PM (GeoSyntec 1998) was used to calculate Newmark-type sliding deformations based on an integration of relative velocities procedure. The analyses were performed assuming sliding occurred in only one direction, and for yield accelerations corresponding to peak, residual, and peak to residual transitional soil shear strengths. Program YSLIP_PM allows for input of 10 displacement-yield acceleration points to define a displacement-dependent yield acceleration reduction that occurs for sensitive soils (Matasovoc et al., 1997). For these studies, the degrading yield acceleration curve was based on the vane shear tests conducted after each experiment. In defining the displacement-yield acceleration curve, circumferential displacements from the vane shear tests were assumed to be equal to linear displacements.

The analyses were performed using acceleration-time histories recorded on the shaking table (equivalent to a "rock" or rigid base motion). Figures 6 and 7 presents the results of the modified Newmark analyses along with measured displacements for tests motions one and two, respectively. For the first test, the yield acceleration was based on the standard displacement-dependent transition from peak to residual shear strength. Recognizing that about 1.3 cm of slope displacement had already occurred prior to the second test, the yield acceleration transition for the second test was defined using post-peak (strength at 1.3 cm) to residual strength parameters. For comparison purposes, the Newmark analyses based on peak and residual strengths are also presented.

For first test, the displacement-time histories show that displacements measured at the top of slope are intermediate to those measured at the toe and near the back of the slope. Figure 6 shows that displacements at the top and back of slope are nearly identical, suggesting that the upper region of the slope moved as a more intact mass during the second test. For the first test, the displacement predicted using the degrading yield acceleration underpredicted the maximum measured displacement by 52 percent, or about 5.8 mm. The modified

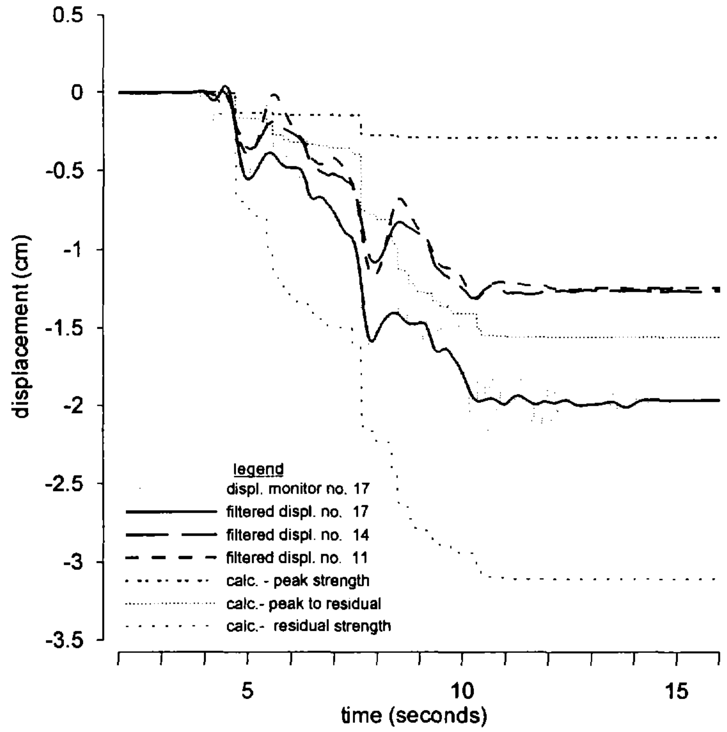

Figure 6 - Measured and calculated relative displacements versus time for the first test. (reference Figure 1 for instrumentation locations). For clarity, the displacement-time histories for were low-pass filtered to remove their high frequency elastic component.

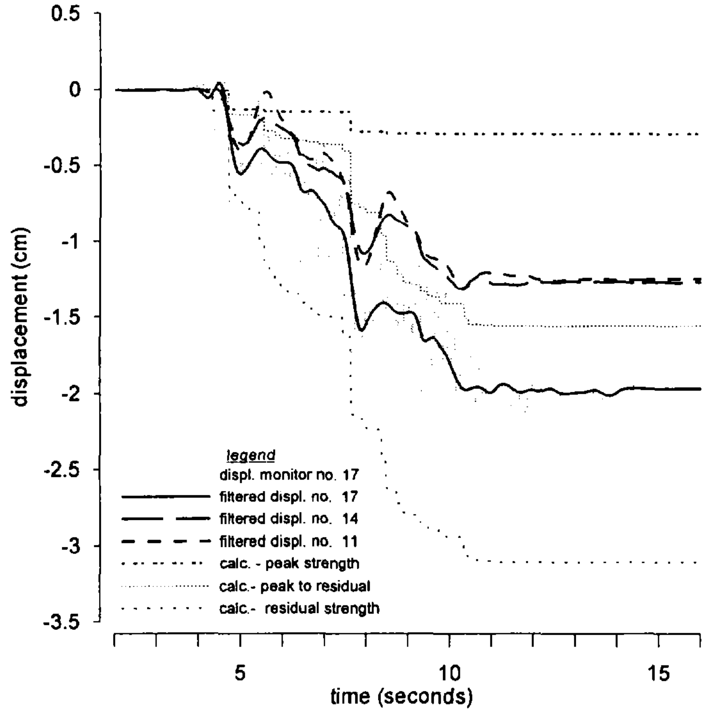

Figure 7 - Measured and calculated relative displacements versus time for the second test. (reference Figure 1 for instrumentation locations). For clarity, the displacement-time histories for were low-pass filtered to remove their high frequency elastic component.

Newmark analysis was more reliable for the second test with ma maximum displacements exceeding the calculated values by 20 percent, or 4.0 mm. For both tests, the measured displacements are intermediate to those calculated using the Newmark-type procedures with peak and residual soil strengths.

DISCUSSION

The displacement-time histories indicate that sliding initiated near the toe of the slope and then propagated towards the back. It is not known if the shear simultaneously progressed along the two nearly parallel surfaces, or if these surfaces developed at different times. As an existing shear plane would serve as a preferential slip surface, it is likely that displacement during the second test occurred along a surface (or surfaces) that developed during the first test. Therefore it is not believed that each the surfaces can be attributed to a particular test. Referencing Figure 4, it is possible that slip initiated at the toe and then split into two shear surfaces. As shaking continued, deformation localized, possibly on a single shear surface, and propagated to the back. As shearing continued towards the back, the single shear plane split into two surfaces that approach the surface of the model. It is noted that the shear surfaces shown in Figure 4 had pseudostatic yield coefficients within 5% of the calculated lowest value, and thus each may be thought of as having a near-equal likelihood of sliding.

Although not presented here, it is noted that FFT graphs indicate that for a given motion, the sliding mass responds with slightly less intensity when a pre-existing shear plane exists. For test one, the shear surface did not fully develop until several seconds into the strong shaking. During this time, the model generally responded as a continuum, with shear waves propagating from the base to the top of the model. Measured surface accelerations decreased after the shear surface formed during test one and remained lower for the second test suggesting that the shear surface partially impeded vertical propagation of shear waves though the model.

Although less energy was measured in the slope for the second motion, displacements were greater during this test because of the reduced shear resistance of the model clay. For test motion one, the Newmark analyses provided fairly accurate predictions of displacement. The Newmark analysis was more reliable for the second test motion, when soil strengths were closer to their residual values.

The curved shapes of the first several spaghetti strands in Figure 4 suggest that deviatoric straining may account for some of the slope face displacement. The multiple shear surfaces at the base make it difficult to precisely determine the relative proportion of localized and distributed deformation. However, comparison of the measured surface deformation with the offsets in the spaghetti strands suggest that as much as 35% of the total toe deformation may be the result of deviatoric straining within the sliding mass above the distinct shear surfaces.

CONCLUSIONS

The following conclusions are drawn from this experiment.

1) The model displaced along two localized shear surfaces that were of the same orientation and located within close proximity of each other. For this experiment, the Newmark (1965) assumption that deformation occurs along a single well-defined slip surface single surface reasonably approximated the actual deformation behavior of the model.

2) Surface deformations varied over the length of the model, with the largest displacements occurring at the toe and along the face of the slope. This contrasts with Newmark's rigid block assumption, which presumes that the sliding mass has evenly distributed or uniform deformations. The variation in surface displacements was related to two factors: (a) displacement initiating at the toe of the slope that results in more fully developed shear surface at the front of the model as compared to the back, and (b) distributed deviatoric straining within the sliding mass, which tends to focus deformations near the toe of the slope.

3) The Newmark (1965) analysis generally provided moderately accurate estimates of seismically induced permanent deformations that were within 40% to 85% of the maximum measured. The accuracy of the Newmark (1965) formulation was greatest when displacement-dependent degrading yield acceleration was used to model the soil's transition from peak to residual shear strength. It is interesting to note that the Newmark analyses were most reliable for the second test that experienced relatively large deformations, and thus where the sliding resistance was controlled by post-peak to residual strengths. This is probably because the deformation-strength relationship is more stable at large strains as compared to lower strains, where shear strength rapidly deteriorates with deformation.

ACKNOWLEDGEMENTS

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