GEOTECHNICAL SPECIAL PUBLICATION NO. 75

GEOTECHNICAL EARTHQUAKE ENGINEERING AND SOIL DYNAMICS III

Volume 1

PROCEEDINGS OF A SPECIALTY CONFERENCE

SPONSORED BY
Geo-Institute of the American Society of Civil Engineers

CO-SPONSORED BY
US Air Force Office of Scientific Research

August 3–6, 1998
University of Washington
Seattle, Washington

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ESTIMATING SEISMIC DISPLACEMENTS OF MARGINALLY STABLE LANDSLIDES USING NEWMARK APPROACH

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ABSTRACT

This paper presents a Newmark approach to account for visco-dynamic rate effects on clay soils in marginally stable landslides during earthquakes. One of the assumptions in the Newmark analysis is that the shear strength of the soil remains constant during displacement. Recent laboratory ring shear testing by the authors of hand-carved specimens obtained from a landslide shear zone indicates increasing residual shear strength with increased rate of shear. In the proposed method, the shear strength (yield acceleration) in the Newmark procedure is increased to account for visco-dynamic behavior of the soil. Several case histories are presented where the observed displacement of active clay soil landslides are much lower than that predicted using a near-zero yield acceleration in a Newmark analysis. Finally, the proposed analysis is used to estimate seismic displacements of several landslides under various earthquake events. The results of these analyses give estimated displacements which are in good agreement with actual case histories.

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INTRODUCTION

The Pacific Northwest has many landslides which exist in a marginally stable state. These slides occur in weathered, volcanic clay soils which develop very low residual strengths. Relatively small groundwater changes or manmade activities can reactivate these slides. Commonly, these landslides are stable during dry summer months and move slowly during the wet winter season. Under these conditions the Newmark yield acceleration of the slide mass would be below zero when moving, and slightly above zero when stable. Designers are faced with the problem of estimating slide movements of these marginally stable landslides during an earthquake. This paper presents a procedure to estimate seismic displacements of marginally stable landslides.

As the Fifth Rankine lecturer, Newmark (1965) presented an approach to estimate the likely deformation of a dam embankment slope during an earthquake. This approach represented an improvement over the commonly used pseudo-static approach since it recognized that the pseudo-static method could indicate factors of safety less than one – yet an embankment would perform adequately during an earthquake. In recent years, the Newmark approach has been extended to natural slopes and landslides (Jibson, 1993).

Newmark's analysis assumes that when the earthquake acceleration exceeds the yield acceleration of the potential failure mass, movement occurs. One of the key assumptions incorporated into the analysis is that the shear strength along the failure zone remains constant during displacement. However, in brittle, strain-softening, or liquefiable material, the shear strength decreases with increasing strain. In this case, the Newmark approach can underestimate seismic displacements. On the other hand, an existing landslide in clay soils at residual strength would undergo additional straining without "softening" or significant pore-water pressure changes. Furthermore, numerous studies regarding rate effects on the shear strength of clays indicate increasing shear strength with increasing rate of shear. These studies have been summarized by Kulhawy and Mayne (1990), which indicate, on average, a 10 percent strength increase per order of magnitude increase in shear rate. Since typical earthquake velocities (inches/second) can be six to eight orders of magnitude greater than a slow-moving landslide, the Newmark approach can greatly overestimate seismic displacements in residual clay soils.

RING SHEAR TESTING OF SLIDE MATERIAL

To investigate rate effects on the shear strength of residual clay, the authors recently performed several ring shear tests of residual soil from a slow-moving landslide in Portland, Oregon. Bulk samples of the shear zone were obtained from a shaft excavation at a depth of 18.3 m, and relatively undisturbed tube samples were obtained from nearby drillholes. The location of the shear zone for tube sampling was determined from adjacent inclinometer data. The landslide is occurring within a layer of decomposed basalt near the contact with less-weathered basalt bedrock. Inclinometers installed in the slide several years ago have detected an average rate of movement of 0.08 to 0.2 cm per year. The landslide is approximately 800 m long and 365 to 1,000 m wide. The slide is translational, and the ground surface and failure zone are both about 8 to 10 degrees to the horizontal. A three-dimensional, back-analysis of the slide gave a residual friction angle of 7 degrees.

The bulk samples of decomposed basalt consist of stiff to very stiff, mottled, gray-brown-red, silty clay with scattered coarse, sand-sized nodules. Grain size distribution for one of the specimens gave 70 percent passing the No. 200 sieve, and 30 percent passing 0.002 mm. The natural water content was 45 percent, and Atterberg limits were LL = 85, PL = 59. The samples were highly slickensided (see Fig. 1).

To test the soil with minimal disturbance, a steel template was custom-machined to hand-carve the specimens into the ring shear apparatus. Since the outer diameter of the donut-shaped ring shear specimen (10 cm) is larger than the diameter of the Shelby tube (7.6 cm), the cutting template has the shape of one-quarter of the ring shear specimen. Four quarter "donuts" were carved to complete one specimen. A photograph of the trimmed "quarter-donut" specimens are shown on Figure 2.

After consolidating the specimen to the estimated effective stress in the field, shearing was commenced at a rate of 0.12 mm/min to measure the residual strength at a "slow" rate of shear. Once residual strength was obtained, the shearing was stopped, torque removed, and the specimen was allowed to rest for a period ranging from one hour to several days. Shearing was resumed at a higher rate until the strength became relatively constant. Following each stage of shearing at progressively higher rates, the specimen was returned to the "slow" shear rate.

Figure 1. View of highly polished, slickensided chunk sample of stiff, silty clay shear zone.

A cumulative stress-strain plot for one of the specimens is shown on Figure 3. This figure shows the stress-strain plot for different rates of shear and the strength values selected for each rate. For example, at a shear rate of 44.5 mm/min, the ring shear stress drops to 43 kPa on three occasions after initial build-up of stress. These low points were taken as the residual strength for this strain rate. A similar procedure was used for the other strain rates as shown by the horizontal dashed lines on Figure 3. As shown on the graph, there are some temporary peaks in the stress-strain curves at the higher rates of shear. As mentioned, these higher stress values were not used to evaluate the strength increase since residual strength, by definition, is the lowest strength measured under test conditions.

The results of the ring shear tests for one specimen are shown on Figure 4, along with a plot of the 10 percent strength increase noted by Kulhawy and Mayne. As shown on this figure, the results for the relatively undisturbed clay samples are significantly higher than the 10 percent line. A detailed evaluation and explanation of this difference is beyond the scope of this paper; however, the general trend of increasing strength with increasing shear rate is apparent. Similar ring shear testing was performed by Lemos, Skempton and Vaughan (1985) to evaluate the effects of fast shearing on residual shear strength. The results from their findings indicated that, "generally there is substantial gain in strength during fast shear. Predictions of displacement during earthquake are substantially reduced if this effect is included." Their data indicates a strength increase closer to the 10 percent line.

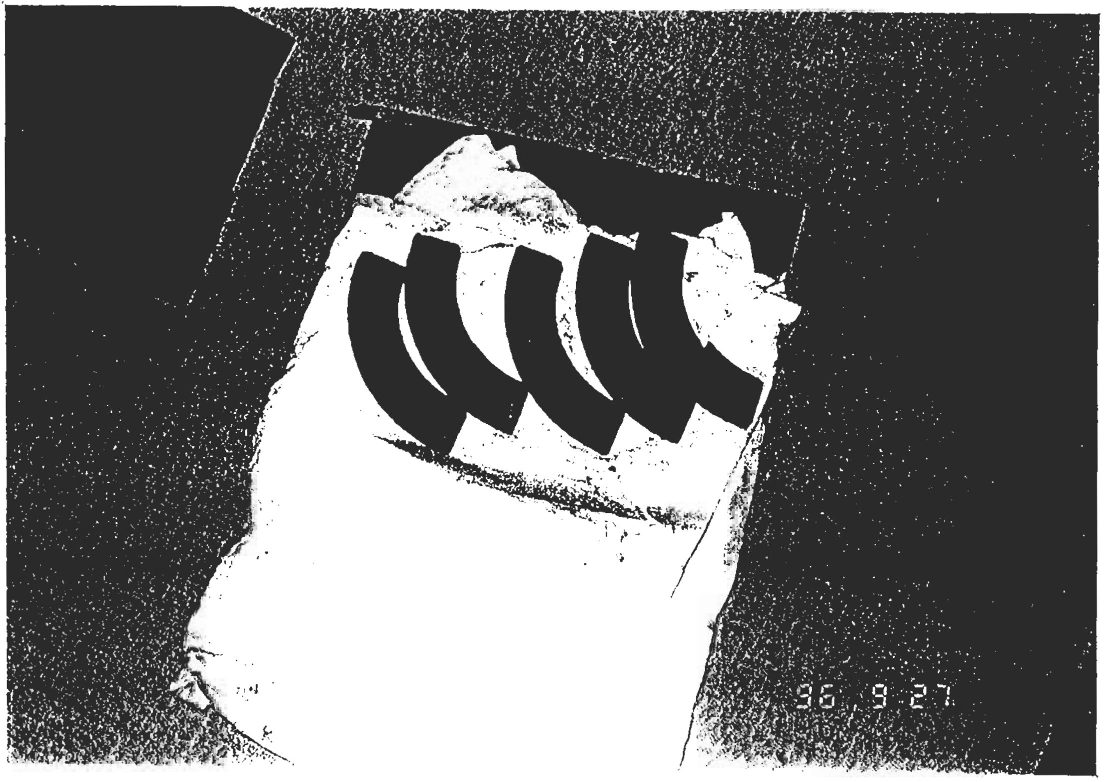

Figure 2. Hand-carved quarter sections of ring shear specimens prior to testing.

SELECTION OF DYNAMIC YIELD ACCELERATION

Ring shear testing of clay soil at residual strength indicates an apparent "viscous" strength increase with increasing rate of shear and similar results have been obtained for first-time sliding clay material. Therefore, calculating the seismic displacement of a marginally stable, clay soil landslide by a Newmark analysis will significantly overestimate actual movements if this strength gain is not accounted for. The Newmark approach can be adjusted by increasing the residual shear strength by 10 percent per order of magnitude increase in the rate of shear (earthquake vs. natural) to account for "visco-dynamic" behavior of residual strength clays. The increased "visco-dynamic" shear strength value can then be used in a limit equilibrium analysis to determine a dynamic yield acceleration (k_{dy}) for input into the Newmark analysis.

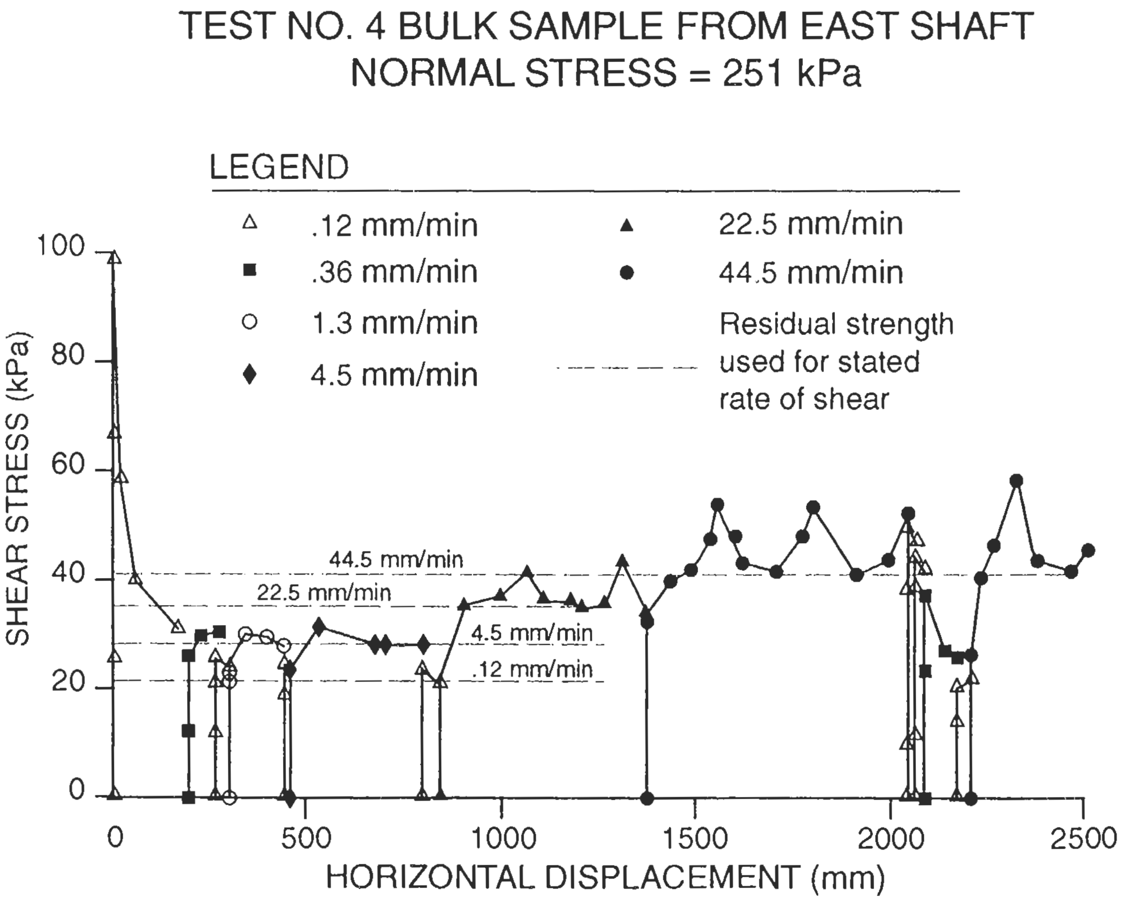

Figure 3. Variable rate ring shear stress-strain plot for hand-carved silty clay specimen from landslide shear zone.

For example, if it is assumed that the maximum rate of movement of the aforementioned landslide under natural "static" conditions is 0.25 cm in 10 days (i.e. movement occurs during an extreme winter storm), the velocity is 0.000018 cm/min (0.0000003 cm/sec). If this rate is compared to a typical Magnitude 6.5 earthquake average velocity of say 20 cm/sec at 10 km, the earthquake velocity is about 7½ orders of magnitude higher than the natural landslide velocity.

Using a 10 percent residual strength increase per order of magnitude velocity increase, there is a 75 percent increase in the "static" residual strength during the earthquake. The landslide in this example has a back-calculated residual friction angle of 7 degrees. Therefore, this value would be increased 75 percent to 12 degrees [$\tan^{-1}$ (1.75 tan 7°)]. The dynamic yield acceleration is then calculated using this higher strength value and incorporated accordingly into the Newmark analysis.

This approach was used to predict the behavior of another landslide in Portland, Oregon located 2 km from the previously discussed landslide. The size, geology, and mechanics of both slides are similar and the back-calculated residual strength for the slide is 12 degrees. A Newmark analysis for this active slide, assuming a near-zero yield acceleration ($k_y = 0.001$) and a postulated crustal earthquake on the Portland Hills Fault (Magnitude 6.9 located 1 km from the site), would result in estimated seismic displacements of 3 to 6 m. This postulated earthquake would produce shear velocities approximately 8½ orders of magnitude faster than the natural slide movement rate. Using the proposed procedure, the residual friction angle of the slide was increased 85 percent and a dynamic yield acceleration, $k_{dy} = 0.14$, was obtained. Estimated displacements using the "dynamic" strength are 25 to 75 cm. As will be discussed in the next section, these lower estimated displacements show good agreement with seismic displacements of active landslides during the Magnitude 7.1 Loma Prieta earthquake.

PERFORMANCE OF ACTIVE SLIDES DURING EARTHQUAKES

During the past several decades, many active landslides have been subjected to earthquake-induced ground motions. The authors have reviewed several case histories documented by earth scientists during post-earthquake reconnaissance. One of the more important observations was that most active or marginally stable landslides have remained relatively stable during seismic events – contrary to what a Newmark analysis using a near zero yield acceleration would predict. Several examples are listed below:

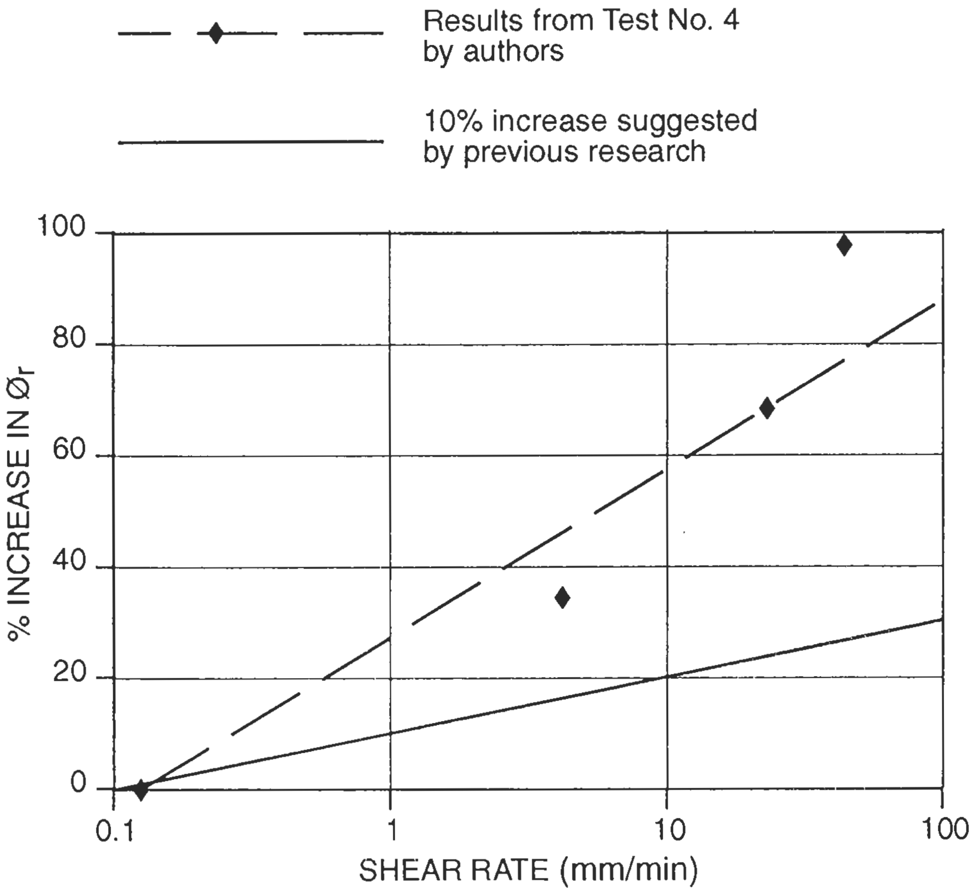

Figure 4. Shear rate influence on residual strength clay and research by others.

- The two largest historical earthquakes in the Pacific Northwest were the 1949 Olympia earthquake (Magnitude 7.1) and the 1965 earthquake near Seattle (Magnitude 6.5). During the Olympia earthquake, it was observed that, "Seismic displacements associated with existing coherent slide blocks were typically less than 1 m" (Chleborad, 1994).

- In 1976, a Magnitude 7.5 earthquake in Guatemala caused over 10,000 landslides. A USGS reconnaissance of the distribution and extent of landsliding indicated that, "Despite strong seismic shaking from the 1976 earthquake, pre-earthquake landslide material mostly appeared to remain stable . . . evidence from other earthquakes shows a similar behavior of dormant landslides during strong seismic shaking" (Harp, et al., 1981).

- In 1991, the Magnitude 7.0 Racha earthquake struck the Republic of Georgia triggering numerous landslides. Another USGS reconnaissance indicated that, "Co-seismic movement generally amounted to only a few centimeters to a few decimeters . . . the small amount of earthquake-triggered movement of many active landslides, particularly earth slides, is puzzling. . . ." The investigators went on to further state that, "According to Newmark's model, if the landslides in the epicentral area had static factors of safety at or near 1, they should have experienced large displacements during the Racha earthquake" (Jibson, et al., 1994).

- The Magnitude 7.1 Loma Prieta earthquake struck the San Francisco Bay area on October 17, 1989. Shortly after the earthquake, engineers and earth scientists performed a reconnaissance of landslide and other geologic damage caused by the earthquake. These observations were summarized by the California Division of Mines and Geology (Manson, et al., 1992). Approximately 50 landslides were documented and seismic displacements were estimated based on ground fractures at the headscarp for each slide. It appears that 12 of these slides were active prior to the earthquake.

  Figure 5 shows a plot of the observed landslide displacements versus distance from the earthquake epicenter. Active landslides prior to the earthquake are plotted as solid triangles and a range of displacements for the existing slides are bracketed on this figure. At an epicentral distance of 10 km, the data suggests that active landslides moved from 5 to 30 cm during the earthquake. A Newmark analysis assuming the existing slides were close to a factor of safety of 1 before the earthquake, i.e. $k_y = 0.001$, and scaling Loma Prieta acceleration time histories to an epicentral distance of 10 km, would result in estimated seismic displacements of approximately 230 cm.

  Also plotted on Figure 5 is a data point from an instrumented, active slide at the Penetencia Water Treatment Plant (PWTP), located 39 km from the epicenter. Based on actual inclinometer data, the PWTP slide moved 0.5 to 1.7 cm during the Loma Prieta earthquake. A Newmark analysis using a low yield acceleration, $k_y = 0.001$, results in an estimated displacement of about 68 cm using scaled Loma Prieta acceleration time histories, an overestimation by almost two orders of magnitude. This slide has also been subjected to two other earthquakes: the 1984 Morgan Hill (Magnitude 6.2, epicenter 18 km from the slide) and the 1986 Mount Lewis (Magnitude 5.7, 17 km from the slide), with movements ranging from 1.2 to 1.9 cm during each earthquake (Salah-Mars, et al., 1995).

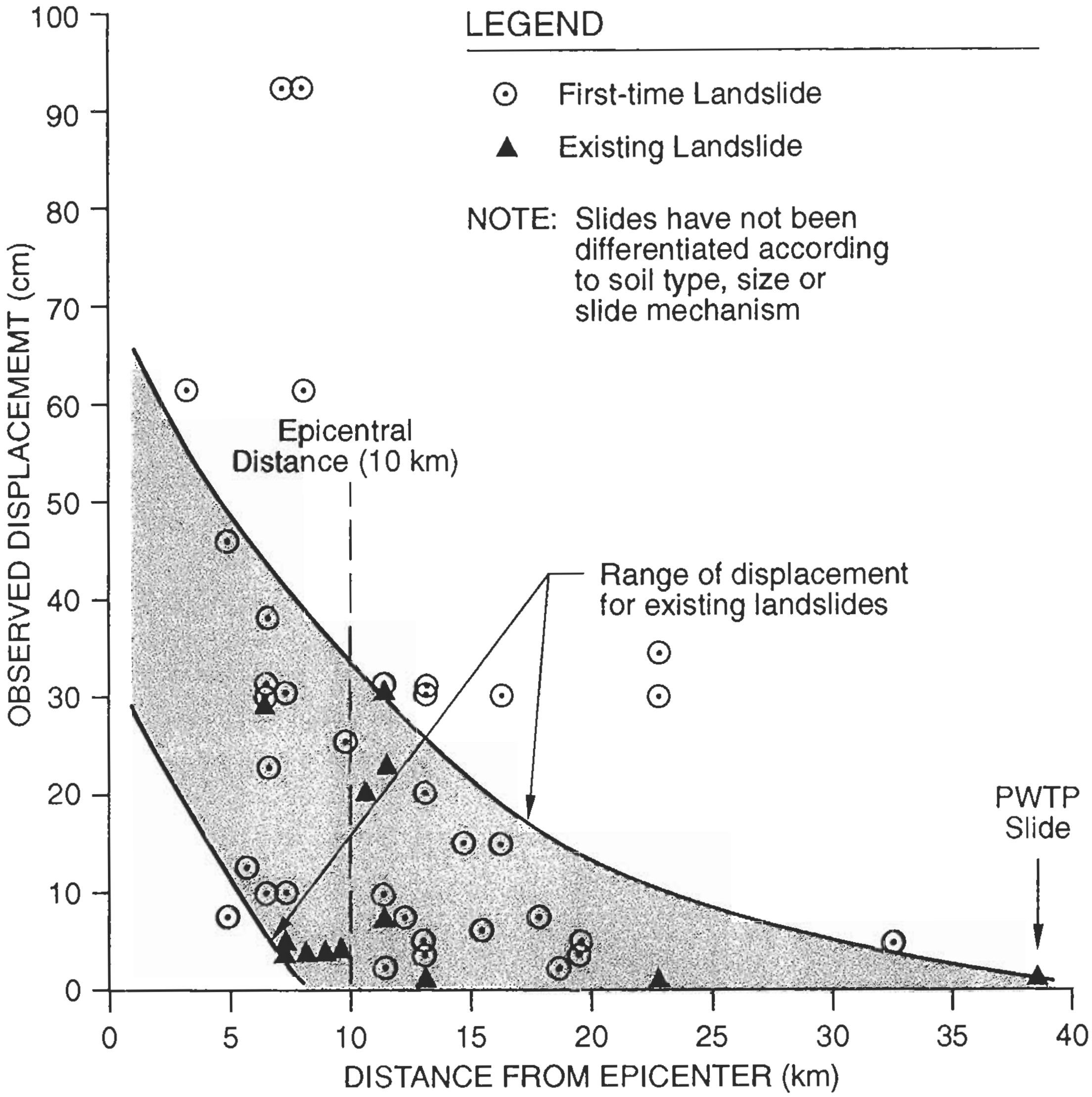

Figure 5. Observed ground displacement during Magnitude 7.1 Loma Prieta earthquake.

CONCLUSIONS

The Newmark approach for estimating seismic displacements of a potential failure surface assumes that the strength along the failure zone remains constant. Recent laboratory ring shear tests of hand-carved, residual strength clay material, along with earlier research on shear rate effects on clays, indicates that shear strengths increase significantly during rapid loading conditions. A review of several case histories of active landslides subjected to strong earthquakes indicates that actual displacements can be one to two orders of magnitude lower than what a Newmark procedure would predict using a near-zero yield acceleration. By increasing the residual shear strength of the slide material 10 percent per order of magnitude increase in the rate of earthquake shearing compared to the natural movement rate, a "dynamic" yield acceleration can be calculated. Incorporating this "dynamic" yield acceleration into a Newmark analysis gives estimated displacements which more closely represent observed movements in various case histories.

As shown on Figure 5, the bracketed range of displacements for active landslides during the Loma Prieta Magnitude 7.1 earthquake at an epicentral distance of 1 km is approximately 30 to 65 cm. Using the "dynamic" residual shear strength method proposed in this paper, the calculated displacements for a 85 percent increase in the back-calculated residual strength are in the range of 25 to 75 cm for the Portland landslide during a Magnitude 6.9 earthquake on the Portland Hills Fault. In this example, the calculated range is in good agreement with the observed range in California for a similar magnitude earthquake, and suggests that the proposed method is a reasonable approach for estimating the seismic displacements of marginally stable landslides.

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