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Seismic Instrumentation of Landslides: Building a Better Model of Dynamic Landslide Behavior

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Abstract Although the geologic, topographic, and threshold shaking conditions required to trigger landslides in earthquakes are probabilistically predictable, models used to estimate the behavior of slopes under dynamic shaking conditions are overly simplistic because of the lack of direct measurement of landslide behavior during seismic shaking. Two permanent instrument arrays have been installed on seismically active landslides to simultaneously record acceleration, pore pressure, and permanent landslide displacement, which will permit more accurate modeling of seismic landslide response.

Introduction

Landslides are a major cause of damage in most large earthquakes. In the 1964 Alaska earthquake, for example, landslides caused more than half of the economic losses and a third of the fatalities (Keefer, 1984). Also, large areas can be affected by earthquake-triggered landslides. For example, the 1906 San Francisco earthquake triggered landslides over an area of about 40,000 km^2 (Keefer, 1984), and the 1989 Loma Prieta, California, earthquake, despite occurring during the driest part of the year after a prolonged drought, triggered thousands of landslides that caused at least $30 million in damage over an area of about 15,000 km^2 (Keefer and Manson, 1995). Recent research advances have made it possible to predict the geologic and topographic conditions that contribute to seismic slope instability and the threshold seismic conditions required for triggering (Wieczorek *et al.*, 1985; Harp and Keefer, 1985; Wilson and Keefer, 1985; Keefer and Wilson, 1989). However, further development of the physical models used to predict the behavior of slopes during earthquakes is hindered by the lack of direct measurements of landslide behavior during the actual time of seismic shaking. This article describes two permanent instrument arrays on landslides that have moved during recent earthquakes. These arrays are designed to measure the critical phenomena that will permit more accurate modeling of seismic landslide response. We begin by briefly summarizing current methods for modeling seismic landslide behavior and discussing their limitations. We then describe the permanent instrument arrays that have been installed to gather the data needed to address these limitations and discuss the advances that successfully recording the dynamic response of a landslide would make possible.

Current Methods of Analyzing Seismic Landslide Behavior

Predicting the seismic performance of slopes has been approached in several ways. The simplest approach is pseudo-static analysis, in which an earthquake acceleration acting on a landslide mass is treated as an additional static body force in a limit-equilibrium (factor-of-safety) analysis. Different earthquake accelerations are then applied until the factor of safety is reduced to 1.0. The earthquake acceleration needed to reduce the factor of safety to 1.0 is called the yield acceleration, the exceedance of which is defined as failure. This procedure is simple and requires no more information than is needed for a static factor-of-safety analysis, principly the shear strength and unit weight of the material and the slope geometry. Pseudo-static analysis is useful for identifying yield accelerations and, hence, peak ground accelerations (PGA), below which no slope displacement will occur. In cases where the PGA does exceed the yield acceleration, pseudo-static analysis has proved to be vastly overconservative because many slopes experience transient earthquake accelerations well above their yield accelerations but experience little or no permanent displacement (Newmark, 1965; Wilson and Keefer, 1983). The utility of pseudo-static analysis is thus severely limited because it provides only a single numerical threshold, below which no displacement is predicted and above which total but undefined failure is predicted. In fact, pseudo-static analysis tells us nothing about what will occur when the yield acceleration is exceeded.

On the other end of the spectrum, advances in finite-element modeling have facilitated very accurate modeling of strain potentials and permanent slope deformation (e.g., Elgamal *et al.*, 1987). But these more sophisticated methods require a broad spectrum of data of extremely high quality and density that are seldom available, which, combined with the intensive computing capacity required, make their general use extremely expensive. Even in cases where finite-element modeling is appropriate, many assumptions regarding dynamic soil behavior must be made, which limits the reliability of the model results, however sophisticated the actual modeling procedure might be.

Newmark (1965) proposed a method of analysis that bridges the gap between simplistic pseudo-static analysis and more sophisticated, but generally impractical, finite-element modeling. Newmark's method models a landslide as a rigid-plastic friction block having a known yield or critical acceleration, the acceleration required to overcome frictional resistance and initiate sliding on an inclined plane. The analysis calculates the cumulative permanent displacement of the block as it is subjected to the effects of an earthquake acceleration-time history by double integrating the positive portions of the horizontal acceleration time history that lie above the critical acceleration, and the user judges the significance of the displacement (Fig. 1). Laboratory model tests (Goodman and Seed, 1966) and analysis of earthquake-induced landslides in natural slopes (Wilson and Keefer, 1983) confirm that Newmark's method fairly accurately predicts slope displacements if slope geometry, soil properties, and earthquake ground accelerations are known accurately. Newmark's method is simple to apply and provides a quantitative prediction of the inertial landslide displacement that will result from a given level of earthquake shaking (Jibson, 1993). This method has been used for both site-specific and regional purposes (Wilson and Keefer, 1983; Wilson and Keefer, 1985; Keefer and Wilson, 1989; Jibson and Keefer, 1993) to estimate seismically induced landslide displacements. Results from Newmark's method also are useful in probabilistic analyses (e.g., Yegian *et al.*, 1991), which further enhances their utility.

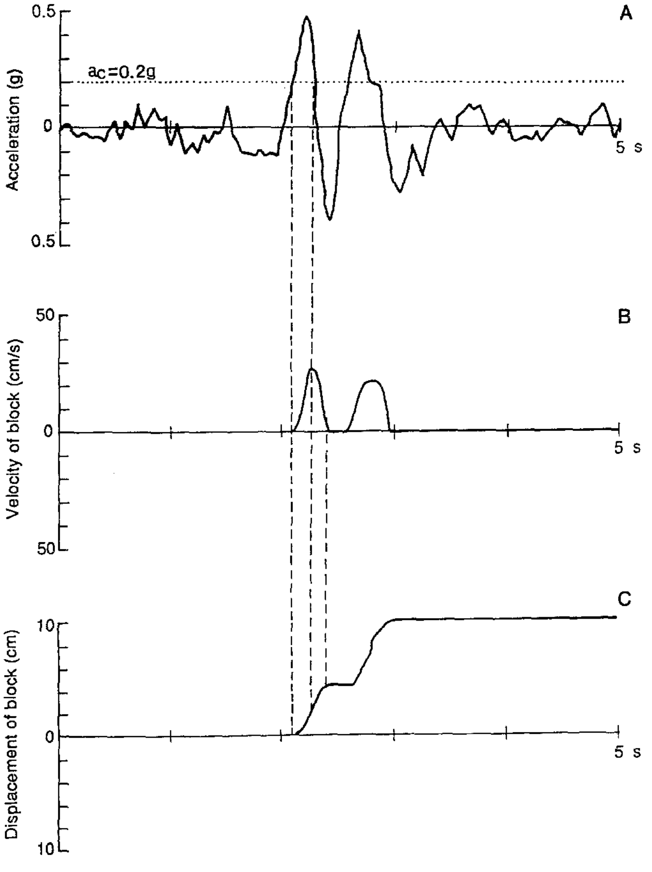

Figure 1. Demonstration of the Newmark algorithm (adapted from Wilson and Keefer, 1983). (a) Earthquake acceleration time history with critical acceleration (dotted line) of 0.20 *g* superimposed. (b) Velocity of landslide block versus time. (c) Displacement of landslide block versus time.

Newmark's method and, in fact, all these methods, generally ignore several potentially important aspects of the seismic behavior of landslides because no direct measurements of landslide response to earthquake shaking have ever been published. The most critical gaps in our understanding include (1) strain-dependent reduction in shear strength along the landslide basal slip surface, (2) dynamic pore-pressure changes within the landslide mass, (3) the effects of the vertical component of ground shaking, (4) estimation of strong shaking at landslide sites, and (5) differentiating between co-seismic inertial landslide displacement and postseismic gravitational displacement.

Landslide Instrument Arrays

To address these gaps in the data and weaknesses in the modeling procedures, and to accurately measure the dynamic response of landslides during earthquake shaking, we have installed two permanent instrument arrays on recently active landslides in California. Each array simultaneously measures strong shaking on the landslide, strong shaking at an adjacent stable site, pore pressure within the landslide mass (Week's Creek site only, see below), and permanent landslide displacement during seismic shaking. Criteria for selecting these landslides included (1) proximity to active faults likely to produce levels of strong shaking sufficient to trigger movement within the next several years, (2) history of limited (as opposed to very large or catastrophic) movement during recent earthquakes, (3) simple geometry and movement mechanism, (4) well-defined head or lateral scarps across which extensometers can be installed, and (5) access and security. The sites we selected using these criteria are the Week's Creek landslide in the San Francisco Bay area and the Chantry Flat landslide near Los Angeles.

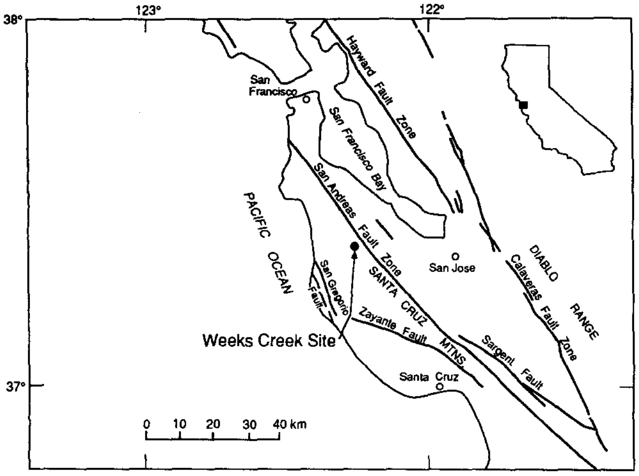

Figure 2. Location of Week's Creek landslide instrument site in the San Francisco Bay area and prominent faults in the region. Fault locations from Wesson *et al.* (1975).

Week's Creek Landslide

The Week's Creek landslide is a large slump/earthflow complex about 4 km southwest of the San Andreas fault in the San Francisco Bay area, California (Fig. 2). The landslide formed in deeply weathered Tertiary siltstones and sandstones of the Lambert Shale and San Lorenzo Formation. A portion of the landslide complex is periodically active and shows displacement along its lateral margins in most moderate to heavy rainfall seasons; landslide displacement is visible where it crosses California State Highway 84 (Fig. 3). Although the landslide is more than 40 km from the epicenter of the 1989 Loma Prieta earthquake, we measured 0.5 cm of left-lateral coseismic displacement (downslope) along its north lateral margin. Youd and Hoose (1978) and Lawson (1908) reported about 0.9 m of displacement of this landslide during the 1906 San Francisco earthquake.

Figure 3 shows some features of the Week's Creek landslide and the deployment of instruments, including two three-component strong-motion accelerometers (FBA-13), two extensometers, and four piezometers, all of which are connected to Kinemetrics[1] SSA-1 digital recorders, which provide a common time base for the instruments. The recorders are triggered by vertical accelerations of 0.01 *g*, and signals from these instruments are recorded at 200 samples per second during the earthquake shaking. A separate data logger records signals from the piezometers and extensometers continuously to provide long-term background data prior to and after an earthquake. One accelerometer is located on the ground surface near the center of the active slide mass; the other is anchored to the concrete floor of a one-story farm building off the active part of the slide. The accelerometers are aligned with one of the horizontal components parallel to the predominant direction of slide movement. Except for the accelerometer and recorder located within the farm building, which has line power, the instruments and recorders are all powered by 12-volt batteries attached to solar cells for recharging.

The extensometers are deployed across the northern lateral shear surface (right margin) of the active earthflow at about 30° to the lateral shear (Fig. 3). Each extensometer consists of a self-contained potentiometric transducer with a spring-retractable metal wire (Fig. 4). The transducer is bolted to grouted metal stakes off the active earthflow, and the retractable wire extends through buried telescoping PVC pipes and is attached to a grouted metal post on the active part of the slide (Fig. 4). The telescoping function of the PVC is to protect the buried extensometer cable during extension. The pipe was laid in trenches and buried to a depth of about 80 cm to avoid disturbance during periods of agricultural cultivation. The extensometer signals are recorded on two of the four channels of the SSA-1 recorder in the nearby instrument hut (Fig. 3). The resolution of the extensometers is about 2.0 mm.

Three piezometers are buried within the active earthflow about 15 m south of the extensometer trenches (Fig. 3) at depths of 15.0 (number 1), 12.0 (number 2), and 7.6 (number 3) m. The basal shear surface of the earthflow at this location is about 15-m deep as estimated from borehole samples (G. F. Wieczorek, U.S. Geological Survey, unpublished data). Signals from piezometers number 1 and number 3 are recorded on the remaining two channels of the SSA-1 in the instrument hut. Piezometer number 2 is a backup in the event of malfunction of either of the other piezometers; it is not presently connected to the SSA-1 because no additional channels are available. These piezometers, as well as the extensometers, are all continuously recorded on a separate data logger to provide long-term background data for comparison with dynamic response during an earthquake. Piezometer 4, at a depth of 9.6 m, is located near the instrument hut on the center of the landslide and is connected to the SSA-1 recorder there. The pressure transducers have a natural frequency of approximately 38 kHz and are capable of accurately measuring pressure fluctuations of several thousand Hz. The limiting factor in the response of the soil-instrument system at the site is the permeability of the soil. Resolution of the pressure transducers is in the range of hundredths of kilopascals (kPa).

All the piezometer holes are fully cased and are sealed with bentonite immediately above the piezometer outside the casing. The interfaces at the hole bottoms inside the casings allow pore-pressure transducers to be screwed into a threaded seat in the PVC bottom cap where their

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[1] Use of trade names is for descriptive purposes and does not imply endorsement.

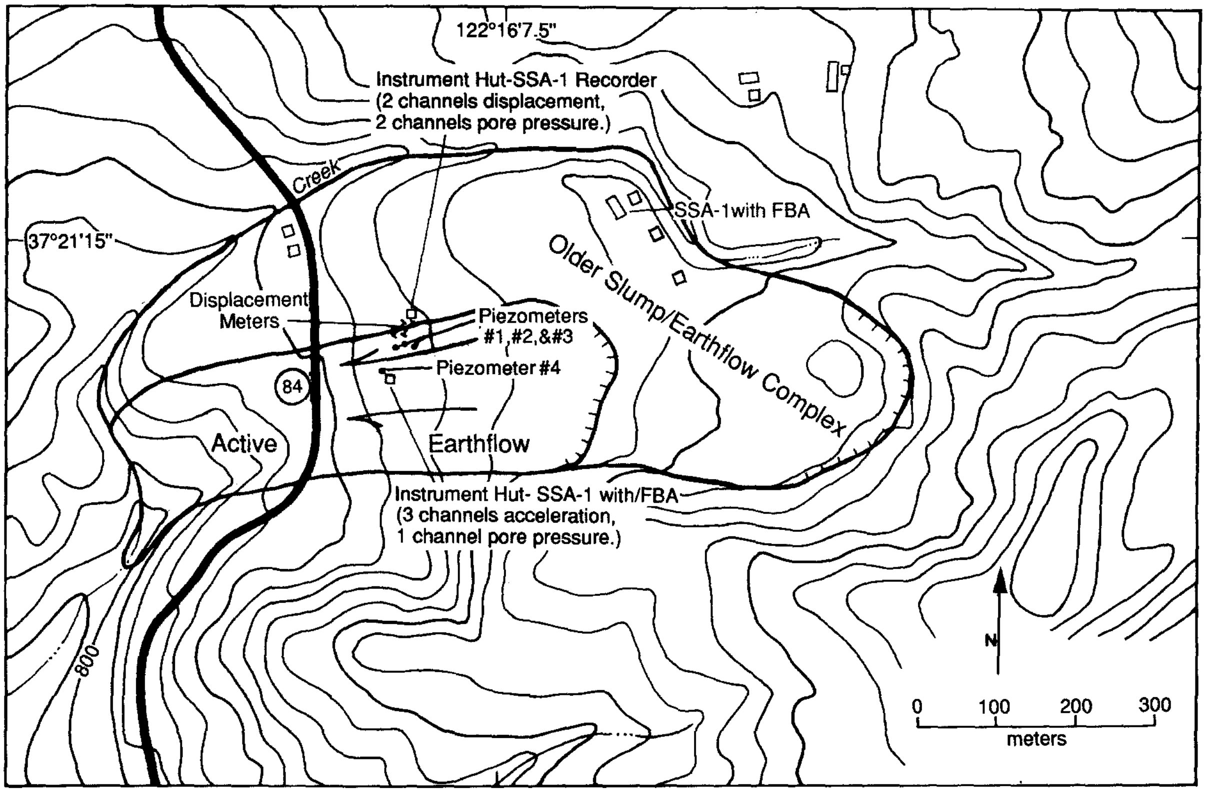

Figure 3. Topographic map of Week's Creek landslide showing instrument layout and boundaries of old slump/earthflow complex and recently active earthflow (from Wieczorek, unpublished data). Topographic base from U.S.G.S. $7^1/_2'$ La Honda quadrangle; contour interval is 40 ft, datum is mean sea level.

sensing surface has access to the pore water just outside the casing. The interfaces at the hole bottoms allow for removal of transducers for calibration, repair, or replacement.

Chantry Flat Landslide

Chantry Flat is a picnic area and trailhead in the Angeles National Forest in the San Gabriel Mountains (Fig. 5). The flat is the head of a large prehistoric landslide that extends to the canyon bottom (Fig. 6). Our observations following the 28 June 1991 Sierra Madre earth-

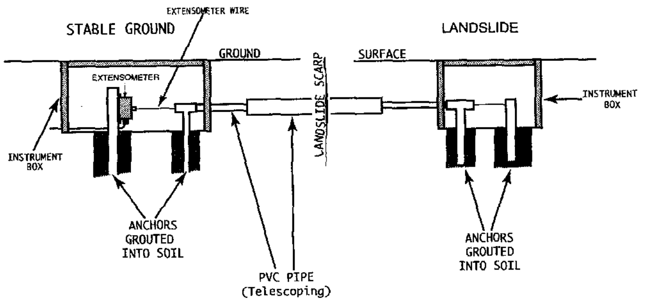

Figure 4. Diagram of extensometer deployment. Sketch is not strictly to scale; however, extensometer at left of drawing is approximately 6 cm in vertical dimension.

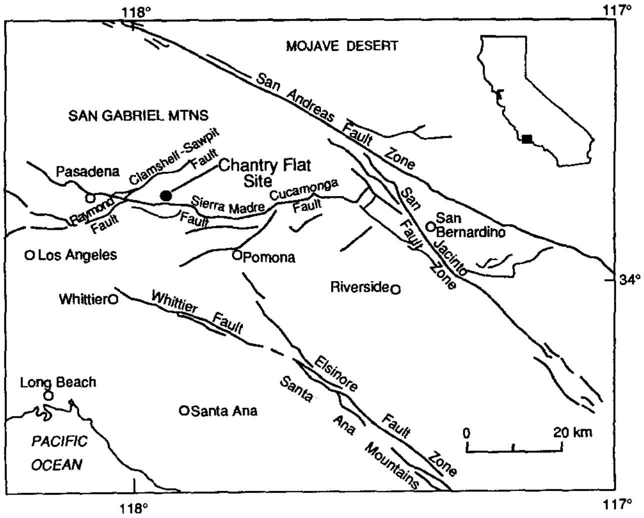

Figure 5. Location of Chantry Flat landslide instrument site in the Los Angeles area and prominent faults in the region. Fault locations from Ziony and Yerkes (1985).

quake (*M* 5.8), centered about 6.5 km north-northwest of Chantry Flat, indicated that the earthquake activated the distal portion of the ancient landslide mass and formed a scarp 40-m long that had a maximum displacement of 20 cm. The geology at Chantry Flat is characterized by thin sandy soil overlying deeply weathered granitic metamorphic rocks of the Archean San Gabriel Complex of Miller (1946). Bedrock hardness is highly variable because numerous anastomosing dikes pervade the host rocks, and differential weathering has produced a soft, friable residual regolith in the more mafic portions of these rocks, while the granitic rocks and quartz-rich dikes remain hard and resistant.

Figure 7 shows the instrument layout at the reactivated part of the landslide. Two SSA-1 recorders are located in the larger instrument hut south of the landslide scarp, one with a self-contained accelerometer. One accelerometer in the smaller instrument hut (sensor only, see Fig. 6) is on the part of the landslide that was reactivated by the Sierra Madre earthquake; the other, in the larger instrument hut, is upslope from the recent scarp on the ancient landslide mass. Both accelerometers are aligned having one horizontal component parallel to the scarp azimuth (N75°W) and the other horizontal component normal to the scarp and thus parallel to the direction of anticipated landslide movement. A third accelerometer and SSA-1 recorder are located about 450 m to the south (Fig. 6), above the headwall scarp of the prehistoric landslide, in a metal one-story building adjacent to the main Chantry Flat helipad (upper helipad

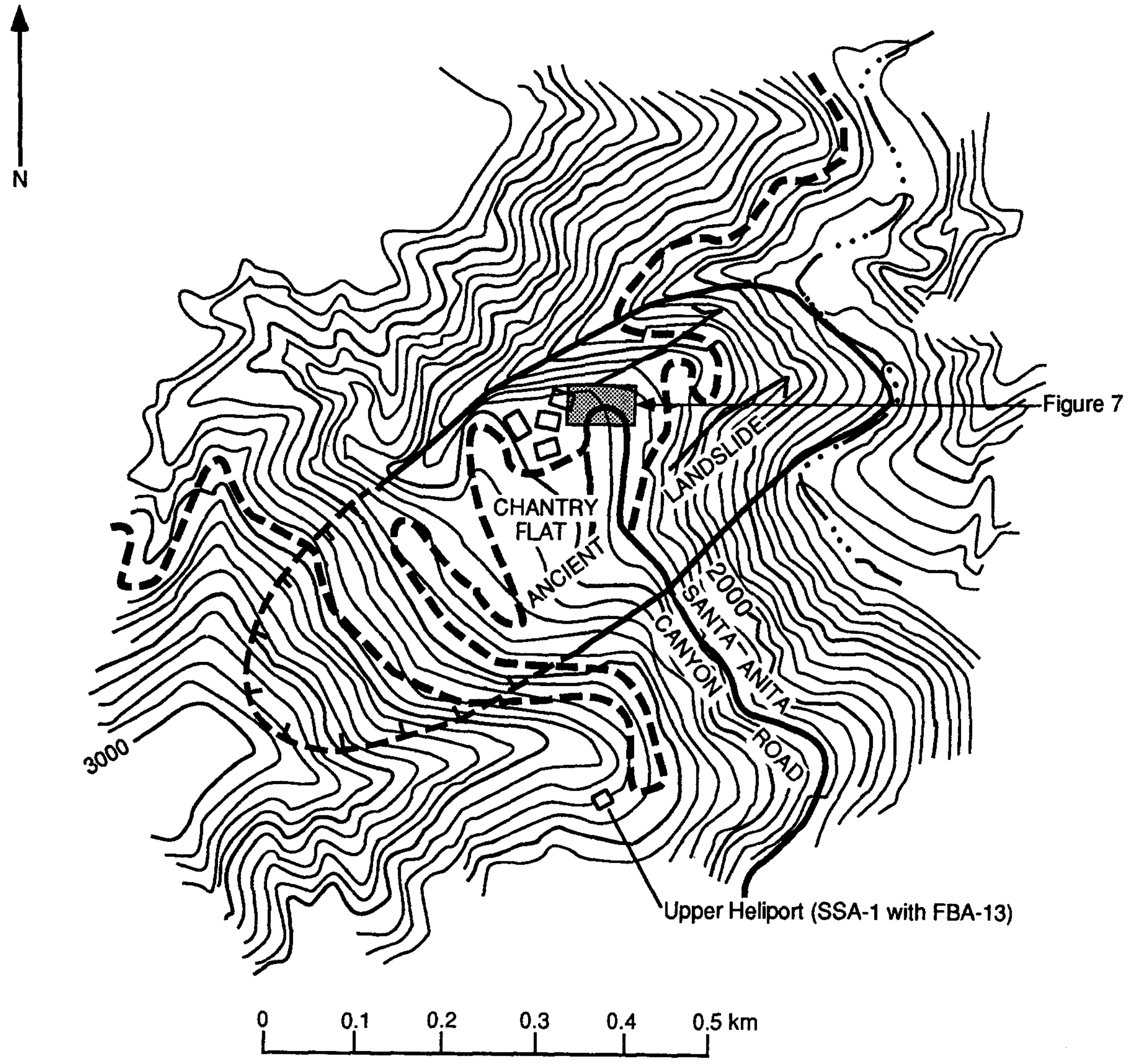

Figure 6. Topographic map of Chantry Flat instrument site and vicinity. Location of the strong-motion accelerometer and recorder at the upper helipad is shown; detail of the instrument layout near the scarp is shown in Figure 7. Topographic base is U.S.G.S. 7½′ Mt. Wilson quadrangle; contour interval is 40 ft, datum is mean sea level.

shown in Fig. 6). The recorder and accelerometer are bolted to the concrete building slab and oriented similarly to the accelerometers near the lower Chantry Flat helipad (concrete pad with a large "H" shown in Fig. 7). This additional accelerometer was installed in the event that future movement on the landslide took place upslope from the scarp created in the Sierra Madre earthquake and to provide a comparison of strong motion recorded on stable bedrock with that recorded on a large ancient landslide.

Because of difficulties in drilling owing to the nature of the bedrock and the local topography, piezometers have not been installed at this site as yet.

Importance of Direct Measurements

With the simultaneous recording of co-seismic ground acceleration, permanent landslide displacement, and pore-water pressure during a future earthquake, we expect to collect data that will facilitate more accurate modeling of the seismic behavior of landslides. Such data will allow direct evaluation of the fundamental basis of the Newmark analysis by comparing the displacement time history recorded at the site with that derived from double integration of the acceleration time history. More detailed analysis may permit more realistic modeling of several aspects of landslide behavior during earthquake shaking. (1) Laboratory tests and field observations indicate that most landslides experience a reduction in shear strength along their basal slip surface as displacement occurs (*e.g.*, Skempton, 1964), but no direct measurements of this phenomenon or its magnitude within real slopes have been reported. (2) Pore pressure can play a major role in determining the overall shear resistance of a landslide, but no direct measurements of seismically induced pore pressures within landslides have been published. (3) Scientists and engineers traditionally have ignored the vertical component of seismic shaking as being insignificant in producing displacements of landslides, despite the fact that some vertical acceleration records show significant contributions to the total acceleration experienced at a site and may even exceed levels of the corresponding horizontal components. By recording three components of seismic shaking on active landslides, we can expand Newmark's method to account for both horizontal and vertical components of ground shaking in the plane of the model and more closely approach a truly two-dimensional analysis. (4) By recording strong shaking both on active landslides and on adjacent stable ground, we can compare site responses and develop appropriate site-response functions for landslides. This will alleviate the previous necessity of using nearby strong-motion recordings that may not be from a site of similar materials or slopes. (5) In some cases, reduction in shear strength along the basal slip surface of a landslide is sufficient to render the slide statically unstable even after the earthquake shaking ceases. Unfortunately, even with eyewitness accounts during postearthquake investigations of landslides, it is virtually impossible to differentiate precisely between co-seismic and postseismic displacement. With our instruments, co-seismic as well as postseismic pore pressure and displacement can be recorded so that the effects of seismic shaking and strength reduction on displacement can be discriminated and compared.

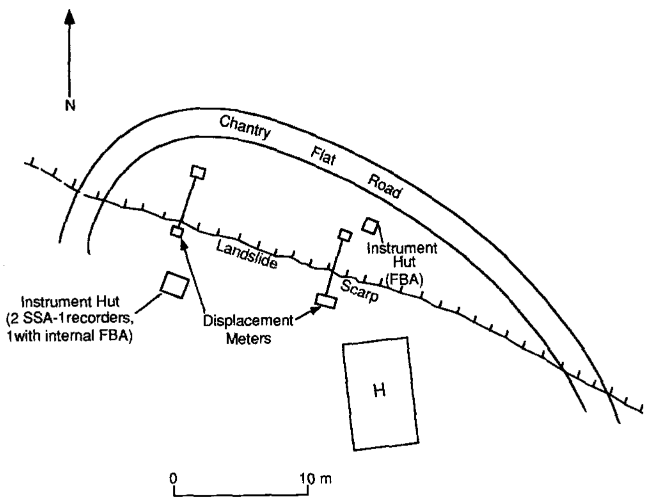

Figure 7. Sketch map of instrument layout at Chantry Flat near location of recently formed landslide scarp. Rectangular area marked "H" is lower helipad at Chantry Flat.

Summary

Simultaneous recording of ground shaking, permanent displacement, and pore-pressure response of landslides during future earthquakes will provide the data needed to improve our ability to model seismic landslide behavior. Strain-dependent shear-strength variation, dynamic pore-pressure response, vertical accelerations, and the relative contribution of gravitational versus seismic effects all have been virtually ignored in existing analytical procedures because of lack of field data. But all of these phenomena significantly affect landslide behavior. Only the direct measurement of the acceleration, displacement, and pore pressure of a landslide during an earthquake will allow accurate assessment of the relative importance of each of these phenomena and yield insight as to how to modify current analytical methods or formulate new methods to better predict seismic landslide behavior.

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