Bulletin of the Seismological Society of America, Vol. 92, No. 8, pp. 3180–3189, December 2002

Anomalous Concentrations of Seismically Triggered Rock Falls in Pacoima Canyon: Are They Caused by Highly Susceptible Slopes or Local Amplification of Seismic Shaking?

by Edwin L. Harp and Randall W. Jibson

Abstract Anomalously high concentrations of rock falls were triggered in Pacoima Canyon (Los Angeles, California) during the 1994 Northridge earthquake. Similar concentrations were also documented from the 1971 San Fernando earthquake. Using an engineering rock-mass classification that evaluates the susceptibility of rock slopes to seismic failure based on the fracture properties of a rock mass (in terms of a numerical "*Q*-value" that describes rock quality), the rock slopes in Pacoima Canyon were compared with rock slopes in surrounding areas where topography and lithology are similar, but rock-fall concentrations from the earthquakes were much lower. A statistical comparison of *Q*-values from five sites surrounding Pacoima Canyon indicates that seismic susceptibilities are similar to those within Pacoima Canyon; differences in the characteristics of rock slopes between these sites are not sufficient to account for the relatively high concentrations of rock falls within Pacoima Canyon as compared to low concentrations elsewhere. By eliminating susceptibility differences as a cause, the most likely explanation for the differences in rock-fall concentrations is anomalously high shaking levels in Pacoima Canyon, possibly resulting from topographic amplification within the canyon.

Introduction

The 17 January 1994 Northridge, California, earthquake (M_w 6.7) triggered more than 11,000 landslides over an area of about 10,000 km^2 (Harp and Jibson, 1995, 1996). Greater than 90% of these landslides consisted of rock falls and rock slides that were concentrated in an area of about 1,000 km^2 that lies north and northwest of the epicenter in the Santa Susana Mountains and the mountains north of the Santa Clara River (Fig. 1). Landslides were more sparsely scattered throughout the remainder of the region with one notable exception: Pacoima Canyon on the southern flank of the San Gabriel Mountains produced a dense concentration of rock falls that is anomalous with respect to the surrounding area. Interestingly, Pacoima Canyon likewise produced anomalously high concentrations of rock falls in the 1971 M_w 6.7 San Fernando earthquake (Hauksson, 1995).

Why has Pacoima Canyon been the site of such relatively high concentrations of rock falls and rock slides in both of these earthquakes? Are the rocks in Pacoima Canyon more susceptible to slope failure than the rock slopes of other adjacent canyons? Or do the slopes of Pacoima Canyon experience stronger shaking than adjacent canyon slopes because of topographic amplification? We briefly address these questions in this article by comparing the susceptibility of the rock slopes in Pacoima Canyon to those of surrounding canyons that experienced far fewer rock falls in the Northridge earthquake. If susceptibilities do not differ significantly, then we can surmise that the most likely cause of the anomalous rock-fall concentrations is enhanced seismic shaking in Pacoima Canyon owing to local topographic amplification.

Landslides Triggered by the 1994 Northridge and 1971 San Fernando Earthquakes

Landslides triggered by the 1994 Northridge earthquake were mapped from aerial photographs taken by the U.S. Air Force onto U.S. Geological Survey (USGS) 1:24,000-scale topographic quadrangle maps. More than 11,000 individual landslides were mapped and digitized in a Geographic Information Systems (GIS) database. More than 90% of the landslides were rock falls and rock slides ranging from a few decimeters to a few meters in depth. Average volumes of these types of landslides were less than 1000 m^3, but many had volumes exceeding 100,000 m^3. Many of the larger disrupted slides traveled more than 50 m, and a few moved as far as 200 m from the bases of steep parent slopes.

The area of greatest landslide concentration was in the Santa Susana Mountains and the mountains north of the

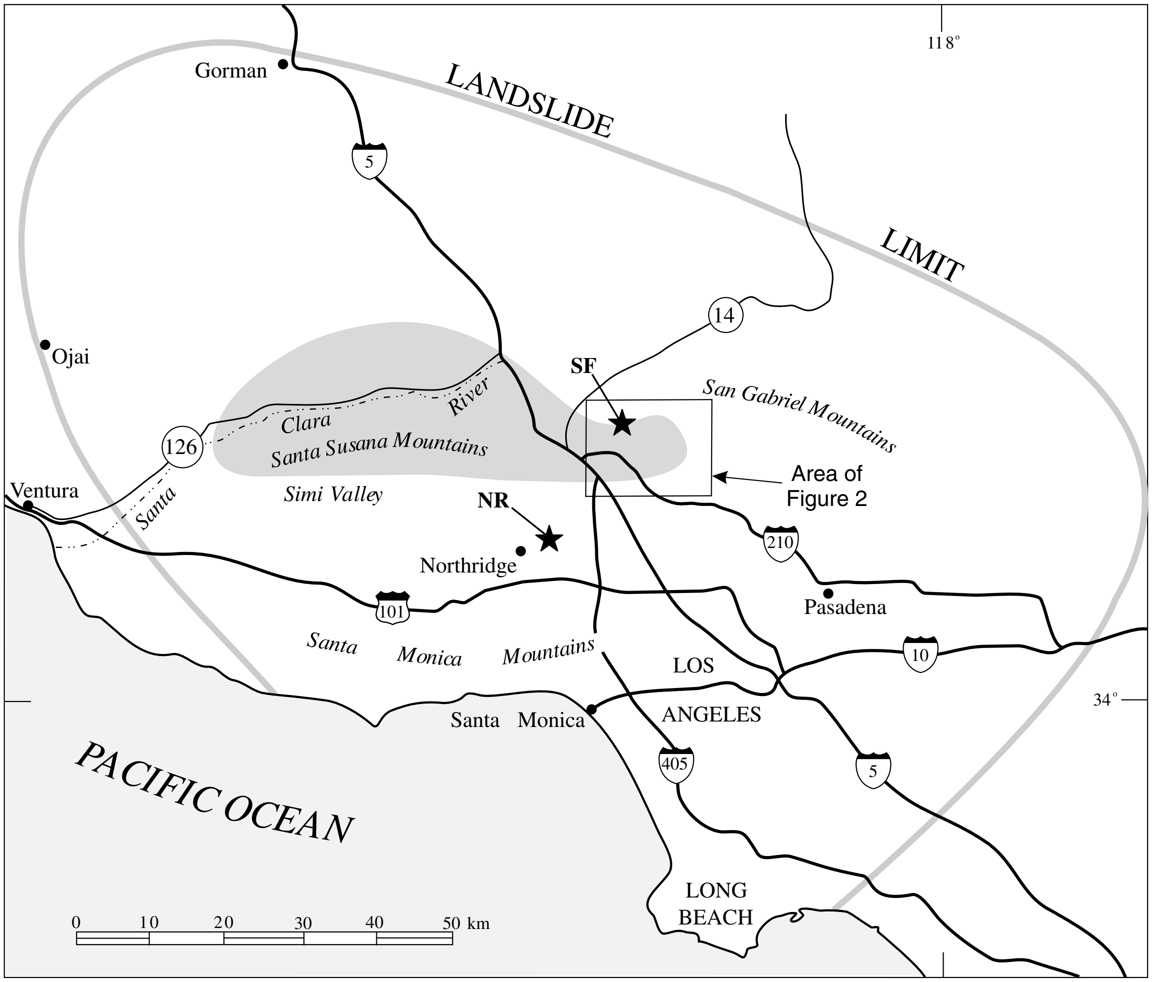

Figure 1. Map of southern California showing limit of landslides triggered by 1994 Northridge, California, earthquake and epicenters of the 1971 San Fernando (SF) and 1994 Northridge (NR) earthquakes. Shaded area indicates area of highest landslide concentration from the Northridge earthquake. Box shows area of Figure 2.

Santa Clara River (Fig. 1). The slopes of these mountains consist of weakly cemented to uncemented late Miocene through Pleistocene clastic sediment that has been folded and uplifted by rapid tectonic deformation. This young, weak material lacks significant tensile strength and erodes readily to form steep-walled canyons. The combination of low strength and steep relief makes these deposits highly susceptible to failure during seismic shaking.

Northeast of the epicenter, fewer and more widely scattered rock falls and rock slides were triggered in the San Gabriel Mountains, which consist primarily of Mesozoic granitic and Precambrian metamorphic rock that is somewhat more competent and resistant to shaking than the weak sediment of the Santa Susana Mountains. An exception to this pattern is the southwest corner of the San Gabriel Mountains, where younger sediment produced landslide concentrations comparable to those in the Santa Susana Mountains. Another exception is the subject of this paper: the Mesozoic granitic rock of the San Gabriel Mountains near the mouth of Pacoima Canyon produced landslide concentrations as high as in the Santa Susana Mountains (Fig. 2).

A similar landslide distribution resulted from the 1971 San Fernando earthquake (Morton, 1975; Barrows *et al.*, 1995). The 1971 earthquake epicenter was close to Pacoima Canyon, and landslide concentrations in the San Gabriel Mountains generally were much higher in 1971 than in 1994. But even in 1971, the concentration of rock falls and rock slides in Pacoima Canyon was very high relative to the surrounding canyons. Although slopes of other canyons adjacent to Pacoima Canyon have less relief, they have similar steepness and rock types but far fewer rock falls and rock slides. A comparison of rock-fall and rock-slide distribution from both earthquakes in the vicinity of Pacoima Canyon is shown in Figure 3.

The rock falls and rock slides from both earthquakes did considerable damage to the engineered slopes adjacent to Pacoima Dam and to structures on these slopes related to the dam (Fig. 4). Cracks in the shotcrete facing of the slopes

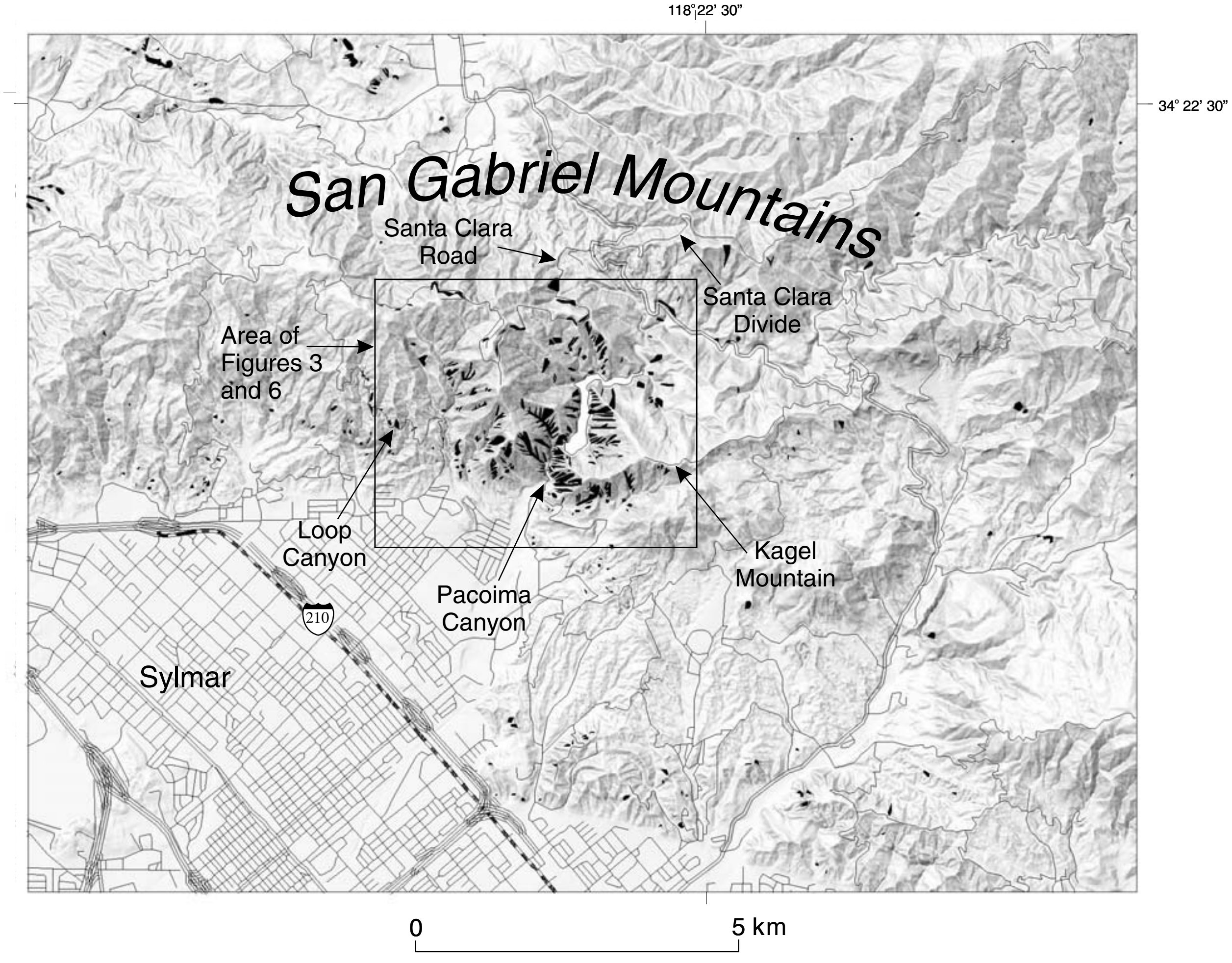

Figure 2. Map of part of the San Gabriel Mountains showing high concentration of rock falls around Pacoima Canyon as compared to surrounding areas. Arrows show sites where rock-fracture data were gathered to compare *Q*-values between Pacoima Canyon and adjacent sites. Location shown in Figure 1.

adjacent to the dam were numerous, and many moderate sized (10–20 m^3) wedge failures in rock protruded from the shotcrete facing (Fig. 5). Considerable damage also occurred to the stairways extending up the slope next to the dam and to drainage structures. Thus, the slopes at the mouth of Pacoima Canyon have produced anomalously high concentrations of landslides in two well-documented earthquakes having rupture sources in different locations.

Seismic Shaking in Pacoima Canyon

Extreme ground accelerations were measured in Pacoima Canyon in both the Northridge earthquake (Shakal *et al.*, 1994) and the San Fernando earthquake (Cloud and Hudson, 1975) by a strong-motion station located on a steep, narrow ridge above the dam. The peak ground acceleration (PGA) of 1.25*g* recorded at Pacoima Dam in the 1971 earthquake was twice as large as any previously recorded PGA anywhere; in fact, it was so large that it was considered suspect for many years. The location of the recording site on the hanging wall directly above and within 2–4 km of the thrust-fault rupture surface was generally considered to be the reason for the extremely high PGA (Cloud and Hudson, 1975). However, other nearby strong-motion instruments recorded more typical PGA values of 0.2–0.3*g*, illustrating the uniqueness of the shaking conditions in that part of Pacoima Canyon.

The same instrument site that recorded the extreme PGA in 1971 recorded a PGA of 1.53*g* in the 1994 Northridge earthquake. Although both earthquakes had the same magnitude, the Northridge earthquake occurred much farther from Pacoima Canyon than did the 1971 earthquake; the focal distance was about 27 km, although the edge of the modeled rupture surface (Wald and Heaton, 1994) did extend to within 6–7 km of the canyon. A strong-motion instrument located in the bottom of the canyon downstream from the dam (less than 1 km away) recorded a PGA of only 0.44*g*; another station on Kagel Mountain, less than 2 km from the dam, recorded a PGA of 0.44*g* (Fig. 6). Clearly, the ridge above the dam experienced very different shaking conditions than other nearby areas.

The high PGA in 1971 was not solely attributable to hanging-wall effects because the 1994 PGA of 1.53*g* was not on the hanging wall above the fault rupture. Source effects also fail to explain the anomalous shaking: in 1971 the source was a north-dipping thrust fault directly beneath the site, whereas the 1994 source was a south-dipping thrust fault from 6 to 27 km to the west.

Susceptibility of Rock Masses to Seismic Shaking

The susceptibility of rock slopes to failure depends strongly on both the rock type and the physical properties of the rock mass. Variations in landslide concentrations that correlate with differing rock types have been documented qualitatively in numerous earthquakes (Morton, 1975; Harp *et al.*, 1981; Keefer, 1984; Harp and Keefer, 1990). Similar correlations have been noted regarding physical properties of rock masses such as weak cementation, closely spaced fractures, and open fractures near the surface (Harp *et al.*, 1984; Keefer, 1984).

The 1980 Mammoth Lakes, California, earthquake sequence (**M** 6.1) had a diffuse source region (Archuleta *et al.*, 1982) that led to the triggering of widespread rock falls and rock slides. Analysis of the distribution of these slides facilitated a quantitative comparison of many different rock types and their corresponding concentrations of rock falls and rock slides under broadly uniform shaking conditions. Harp and Noble (1993) used an engineering classification originally developed for mining and tunnel design (Barton *et al.*, 1974) to quantify the fracture characteristics of rocks. They modified the classification to account for characteristics appropriate to surface outcrops rather than deep underground openings having high stresses. The modified classification quantifies six fracture characteristics, using numerical tables, to calculate the rock-mass quality (Q) for a surface rock outcrop. These characteristics include the following:

1. J_v, the total number of joints per cubic meter, is a measure of the block size of the rock mass and a measure of the degree of fracturing of the rock mass. J_v is modified to be used as a surrogate for rock quality designation (RQD), which is generally evaluated using core samples (Deere, 1963). In the absence of core data, RQD can be approximated by

$$\mathrm{RQD} = 115 - 3.3\,J_v.$$

2. J_n, the joint set number, represents the number of joints sets in a rock mass. This factor is based on the presence of strongly developed discontinuities with similar orientations. Sporadic joints of no particular orientation are considered random.

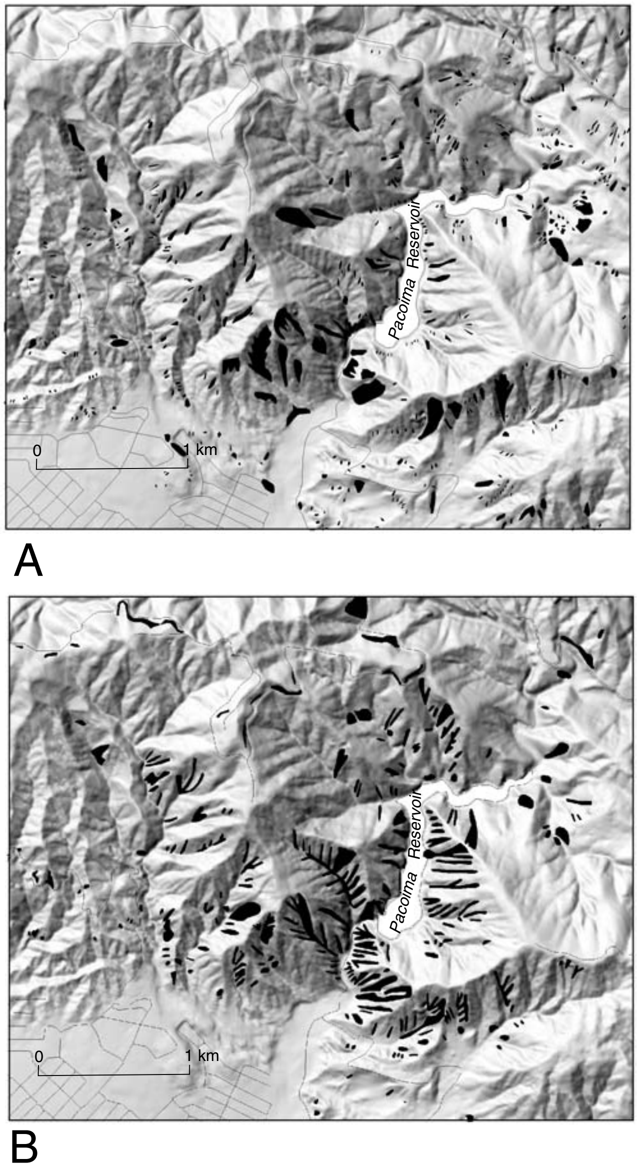

Figure 3. Comparison of rock-fall and rock-slide distributions from (A) the 1971 San Fernando earthquake and (B) the 1994 Northridge earthquake within the vicinity of Pacoima Canyon. Black polygons are rock falls and rock slides triggered by the earthquakes.

3. J_r, the joint roughness number, is based on the departure of the joint from being planar.
4. J_a, the joint alteration number, is either a measure of the weathering on joint surfaces or a measure of the type of weathering material that fills a joint, such as clay minerals, calcite, or quartz. Alteration materials deposited on or filling joint surfaces strongly influence the frictional properties of the joint surface and, in some cases, the shear or tensile strength of the rock mass as a whole.
5. J_w, the joint water-reduction factor, is a measure of the outflow of water from joints and is inversely proportional to the water pressure within the joint network. For the

Figure 4. Oblique aerial photograph of Pacoima Canyon and Dam following the 1994 Northridge earthquake showing abundant triggered rock falls on steep slopes.

purposes of evaluating the seismic stability of slopes at the surface, this usually is not a significant factor because, most of the time, rock slopes are dry, and the value of J_w for dry slopes is 1.0. Certainly, in the case of the Northridge earthquake, the slopes were extremely dry, and pore-water pressure within rock joints was not a factor.

6. *AF*, the aperture factor, deals mainly with the aperture or openness of the joints in the rock mass and is the single-most important factor in determining the susceptibility of rock slopes to failure during earthquakes. Numerous post-earthquake investigations have shown that near-vertical cliffs subject to high levels of shaking produce relatively few rock falls or rock slides. If, however, slopes have loose and open joints, these slopes invariably produced numerous failures because rocks fragments have many degrees of freedom in which to move when joint sets of several orientations are open.

The six factors are combined to calculate rock-mass-quality (Q) by the following equation:

$$Q = \left[\frac{115 - 3.3J_v}{J_n}\right]\left[\frac{J_r}{J_a}\right]\left[\frac{J_w}{AF}\right]. \qquad (1)$$

Low Q-values correspond to high susceptibility to failure, and failure susceptibility decreases as Q increases. Harp and Noble (1993) show rating tables for the individual factors and pictorial examples of different rock types with various Q-values.

The utility of the rock-mass-quality method for numerically ranking the susceptibility of rock slopes to seismic failure is that (1) it is reasonably rapid (determination of the six factors in the field commonly takes less than 10 min per sample), (2) it provides a consistent, quantitative method of comparing rock slopes, and (3) it yields values that can range over 7 orders of magnitude. In general, Q-values less than 0.1 indicate very high rock-fall susceptibility, values between 0.1 and 1 indicate high susceptibility, values between 1 and 10 indicate moderate susceptibility, and values greater than 10 indicate low susceptibility.

We apply this rock-mass classification system to compare the failure susceptibility of rock slopes in Pacoima Canyon to those in nearby canyons that produced fewer rock falls in the Northridge and San Fernando earthquakes.

Comparison of Q-Values: Pacoima Canyon and Adjacent Sites

We measured J_v, J_n, J_r, J_a, J_w, and AF, and calculated Q-values for 16 sample outcrop sites in Pacoima Canyon that contributed to high rock-fall and rock-slide concentrations. Similarly, 16 sample outcrop sites were evaluated in four areas adjacent to Pacoima Canyon where slopes were similar in steepness (50° to vertical) to those in Pacoima Canyon yet produced significantly fewer failures. These four sites are Loop Canyon, Kagel Mountain, Santa Clara Divide, and Santa Clara Road (see Fig. 2).

Figure 7 shows the individual Q-values calculated for the rock slopes evaluated in each of the five areas; Table 1 shows the means and standard deviations of these observations, which are plotted (mean ± one standard deviation) in Figure 8. The range of Q-values shown in Figure 8 is small and is plotted with a vertical axis of 0.0–2.0. The entire possible range of Q-values is 0.0042–1067. When the data

Figure 5. Close-up of fractured rock slopes and shotcrete facing near Pacoima Dam.

shown in Figure 8 are plotted with a vertical axis spanning the entire range, the means and standard deviations appear simply as dots lying near $y = 0.0$ along the x axis and appear identical.

Except for the observations along Santa Clara Road, the plotted means and standard deviations vary only slightly over a narrow range. Measurements along Santa Clara Road indicate much lower Q-values, suggesting greater rock-fall susceptibility there. Interestingly, Pacoima Canyon, where rock falls were most densely concentrated, has the highest mean Q-value and the single highest Q-value of any area, which should indicate the lowest susceptibility to rock fall. Although rock falls were triggered from almost all steep slopes in Pacoima Canyon, the densest concentrations of failures were from rock slopes with the lowest Q-values. All of the values, however, cluster quite closely in the high susceptibility range (0.1–1.0), and differences between them are slight when viewed in the context of the entire range of possible Q-values. Therefore, using the rock-mass-quality index, we can eliminate significant differences in slope susceptibility as the controlling factor in producing the high landslide concentrations observed in Pacoima Canyon.

Discussion

Comparing the rock-fall and rock-slide distribution from both earthquakes in the vicinity of Pacoima Canyon (Fig. 3) provides strong evidence for local amplification of seismic shaking in recent earthquakes. Although the 1994 Northridge earthquake occurred much farther from the canyon, it appears to have produced even more landslides there than did the 1971 San Fernando earthquake. The landslide density from the San Fernando earthquake (Fig. 3A) is greatest in and around Pacoima Canyon and decreases away from the canyon, as would be expected for an earthquake centered near the canyon. The landslide density from the Northridge earthquake (Fig. 3B), however, is greatest far to the west in the Santa Susana Mountains, immediately north of the epicenter. Landslide density in the parts of the San Gabriel Mountains around Pacoima Canyon is quite sparse relative to what occurred there in 1971, but in the canyon proper the landslide density is even greater than what occurred in 1971. This, and the recorded PGA of $1.53g$ (as compared to 1.25 g in 1971) strongly supports topographic amplification as the cause of repeated dense concentrations of triggered landslides in recent earthquakes.

It could be argued that the 1971 earthquake loosened material on the slopes of Pacoima Canyon and thus set the stage for the failures triggered by the 1994 earthquake. However, the surrounding areas that were examined in this study also were shaken in 1971 but experienced no significant landsliding in 1994. Also, the opposite case could be argued, that the 1971 earthquake would have removed most of the susceptible material and thus made the slopes less susceptible to rock falls in 1994. In our experience documenting worldwide earthquakes, neither of these cases appears to be valid; susceptible slopes tend to produce rock falls consistently in each successive earthquake. An earthquake tends to both trigger failure of the most susceptible material on the slope and to fracture and dilate the underlying rock mass and thus set the stage for additional failures in future earthquakes.

Because the rock slopes in Pacoima Canyon are not more susceptible to seismic failure than those of adjacent areas, we can reasonably conclude that the levels of ground shaking in Pacoima Canyon must have been significantly higher than in the surrounding areas. Without strong-motion records from any of the other areas except for Kagel Mountain, which recorded a much lower PGA than did Pacoima Canyon in 1994, we can only speculate that the seismic shaking in Pacoima Canyon was either directed toward that area due to the source characteristics of the earthquake, or the topography of Pacoima Canyon significantly amplifies shaking. As mentioned above, directivity appears unlikely because extreme shaking was recorded in two earthquakes having significantly different source locations and geometries.

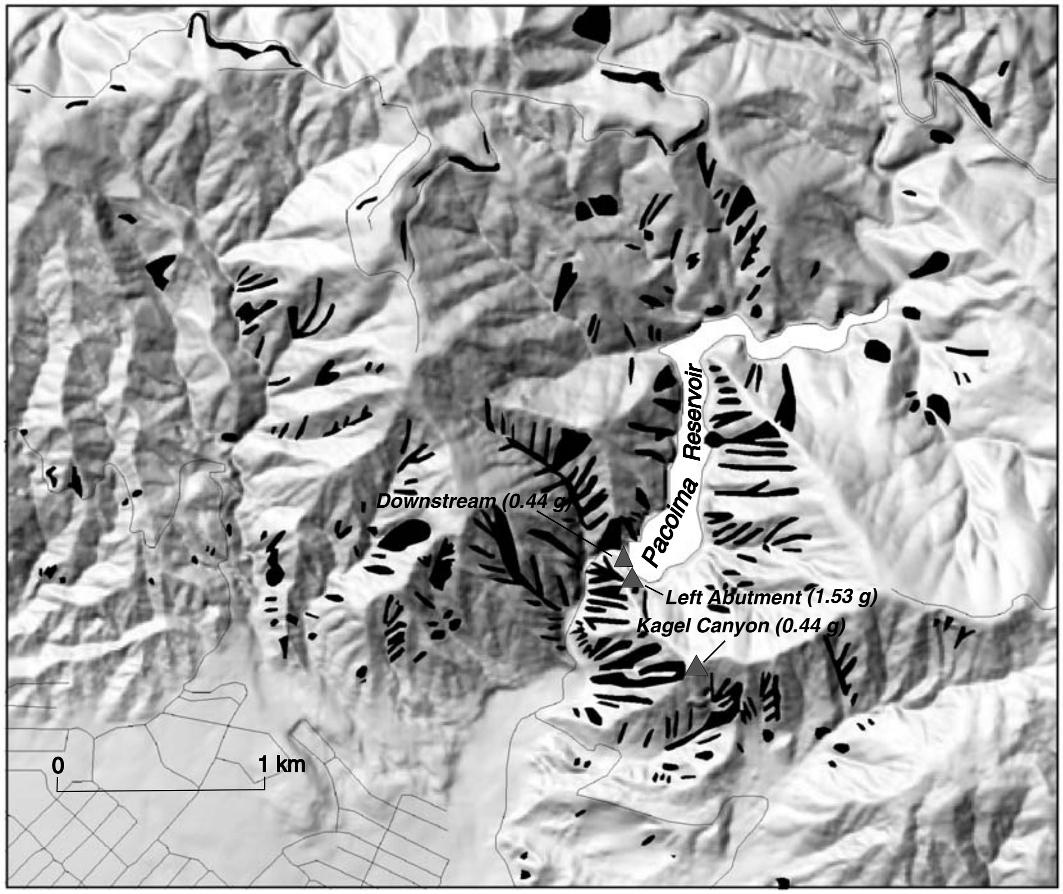

Figure 6. Landslides triggered in 1994 in the vicinity of Pacoima Canyon along with the locations of three strong-motion stations and their respective peak accelerations. Note that landslide concentrations occur on both sides of the ridges defining Pacoima Canyon. Location shown in Figure 2.

In addition, Wald and Heaton (1994) show that, although the earthquake source contained directivity effects, these were well to the west of the study area and were not directed toward Pacoima Canyon.

Topographic amplification appears to be a more likely explanation for the extreme PGAs and consequent rock falls in Pacoima Canyon. Several studies soon after the 1971 San Fernando earthquake attributed the high 1971 PGA to topographic amplification (Boore, 1972, 1973; Bouchon, 1973; Wong and Jennings, 1975), although some others suggested that amplification was not a highly significant factor (Brune, 1984; Anoosshehpoor and Brune, 1989). Significant topographic amplification, with amplification factors as great as 20–30, has been documented in array aftershock and explosion studies (Davis and West, 1973; Celebi, 1987; Hartzell *et al.*, 1994) and by Harp and Jibson (1995) and Barrows *et al.*, (1995) from narrow ridges shattered by the Northridge earthquake, but these studies have led to no simple, consistent method to isolate or predict what effects a specific topographic feature will have on incident seismic waves. The results of these studies do, however, lead to the following conclusions: (1) topographic amplification is most pronounced when the incident seismic-wave length is about the same as the dimensions of the topographic feature, (2) amplification is strongly influenced by the angle and direction of incidence of the seismic waves, and (3) amplification generally occurs in narrow frequency bands that also depend on the shape of the topography. The extreme topography of Pacoima Canyon, the repeated recording of very high PGA values, and the localization of the high PGAs to a single station on the canyon wall support a conclusion that topographic amplification is a significant—and perhaps dominant—factor in the anomalous concentration of rock falls in Pacoima Canyon.

Although we have referred to Pacoima Canyon as having amplified seismic ground shaking, we should clarify terminology to avoid misunderstanding. It is the ridges that form the walls of the canyon that appear to have experienced enhanced ground shaking, not the canyon proper. As stated previously, a strong-motion station on the floor of the canyon downstream from the dam recorded PGAs consistent with those recorded outside the canyon. The extreme PGA values were recorded by a station located on a narrow ridge on the wall of the canyon.

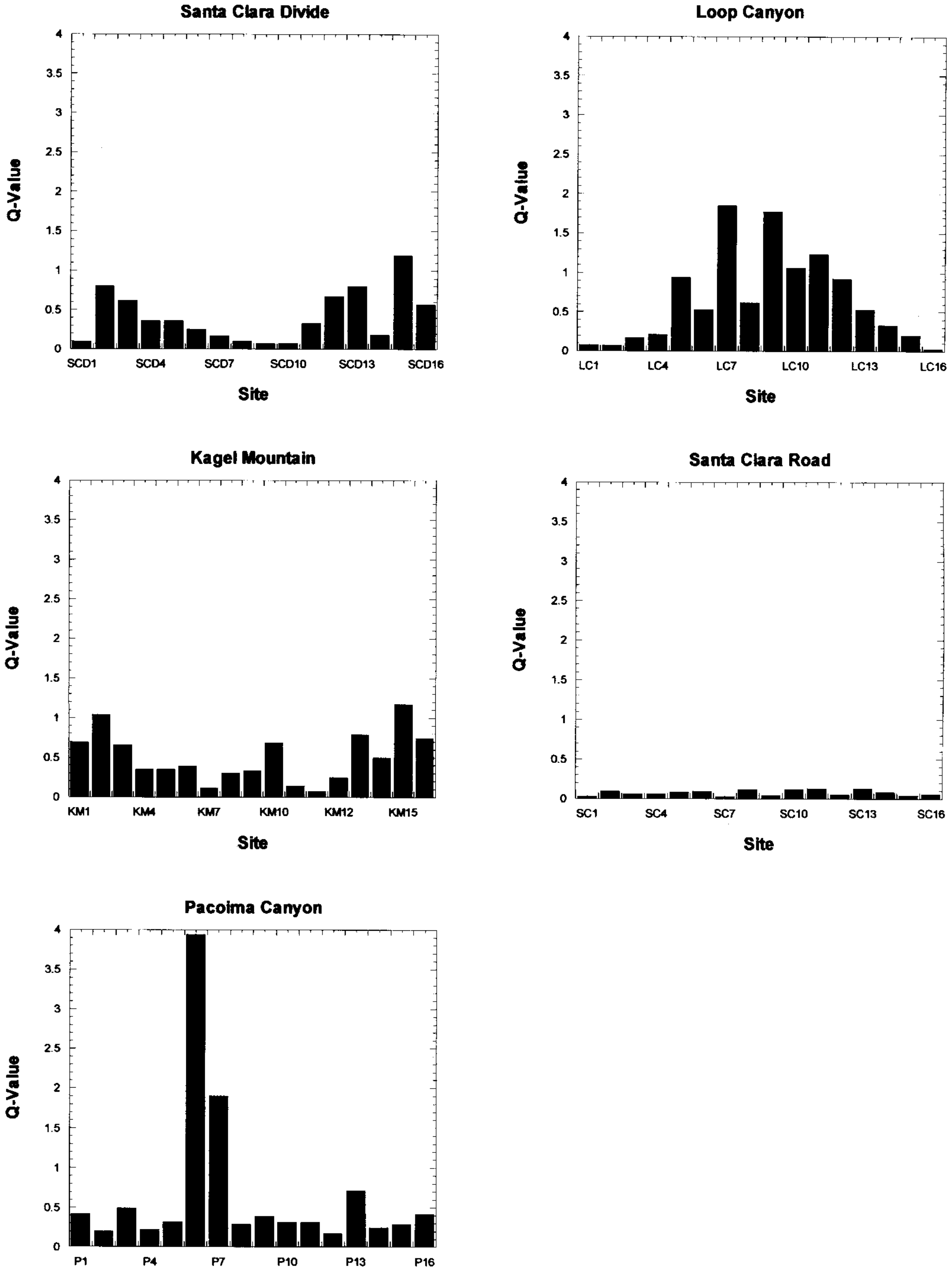

Figure 7. Bar graphs showing populations of Q-values of Pacoima Canyon and adjacent sample sites.

This point is further illustrated by examining the landslide distribution from the 1994 earthquake in the immediate area around Pacoima Canyon (Fig. 6). Dense landslide concentrations were not limited to the walls within the canyon but occurred on both sides of the ridges that define the canyon near its mouth. Thus, the amplification of shaking appears to have affected both of the steep, high ridges that form the walls of Pacoima Canyon. Pacoima Canyon has the greatest local relief of any of the surrounding canyons, which may explain why amplification of shaking is apparent there but not elsewhere in the area.

Whatever the actual reason for differences in the triggered landslide concentrations between Pacoima Canyon and the surrounding areas, it has been consistent for both the 1971 San Fernando and the 1994 Northridge earthquakes and cannot be attributed to any differences in the susceptibilities of the rock slopes in Pacoima Canyon as compared to the surrounding areas. Emplacement of a small array of

Table 1

Q-Values from Five Sample Areas

Sample Area	Sample Size	Mean *Q*-Value	Standard Deviation
Pacoima Canyon	16	0.664	0.965
Kagel Canyon	17	0.503	0.320
Santa Clara Divide Rd.	16	0.415	0.329
Santa Clara Rd.	16	0.075	0.036
Loop Canyon	16	0.659	0.587

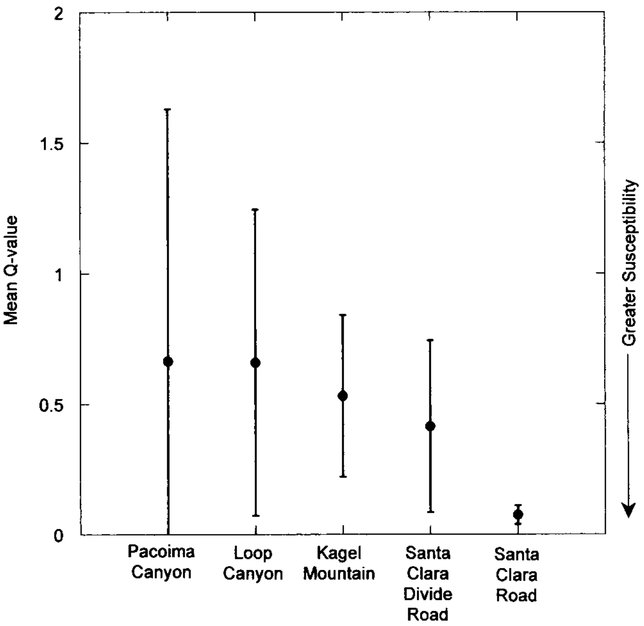

Figure 8. *Q*-values from Pacoima Canyon and four nearby areas. Dot, mean value; bars, one standard deviation on either side of the mean. Data is from Table 1.

additional strong-motion stations on hard-rock sites in areas in and near Pacoima Canyon would likely produce valuable data about relative shaking levels in this area and the processes that may cause these differences.

Conclusion

Q-values (Harp and Noble, 1993) of rock outcrops in Pacoima Canyon and several surrounding areas are comparable, which indicates that the rock slopes in Pacoima Canyon are no more or less susceptible to seismically triggered failure than are slopes of adjacent canyons that produced far fewer rock falls and rock slides in both the 1971 San Fernando and 1994 Northridge earthquakes. Therefore, we conclude that the anomalously high concentrations of rock falls and slides in Pacoima Canyon in these two earthquakes resulted from abnormally high levels of ground shaking in the canyon. The extreme PGA's recorded in the canyon in both earthquakes confirms this conclusion. The most likely cause for these extreme ground-shaking values is topographic amplification; Pacoima Canyon is deeper, narrower, and steeper than surrounding canyons.

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Manuscript received 21 May 2001.