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THE EFFECT OF SIMPLE TOPOGRAPHY ON SEISMIC WAVES: IMPLICATIONS FOR THE ACCELERATIONS RECORDED AT PACOIMA DAM, SAN FERNANDO VALLEY, CALIFORNIA*

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ABSTRACT

A precise analysis of the influence of topographic and geological effects on the significant ground motions recorded near Pacoima Dam during the San Fernando, California, earthquake of February 9, 1971, is an immensely complicated task. Calculations for simple models give results that suggest the following general conclusions: (1) the topography should have influenced the recorded ground motion, and (2) this influence seems to be an amplification of the higher-frequency accelerations by as much as 50 per cent, but is relatively unimportant at the lower frequencies (which control the maximum particle velocities).

In an earlier paper (Boore, 1972a), the author investigated the effect of some simple types of topography on vertically incident *SH* waves. An extension of this work that considered the implications of the effect of the topographic configurations near Pacoima Dam on the accelerogram recorded during the San Fernando earthquake of February 9, 1971, was presented at the National Conference on Earthquake Engineering (Boore, 1972b). That presentation forms the basis of this note. Subsequently, other investigators studying this problem have found results comparable to those presented here (Bouchon, 1973; Davis and West, 1973; Reimer *et al.*, 1972; Rogers *et al.*, 1972; Trifunac, 1973). The problem of the influence of the complex topography and geology near the site is an exceedingly difficult one. The analysis given here does not pretend to be complete, but some of the results will be of interest. An aspect not discussed here is interpretation of the motion in terms of the rupture propagation on the fault surface. This is covered in a number of other papers (Bolt, 1972; Zoback and Boore, 1973; Litehiser, 1972; Hanks, 1972; Mikumo, 1973; Niazy, 1973).

Topographic surface relief in the vicinity of Pacoima Dam is rugged, as clearly shown by the map (Figure 1). For our purposes, we note that locally the accelerometer site, which is near the apex of profile 1, is on a ridge crest, but that relative to the surrounding area it is in a canyon. This is clearly shown by the topographic profiles (Figure 2). On the basis of these profiles, we characterize the ridge and canyon by two-dimensional models (Figure 3); these have been normalized to emphasize the shape. As explained in an earlier note (Boore, 1972a) a numerical simulation (finite difference) of the propagation of a plane *SH* wave at a single angle of incidence is used to find the effect of the topography. There are some obvious simplifications in these models. Studies by Zoback and Boore (1973) show that if the Earth's surface were a plane, a large part of the motion in the vicinity of Pacoima Dam would be due to *SV* waves. The complex surface topography, however, leads to coupling between all of the wave types making it unrealistic to consider a single type of wave motion. As the recorded motion represents waves radiated from a source whose location changes with time, the assumption of a single angle of incidence is another simplification. These and other simplifications will affect the details, but probably not the overall character of the topographic influence.

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Two angles of incidence were considered for the ridge model, 0° and 45°; for the canyon model only vertically incident waves were considered as the canyon seems to be less important than the ridge. In the calculations, distances and frequencies are normalized by characteristic lengths of the topographic configurations and by the velocity of shear-wave

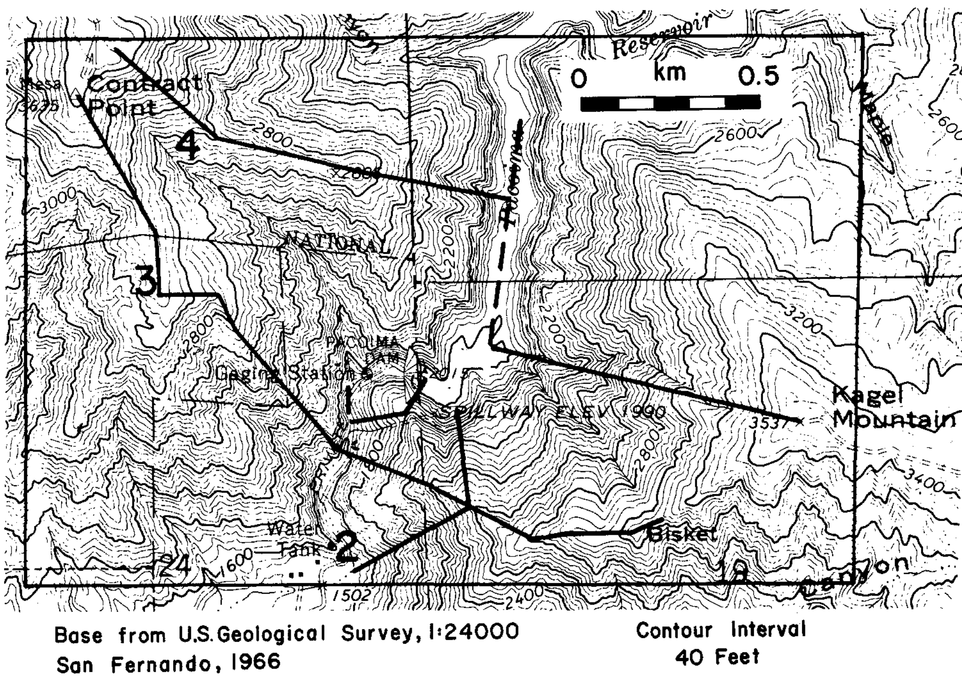

FIG. 1. Topographic map of region near Pacoima Dam showing lines of topographic profiles (Figure 2). The accelerometer site is near the apex of profile 1.

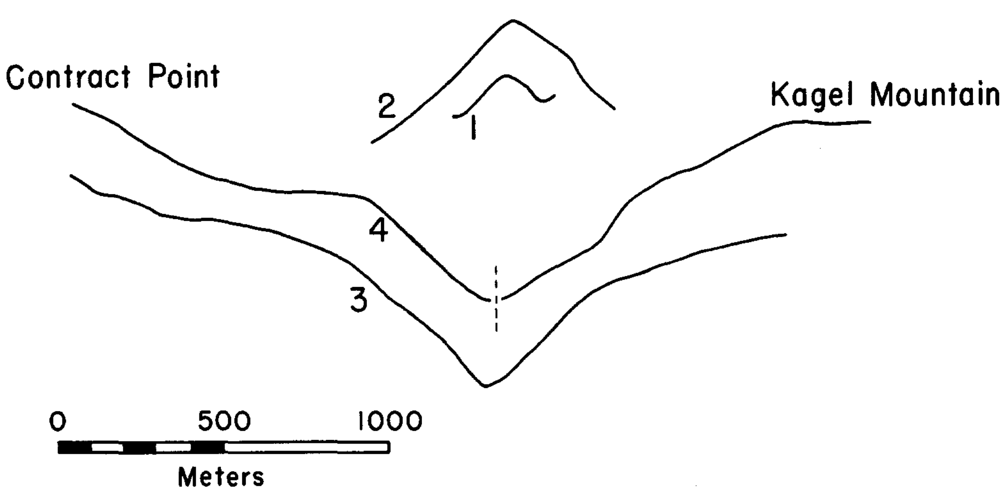

FIG. 2. Topographic profiles near Pacoima Dam.

propagation. The results of the calculations are presented in the normalized frequency domain as amplitude ratios of the Fourier amplitude of wave motion recorded at a particular point on the surface normalized to the amplitude which would be recorded if the surface were horizontal.

A range of characteristic lengths and velocities were used to convert normalized to actual frequency. The result can be used to estimate the amplitude ratio at the accelerometer site from the ridge model (Figure 4) and the canyon model (Figure 5). The three curves in the figures represent various choices of shear velocity and characteristic length, and thus represent the range of amplification that would be expected taking into account the variations and uncertainties in these properties. We see from these curves that for the frequency range of interest (1–15 Hz), the ridge model with vertical incidence produces the greatest amplification (about a factor of 2) in the frequency range between 3 and 10 Hz. At the longer periods, the effect of the canyon becomes relatively more important, and we see that the canyon could actually produce an attenuation of the wave motion.

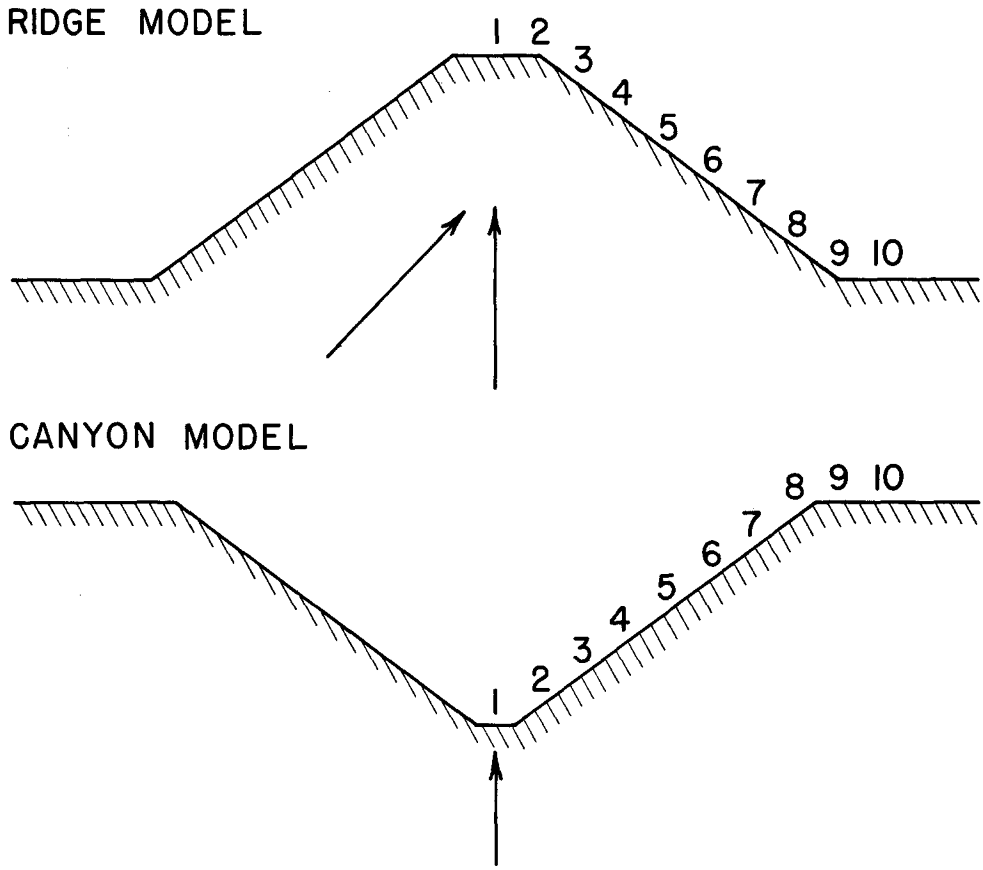

FIG. 3. Idealized models of the topography. Two-dimensional geometry is assumed. The arrows indicate the angle of incidence of the *SH* waves used in the analysis. The numbers indicate points at which seismograms are computed (see Boore, 1972a). The accelerometer site is approximately equal to point 1 on the ridge model and point 4 in the canyon model. Because of normalization, the relative sizes of the two models are not shown in this figure (see Figure 2 for this).

The middle curve in the vertically incident ridge model (Figure 5) was used to test the effect of the simple model on the recorded motion. The trace recorded in the S16°E direction was used because its character serves most clearly to indicate the different amplification at low and high frequencies. The recorded accelerogram was first low-pass filtered with a cutoff of 15 Hz (Figure 6a). This was necessary because the theoretical amplitude ratios were not computed for higher frequencies. Then the spectrum of the recorded motion was divided by the calculated complex spectral ratio (amplitude and phase are included) to produce a "deconvolved" record with the effect of the ridge removed (Figure 6b). As we would expect from the amplification ratio of the ridge model

(Figure 5), the effect is most pronounced in the latter part of the record where the high-frequency accelerations are reduced from 1.12 to 0.73 g. The longer-period motion near the beginning (which controls the maximum particle velocity and, for many structures of engineering interest, may be the most significant part of the record) is less affected by the deconvolution, going from 0.64 to 0.55 *g*.

Values given are the results of applying the simple ridge model to the recorded motion and should not be taken as the effect of the actual topography. The results, however, along with those of other workers (especially Bouchen, 1973), suggest the following general conclusions: the topography definitely would be expected to influence the recorded ground

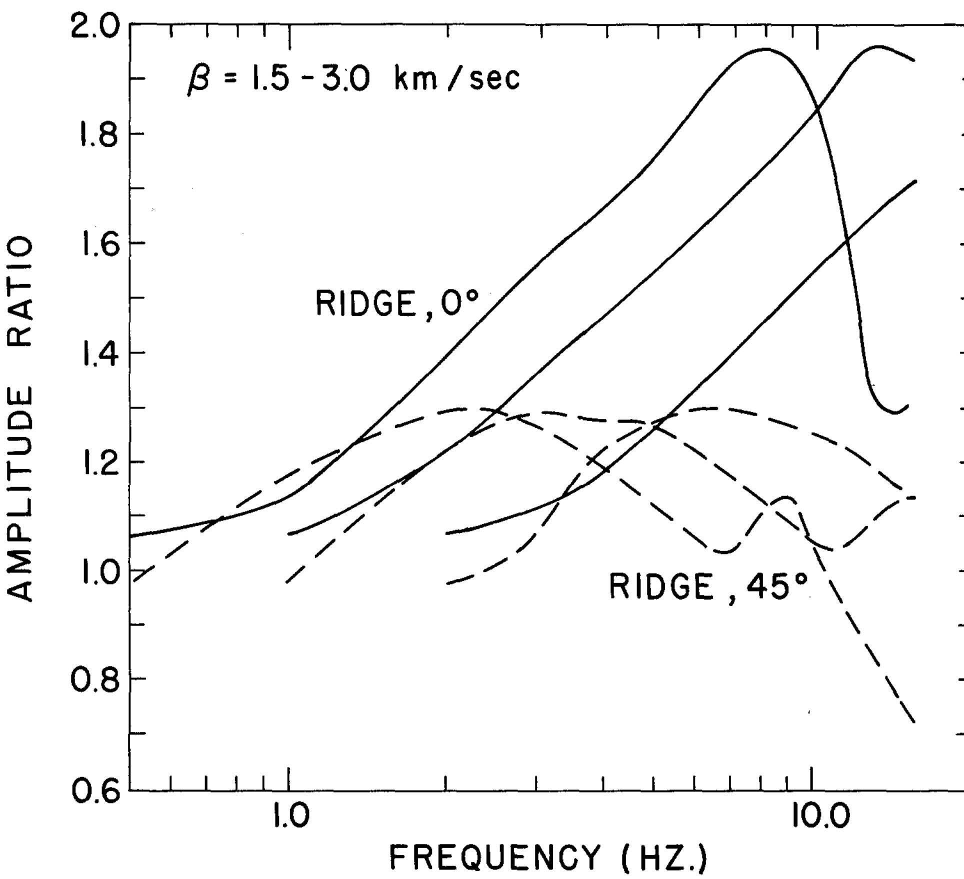

FIG. 4. Amplitude ratio at equivalent accelerometer site as a function of frequency for the ridge model with two angles of incidence. The amplitude is normalized to the motion obtained with no topography present. A range of shear velocities has been assumed to illustrate the dependence of the amplitude ratio on the physical parameters.

motion; this influence seems to be an amplification of the higher-frequency accelerations by as much as 50 per cent, but is relatively unimportant at the lower frequencies. In fact, these lower-frequency motions may even be attenuated, and this attenuation would be more pronounced for nonvertical incidence (not considered here) because of possible formation of shadow zones.

The discussion above suggests that although the peak accelerations are expected to be reduced, the peak particle velocity may be relatively unaffected by the topography. The sensitivity of the higher frequencies, and thus the acceleration trace, to topographic configurations suggests that peak acceleration alone is inadequate to characterize strong ground motions, especially in the near-field of earthquakes. This conclusion can also be drawn from interpretations of the Pacoima Dam accelerograms in terms of faulting kinematics. There, one finds that the lower frequency energy near the front of the record, which contributes most to the large velocities, can clearly be associated with the overall

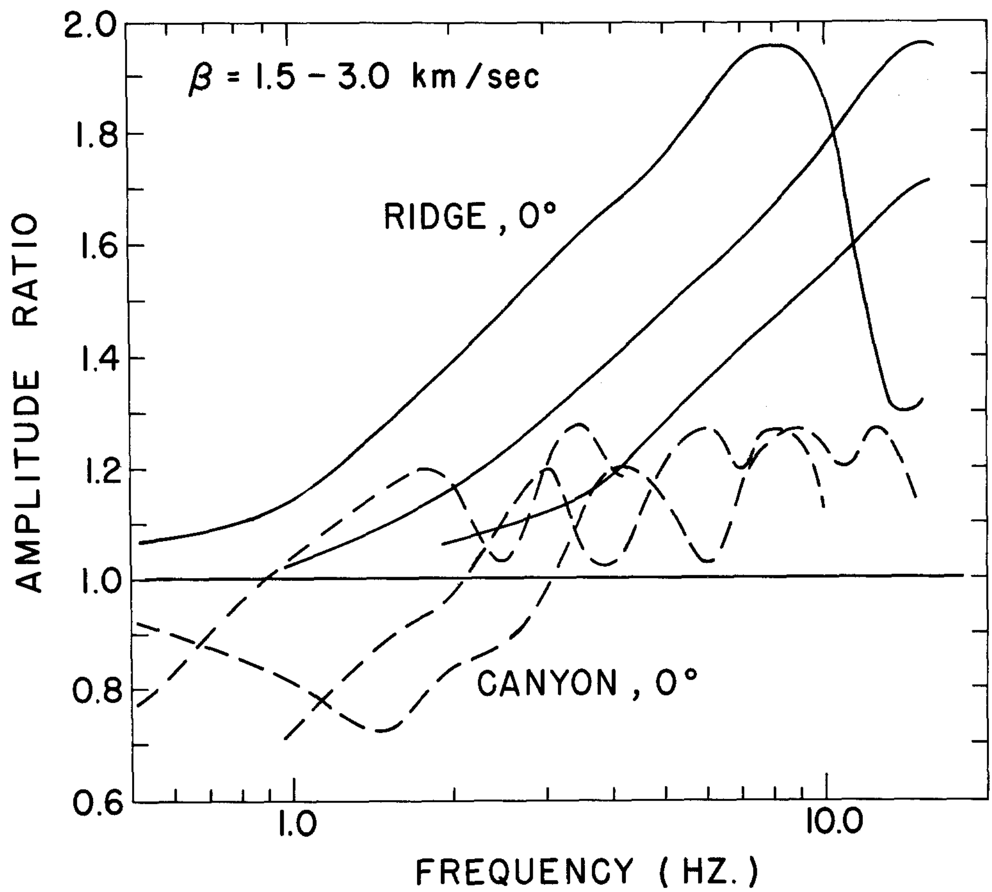

FIG. 5. Amplitude ratio at the accelerometer site for the ridge and canyon models. Vertical incidence of *SH* waves is assumed.

faulting process. The higher-frequency motions near the end of the record, which contribute the most to the high accelerations, can only be explained as random bursts of energy from various irregularities along the fault surface (Bolt, 1972; Zoback and Boore, 1973).

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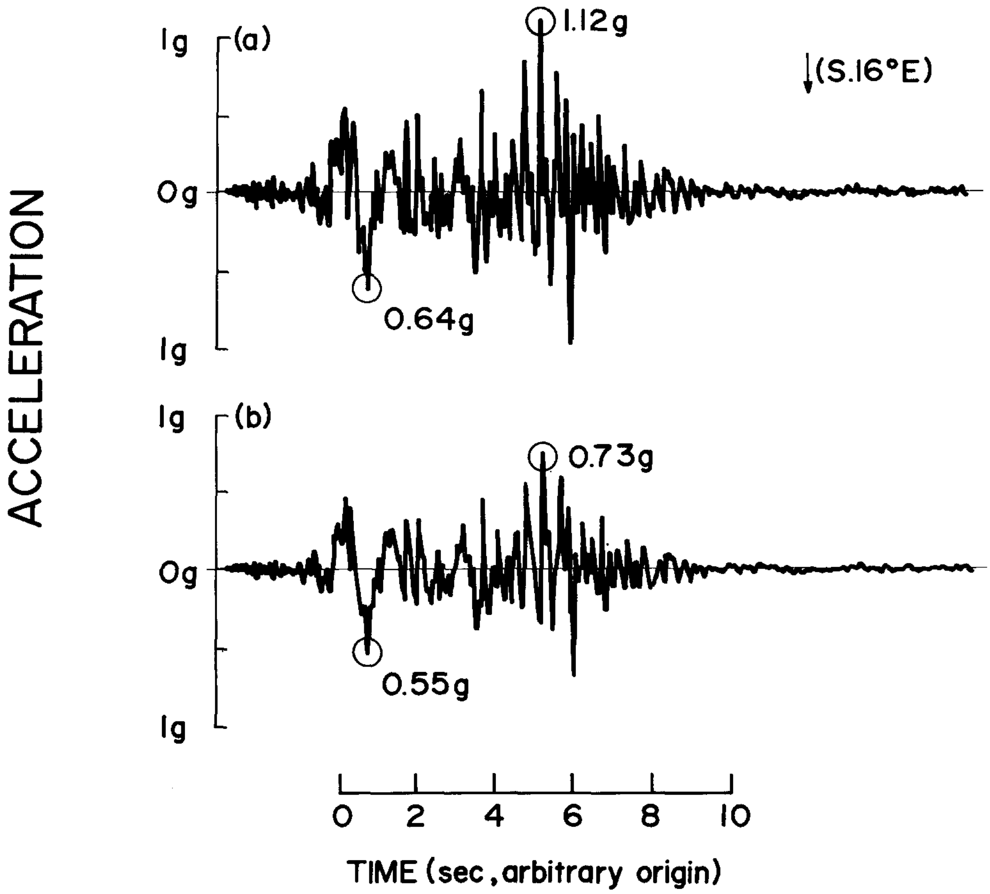

FIG. 6. (a) the recorded motion at Pacoima Dam in the S16°E direction (positive downward) during the San Fernando earthquake of 9 February 1971, after removing all energy above 15 Hz. (b) the same record after removing the amplification predicted by the middle curve in the ridge model with vertical incidence. The effect is very predictable from the frequency domain result, but would have been less so if the amplification ratio had been more complicated in character.

REFERENCES

Bolt, B. A. (1972). San Fernando rupture mechanism and the Pacoima strong-motion record, *Bull. Seism. Soc. Am.* **62,** 1053–1061.

Boore, D. M. (1972a). A note on the effect of simple topography on seismic *SH* waves, *Bull. Seism. Soc. Am.* **62,** 275–284.

Boore, D. M. (1972b). The effect of simple topography on seismic waves: implications for the recorded accelerations at Pacoima Dam (abstract), *Program*, National Conference on Earthquake Engineering (sponsored by the Earthquake Engineering Research Institute), Los Angeles, California.

Bouchon, M. (1973). Effect of topography on surface motion, *Bull. Seism. Soc. Am.* **63,** 615–632.

Davis, L. L. and L. R. West (1973). Observed effects of topography on ground motion, *Bull. Seism. Soc. Am.* **63,** 283–298.

Hanks, T. C. (1972). A contribution to the determination and interpretation of seismic source parameters, *Ph.D. Thesis*, California Inst. of Tech., Pasadena, California.

Litehiser, J. (1972). Near-field accelerations from a propagating dislocation (abstract), *EOS, Trans. Amer. Geophys. Union* **53,** 1048.

Mikumo, T. (1973). Faulting process of the San Fernando earthquake of February 9, 1971 inferred from static and dynamic near-field displacements, *Bull. Seism. Soc. Am.* **63,** 249–269.

Niazy, A. (1973). Elastic displacements due to a propagating crack in an infinite medium: An exact solution, *Bull. Seism. Soc. Am.* **63,** 357–379.

Reimer, R. B., R. W. Clough, and J. M. Raphael (1972). Seismic response of Pacoima Dam (abstract), *Program*, National Conference on Earthquake Engineering (sponsored by the Earthquake Engineering Research Institute), Los Angeles, California.

Rogers, A. M., L. J. Katz, and T. J. Bennett (1972). A model study of *P* waves incident on a two-dimensional topographic feature (abstract), *EOS, Trans. Amer. Geophys. Union* **53,** 1049.

Trifunac, M. D. (1973). Scattering of plane *SH* waves by a semicylindrical canyon, *Intern. J. Earthquake Eng. Struct. Dyn.* **1,** 267–281.

Zoback, M. D. and D. M. Boore (1973). Two dimensional kinematic fault modeling: the San Fernando earthquake of February 9, 1971, submitted to *Bull. Seism. Soc. Am.*

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