

## SEISMOLOGICAL, SOIL AND VALLEY EFFECTS IN KIROVAKAN, 1988 ARMENIA EARTHQUAKE

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**ABSTRACT:** There is substantial evidence that the city of Kirovakan, Armenia, despite its proximity (10 km) to the fault, experienced in general very small intensity of shaking during the 1988 earthquake. Moreover, the distribution of damage in the city was very nonuniform. In this paper, first, arguments are presented to show that seismological and geologic factors, relating to the generation and transmission of the seismic waves, could explain the unusually weak base excitation in Kirovakan. Then, the results of one-dimensional (1D) wave-propagation analysis, using soil profiles with field and laboratory measured parameters, are presented to explain the damage statistics in five zones into which the city was divided. 1D analyses of wave amplification in soil are found to provide adequate answers for zones where the underlying soils consist of less than 30 m dense gravelly sands and stiff clays. However, such analyses fail to explain the disproportionately large degree of damage observed only in one region, where soil profile constitutes a triangular sedimentary basin with maximum soil depth of about 150 m and width-to-depth ratio of about 5. A simplified three-dimensional wave-propagation analysis of the "valley" effects on ground-surface motions, provides a better explanation of the observed damage.

### INTRODUCTION

One of the most striking observations following the 1988 Armenia earthquake was that Kirovakan, located merely 10 km from the surface breakout of the fault, had suffered very little in comparison with Leninakan. This is despite the fact that Leninakan (since renamed Kumayri), Armenia, is 25 km from the fault breakout and that the fault dips to the northeast, toward Kirovakan.

Fig. 1 illustrates this closer proximity of Kirovakan to the seismogenic zone and summarizes the overall damage statistics for these two major cities. Indeed, whereas about 54% of all buildings in Leninakan either totally collapsed or were damaged beyond repair and were later demolished (damage states A and B), the corresponding number for Kirovakan is 26%. Moreover, the percentage of totally collapsed buildings (damage state A) was nearly three times lower in Kirovakan. Furthermore, while the distribution of damage was quite uniform in Leninakan, this was not the case in Kirovakan. In particular, one region of Kirovakan experienced extremely high degree of damage, even higher than Leninakan—a clear reversal of the general trend.

The first part of the present paper explains seismological and geologic factors that may have contributed to very small rock accelerations experienced in Kirovakan. The second part investigates, analytically, the role of

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Note. Discussion open until July 1, 1994. Separate discussions should be submitted for the individual papers in this symposium. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on August 14, 1992. This paper is part of the *Journal of Geotechnical Engineering*, Vol. 120, No. 2, February, 1994. ©ASCE, ISSN 0733-9410/94/0002-0349/\$1.00 + \$.15 per page. Paper No. 4626.



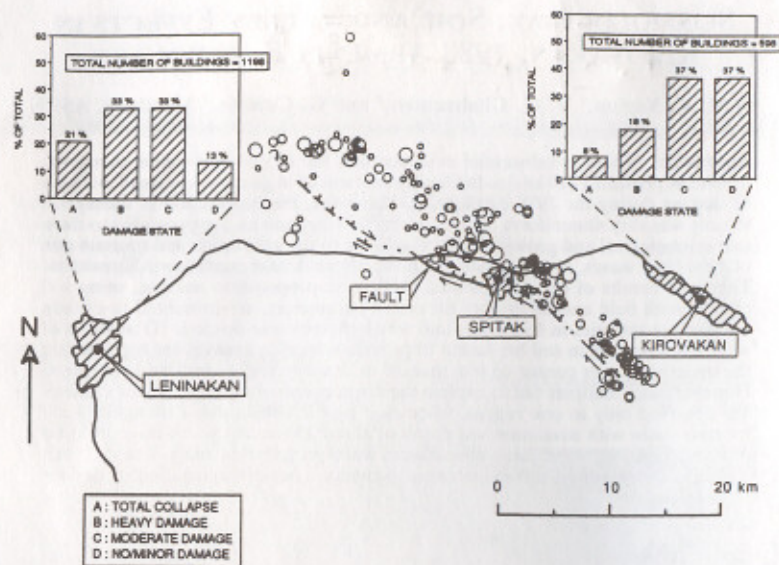


FIG. 1. Overall Building-Damage Statistics in Leninakan and Kirovakan, and their Location with Respect to Ruptured Fault, and Epicenters of Aftershocks

soil in the degree and distribution of damage in Kirovakan, and contrasts with the role of soil in Leninakan, which is discussed in the companion paper (Yegian et al. 1994c). A major conclusion of the present paper is that no single factor could alone explain all that happened during the earthquake. Seismologic, geologic, topographic, and geotechnical conditions have all played a role in affecting the intensity of shaking and the resulting damage.

#### INTENSITY OF BASE EXCITATION IN KIROVAKAN

There is no doubt that the rock-motion intensity during the earthquake in Kirovakan was smaller than that expected at 10 km from the fault of a surface wave magnitude  $M_s = 6.8$  earthquake. We have substantiated this observation by examining the performance of hundreds of grave markers in the old cemetery in the city. Despite their slenderness (aspect ratio of about 0.16) and the fact that they were just resting (in simple contact) on their granitic bases, none was found to have been displaced by sliding and/or rocking during the earthquake. Simple shaking-table tests in our laboratory suggest that peak ground acceleration (PGA) in the cemetery (on rock outcrop) could not have exceeded a mere 0.15 g. By contrast, several grave markers had toppled or rocked in the cemetery of Leninakan, consistent with acceleration levels of 0.30 g or more. And while soil amplification has had an effect on this value of PGA in Leninakan, we have shown in Yegian et al. (1994c) that rock-outcrop motion would have still been at least 0.25 g.

#### CONTRIBUTING SEISMOLOGICAL AND GEOLOGIC FACTORS

The precise cause or causes of such small levels of rock acceleration in Kirovakan are not known. However, several alternative hypotheses have

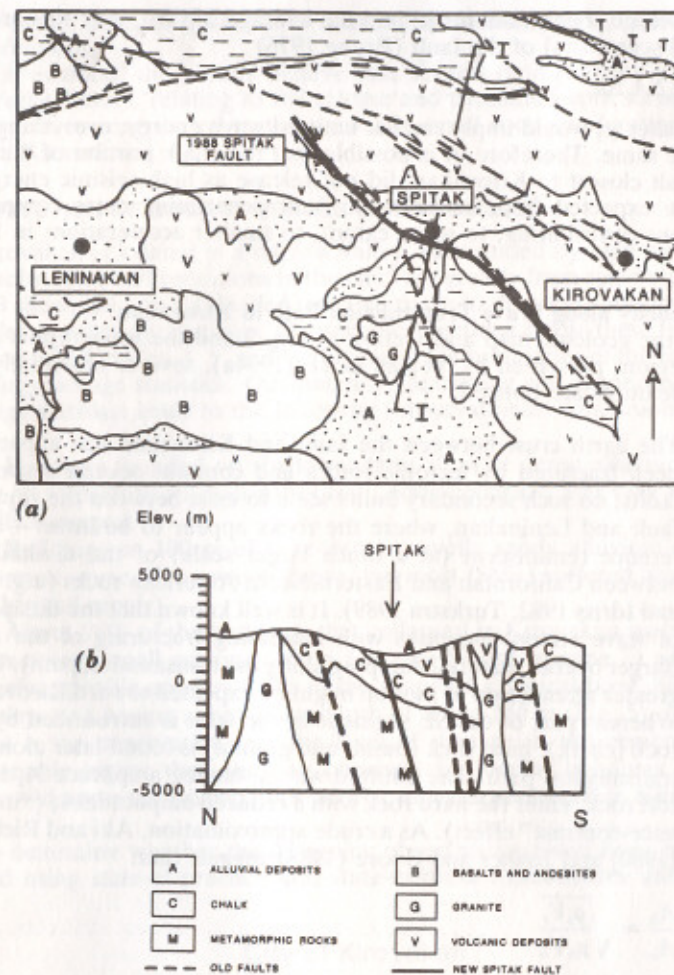


FIG. 2. Devastated Region (from Baghdasarian 1961): (a) Geologic Map; (b) Cross Section

been formulated by the writers, based on the available geologic as well as geographic information. With reference to Figs. 1 and 2, and to Yegian et al. (1994a), the following factors relating to the geology of the source and of the wave-transmission path could have played a role:

#### Chalk Formation in Southeast Segment of Fault

The southeastern segment of the earthquake fault is the closest segment to Kirovakan. Being parallel to (and 10 km away from) Kirovakan, this segment cuts through about 2 km of chalk—a rock substantially softer than the granite, basalt, and other igneous rocks through which the central and northwest segments of the fault (the closest to Leninakan) penetrate. The energy  $\Delta E_s$  radiated by a rupturing fault segment of area  $\Delta A_s$  is proportional



to the average shear modulus  $\mu_s$  and the average slip  $\Delta\bar{u}$ , over this area of activated segment(s) of the fault (Brune 1976)

$$\Delta E_s \sim \mu_s \Delta A_s \Delta \bar{u}_s \dots \dots \dots (1)$$

thus, smaller  $\mu_s$  would imply smaller emitted wave energy, everything else being the same. Therefore, it is possible that the chalk portion of the ruptured fault closest to Kirovakan did not release as high seismic energy as would be expected from an activated fault penetrating more competent rocks, thus contributing, to some extent, to smaller accelerations in Kirovakan.

#### Heterogeneity along Wave Transmission Path to Kirovakan

From the geologic map and section of Fig. 2 and the topographic relief of the region, presented by Yegian et al. (1994a), several potentially important features are noticed:

- The earth crust between the fault and Kirovakan has apparently been fractured by tectonic forces and contains several secondary faults; no such secondary faults seem to exist between the ruptured fault and Leninakan, where the rocks appear to be intact—a difference reminiscent (at a much larger scale) of the dissimilarity between Californian and Eastern North American rocks (e.g. Seed and Idriss 1982; Turkstra 1989). It is well known that the dissipation of wave energy increases with increasing fracturing of the rocks (larger overall material damping along the transmission path). Thus, greater attenuation of motion might be expected toward Kirovakan.
- Whereas part of the SE segment of the fault is surrounded by soft rock (chalk), hard rock (basalt and granite) is found later along the transmission path. The emitted waves, having amplitude  $A_s$  in the soft rock, enter the hard rock with a reduced amplitude  $A_h$  ("impedance-contrast" effect). As a crude approximation, Aki and Richards (1980) and Joyner and Boore (1988) suggest that:

$$\frac{A_h}{A_s} \approx \sqrt{\frac{\rho_s V_s}{\rho_h V_h}} \dots \dots \dots (2)$$

where  $\rho_s$  and  $V_s$  = mass density and shear-wave velocity of the soft rock, respectively;  $\rho_h$  and  $V_h$  are those of the hard rock. Eq. (2) is based on the assumption that the energy of the incident wave equals to the energy of the transmitted wave. Thus, presence of chalk may have contributed to additional attenuation of motion toward Kirovakan.

Some high mountain peaks lie between Kirovakan and its nearest (south-east) segment of the fault. By contrast, there are mostly plains between the central and northwest segment of the fault and Leninakan. We, admittedly only speculatively, suggest that the presence of such mountains might have had some effect on the ground motions in Kirovakan. A search in the literature failed to produce any related evidence. It is important, however, to mention this plausible cause of the reduced intensity of motion, with the intent that it will receive more attention in the future.

Other factors relating to the mechanics of the rupture, such as reduced local stress drop and the presence of asperities in the near-Kirovakan seg-

ment of the fault, may have also contributed to the weak ground shaking in Kirovakan.

In conclusion, the writers believe that several (and perhaps all) of the preceding factors, relating to the release and transmission of seismic wave energy, have contributed to the unusually small rock accelerations in the city of Kirovakan.

#### DISTRIBUTION OF DAMAGE VERSUS SOIL PROFILES

Kirovakan is located in a narrow valley, surrounded by high mountains. The subsurface soil conditions in the city vary greatly from region to region. Fig. 3 shows the city subdivided into five zones to describe variations in soil profiles and damage statistics. Geotechnical sections across these five zones are presented in Figs. 4, 5, and 6, along with the summaries of the respective building-damage statistics. Qualitatively contrasting soil properties against damage statistics leads to the following (observational) conclusions:

1. Buildings founded on shallower than 30 m of dense alluvium (zones 3, 4 and 5) performed reasonably well; none collapsed and very few were heavily damaged.
2. Buildings on 100 m of very dense gravelly sandy alluvium (zone 1) performed worse; there was collapse, but most (86%) suffered heavy damage (beyond repair).
3. About 98% of the buildings that collapsed in Kirovakan were located within a very small region (only a few city blocks in zone 2) where the subsurface profile appears to be in the shape of a conical bowl, filled with stiff clays and having a maximum depth of about 150 m (Fig. 5). Of significance is the observation that the level of damage in this region is even appreciably higher than the one observed for similar buildings in Leninakan—despite the smaller rock accelerations experienced in Kirovakan.

To determine whether the foregoing observations could have been predicted using state-of-practice and state-of-the-art procedures and knowl-

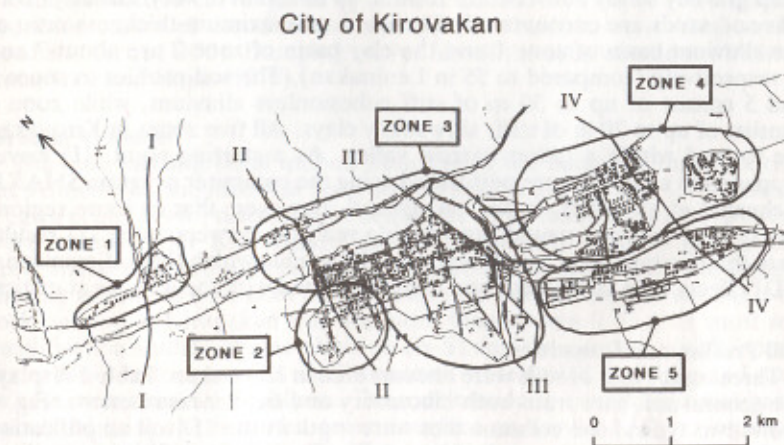


FIG. 3. Map of Kirovakan Subdivided into Five Zones



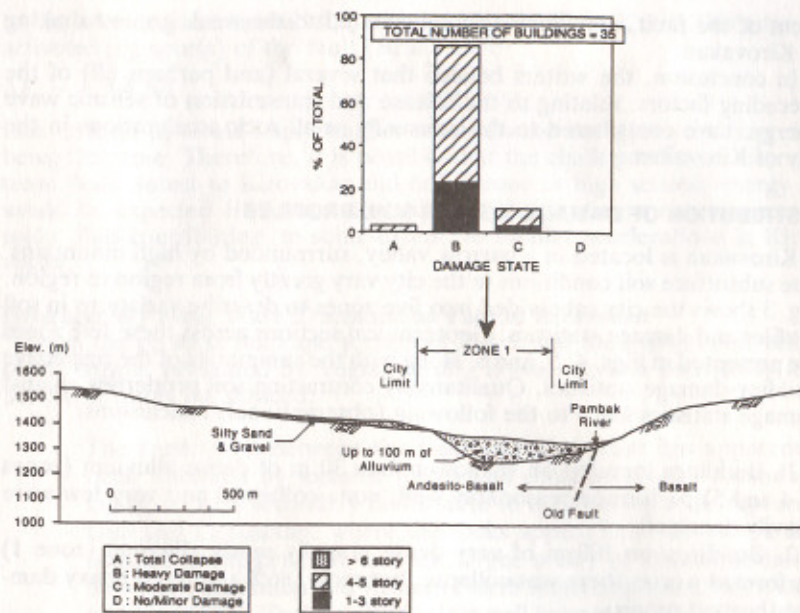


FIG. 4. Geotechnical Profile I-I through Zone 1 in Kirovakan and Its Corresponding Damage Statistics

edge, soil response analyses were performed, using soil properties from laboratory and field measurements. The results of these analyses follow.

#### SOIL RESPONSE STUDIES FOR KIROVAKAN

Unlike Leninakan, the geology of Kirovakan is quite complex, as can be seen in Figs. 4, 5, and 6. The profile for zone 1 consists of about 100 m deep gravelly sandy alluvium. In zone 2, up to 150 m of very stiff clays with silts and sands are encountered. The width-to-maximum-thickness ratio of the alluvium basin of zone 1 and the clay basin of zone 2 are about 7 and 5, respectively (compared to 55 in Leninakan). The soil profiles in zones 3 and 5 consist of up to 30 m of stiff cohesionless alluvium, while zone 4 consists of up to 20 m of stiff, silty-sandy clays. All five zones in Kirovakan are located within a rather narrow valley. As a starting point, 1D wave-propagation analyses were performed using the computer program SHAKE (Schnabel et al. 1972). It was recognized, however, that in some regions this type of analyses would not provide realistic answers; such 1D results were thereby only used as reference results against which three-dimensional (3D) effects were compared, and then correlated with the damage statistics.

#### Soil Profiles and Properties

Three basic types of soils were encountered in Kirovakan. Table 1 displays the general soil data from both laboratory and field measurements. Fig. 7 shows two typical soil columns that were input in the 1D soil amplification analyses. The shear-wave velocities of the alluvium at shallow depth were obtained from cross-hole and geophysical surface-wave tests. The shear-

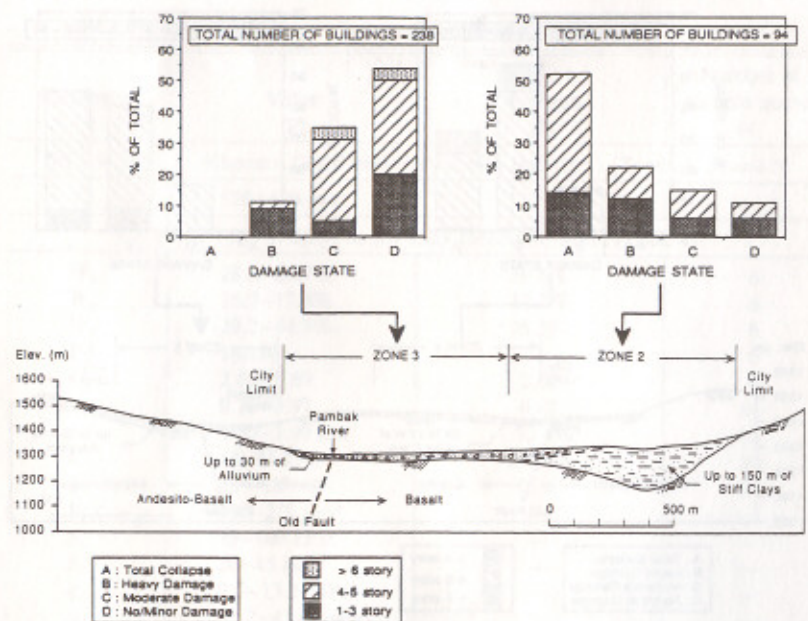


FIG. 5. Geotechnical Profile II-II through Zones 2 and 3 in Kirovakan and Their Corresponding Damage Statistics

wave velocities of the medium-stiff and stiff clay at shallow depths were obtained from cone penetration and geophysical surface wave tests (Table 1). These velocity values for depths below 50 m were estimated from those at shallower depths considering the effect of overburden pressure according to Seed and Idris (1970).

In all the 1D soil amplification analyses, the nonlinear behavior of the stiff clays (soil types 2 and 3 in Table 1) was characterized by the shear modulus reduction curves given by Vucetic and Dobry (1991). The modulus reduction curves of the alluvium (soil type 1) was that for sands given by Seed and Idris (1970). Damping curves for all the soils were also obtained from Seed and Idris (1970).

#### Ground Motions

The only useful ground motion obtained in the damaged region during the Armenia earthquake was recorded on soil, in the town of Ghoukasian. Yegian et al. (1994b) discussed, in detail, the way peak ground accelerations were estimated for Kirovakan. The aforementioned observations of the grave markers in the old cemeteries in Kirovakan, along with subsequent shaking table tests on model blocks, led to the conclusion that the PGA on rock outcrop in Kirovakan was not more than a mere 0.15 g. In most soil amplification studies, the north-south (N-S) and the east-west (E-W) components of the rock motion in Ghoukasian were scaled to 0.15 g and used as base excitation in the analyses. The rock motion in Ghoukasian was back-calculated using the recorded ground surface motion and 1D wave-propagation theory ("deconvolution"). The resulting record and its response spectrum were compared with other rock motions recorded under similar (in



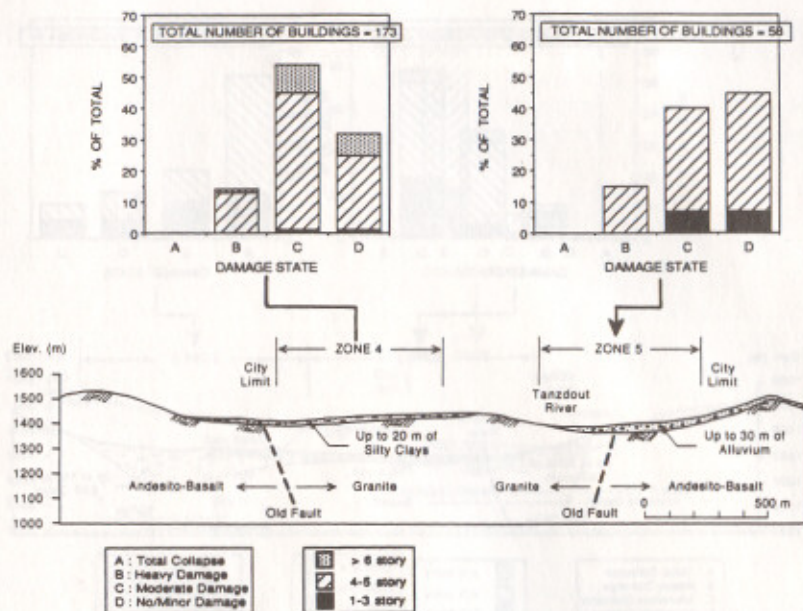


FIG. 6. Geotechnical Profile IV-IV through Zones 4 and 5 in Kirovakan and Their Corresponding Damage Statistics

magnitude and distance) earthquakes, and were deemed reasonable (Yegian et al. 1994b).

### One-Dimensional Soil Amplification Results

Fig. 8 plots the response spectra of the N-S and the E-W components of the computed ground surface motions for soil columns in zones 1 and 2. It is of interest to attempt to reconcile these computed spectra with the damage statistics of the respective zones and thereby get a possible correlation between soil conditions and building damage. In Fig. 8 the spectral accelerations for zone 2 (150 m of clay) in the period range of 0.25–0.40 s (corresponding to four- and five-story structures) are higher (by a factor of 1.5) than the spectral accelerations in zone 1. This would seem to be consistent qualitatively with the difference in the statistics of the collapsed buildings in these zones: 51% versus 3%.

Fig. 9 compares the computed spectral accelerations for soil columns in zone 1 (100 m of alluvium), and zones 3 and 5 (up to 30 m of alluvium). Spectral accelerations for zone 1 are only marginally larger than those for zones 3 and 5 and probably cannot explain the significant difference between damage statistics in these zones. Recall (Figs. 4, 5, and 6) that 89% of the buildings either collapsed or suffered heavy damage in zone 1 whereas in zones 3 and 5 the percentage was only 11% and 16%, respectively. Thus, since the spectra for zones 3 and 5 (corresponding to shallower very stiff alluvium) are, as expected, similar to the input rock spectrum, one may conclude that the 1D soil amplification analysis underestimates the soil effects for zone 1, in which the valley width-to-depth of soil ratio is about 7.

TABLE 1. Soil Properties in Kirovakan

| Parameter (1)   | Value (2)                  | Average (3)            | Number of sample points (4) |
|---|----------------------------|------------------------|-----------------------------|
| (a) Soil Type 1: Alluvium (Sand and Gravel with Boulders) (Zones 1, 3, and 5) |                            |                        |                             |
| $V_s$   | 520–620 m/s <sup>a</sup>   | 570 m/s                | —                           |
| (b) Soil Type 2: Silty, Sandy Clay (Medium–Stiff) (Zone 4)                    |                            |                        |                             |
| $W_n$   | 28.8–33.7%                 | 30.6%                  | 6                           |
| $W_p$   | 16.7–17.8%                 | 17.2%                  | 6                           |
| $W_l$   | 29.2–44.7%                 | 35.3%                  | 6                           |
| P.I.  | 18.1%                      | —                      | 6                           |
| $G_s$   | 2.65–2.69                  | 2.67                   | 6                           |
| $e$   | 0.75–0.97                  | 0.83                   | 10                          |
| $\rho_i$  | 1.85–1.99 t/m <sup>3</sup> | 1.92 t/m <sup>3</sup>  | 10                          |
| $C$   | 12–44 kPa                  | 25 kPa                 | 10                          |
| $\phi$  | 13°–18°                    | 15.6°                  | 10                          |
| $V_s$   | 190–220 m/s <sup>b</sup>   | —                      | —                           |
| $S_u$   | 75–100 kPa <sup>c</sup>    | —                      | —                           |
| $S_w$   | 20–45 kPa <sup>d</sup>     | —                      | —                           |
| $q_c$   | 9.5–13.2 MPa <sup>e</sup>  | —                      | —                           |
| $q_c$   | 32.2–43.0 MPa <sup>f</sup> | —                      | —                           |
| (c) Soil Type 3: Stiff Clays with Silts and Sands (Zone 2)                    |                            |                        |                             |
| $W_n$   | 20–23.3%                   | 21.8%                  | 3                           |
| $W_p$   | 17.2–20.3%                 | 18.7%                  | 4                           |
| $W_l$   | 48.6–52.4%                 | 48.8%                  | 4                           |
| P.I.  | 30.1%                      | —                      | 4                           |
| $G_s$   | 2.65–2.69                  | 2.67                   | 6                           |
| $e$   | 0.64–1.22                  | 0.82                   | 5                           |
| $\rho_i$  | 1.78–2.0 t/m <sup>3</sup>  | 1.88 t/m <sup>3</sup>  | 5                           |
| $C$   | 25–54 kPa                  | 47 kPa                 | 4                           |
| $\phi$  | 19°–20°                    | 19°                    | 4                           |
| $V_s$   | 360–610 m/s <sup>g</sup>   | —                      | —                           |
| $q_c$   | 83.6–153.3 MPa             | 118.0 MPa <sup>h</sup> | —                           |

<sup>a</sup>At 0–14 m deep.

<sup>b</sup>Cone penetration test.

<sup>c</sup>Pocket penetrometer.

<sup>d</sup>Pocket vane.

<sup>e</sup>At 3.5–7.5 m deep.

<sup>f</sup>At 10–11 m deep.

<sup>g</sup>Cone penetration test and geophysical tests.

<sup>h</sup>At 5–6 m deep.

A similar comparison between the spectra for zone 2 (150 m of clay) and zone 4 (up to 20 m of clay) is displayed in Fig. 10. Although the spectral accelerations are slightly higher for zone 2 than for zone 4, their difference is not large enough to explain the very significant disparity of damage statistics in these two zones. For example, in zone 2, where only one to five-story structures were built, 74% of the buildings either collapsed or were heavily damaged beyond repair; whereas, for the same type buildings in



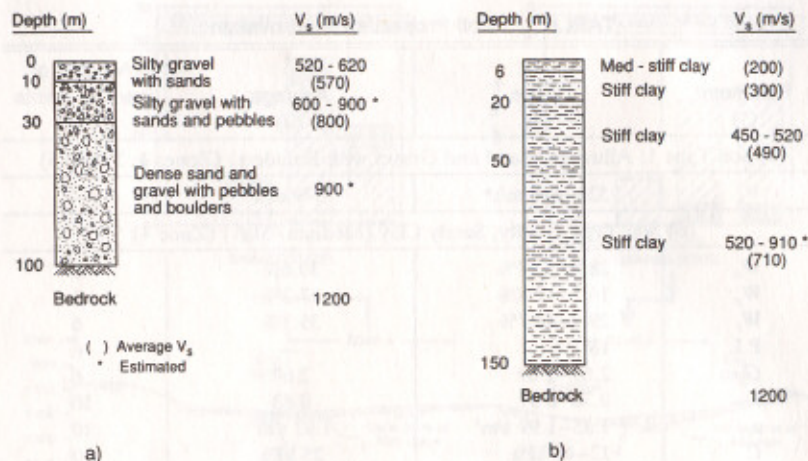


FIG. 7. Soil Columns Used in One-Dimensional Amplification Analyses for Kirovakan: (a) Alluvium in Zone 1 (100 m), and in Zones 3 and 5 (30 m); (b) Clays in Zone 2 (150 m), and in Zone 4 (6–20 m)

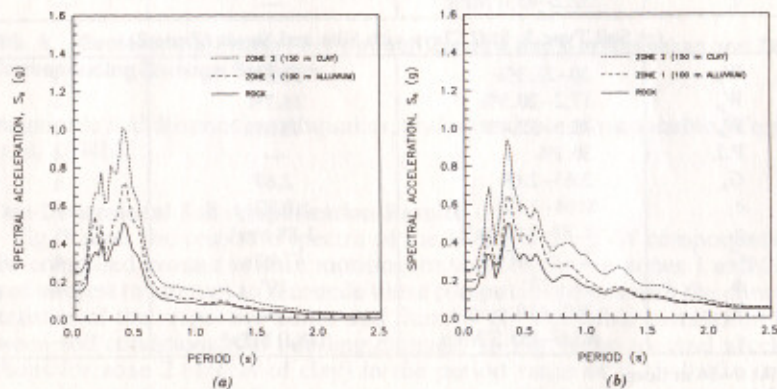


FIG. 8. Computed Spectral Acceleration Response (5% Damping) for 1-D Soil Columns of Zones 1 and 2 in Kirovakan: (a) North-South; (b) East-West

zone 4 none collapsed and only 14% suffered heavy damage. Again, this strongly suggests that the 1D vertical wave-propagation approximation substantially underestimates the amplification of motions in zone 2, where the sedimentary basin width-to-maximum-soil-thickness ratio is only about 5.

Another observation in Figs. 9 and 10 is that the calculated spectral accelerations for higher than six-story buildings (periods 0.5–0.9 s), located in zones 3 and 4, are relatively small (less than 0.25 g). This is consistent with the little damage that these buildings suffered in these zones, where the soil profiles consist of less than 30 m of dense alluvium.

From the preceding discussion, one concludes that 1D soil amplification analysis yields reasonable spectral values only for the shallower deposits (zones 3, 4, and 5). For the deep profiles in zones 1 and 2, such 1D analysis

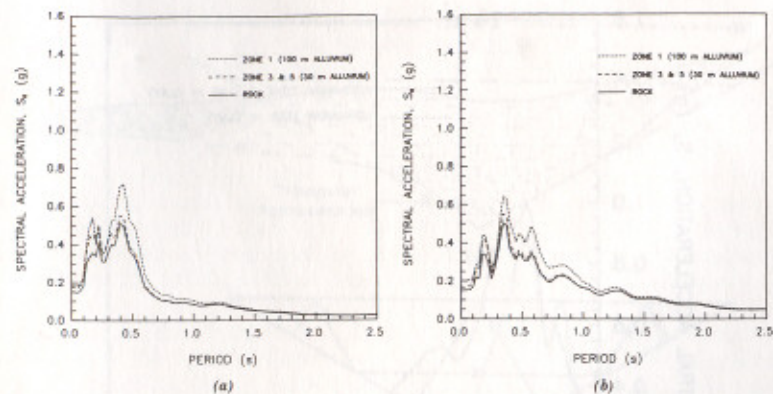


FIG. 9. Computed Spectral Acceleration Response (5% Damping) for 1-D Soil Columns of Zones 1, 3 and 5 in Kirovakan: (a) North-South; (b) East-West

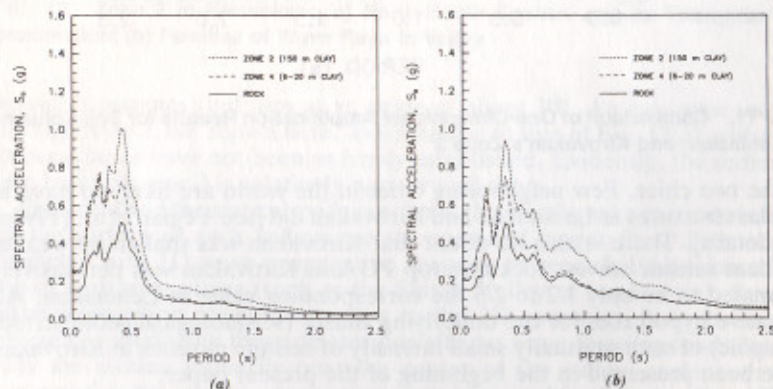


FIG. 10. Computed Spectral Acceleration Response (5% Damping) for 1-D Soil Columns of Zones 2 and 4 in Kirovakan: (a) North-South; (b) East-West

is inadequate for explaining the differences in damage levels—despite the fact that it does predict the correct trend in spectral accelerations. In these two zones (where aspect ratios of the sedimentary basins are only about 5 to 7) two dimensional (2D) and 3D wave-propagation effects, such as wave focussing, generation of laterally propagating surface waves, and developing of valley resonance, may have caused significantly higher ground motions than predicted by 1D analyses. Although there are uncertainties in the analyses described previously, including those associated with the seismic excitation and soil properties, these conclusions are still valid since they are based on comparison of relative (rather than absolute) spectral values.

#### COMPARISON BETWEEN LENINAKAN AND KIROVAKAN

The substantially different damage in the two major cities, Kirovakan and Leninakan, has already been discussed. Undoubtedly, this difference cannot be attributed to any difference in seismic vulnerability of the buildings



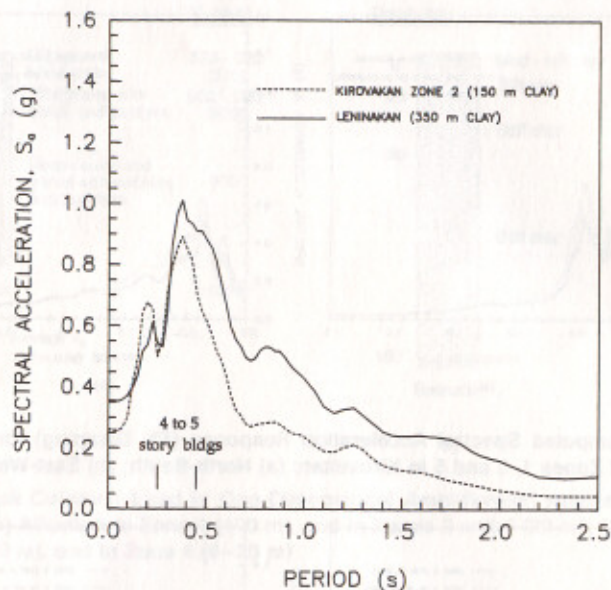


FIG. 11. Comparison of One-Dimensional Amplification Results for Soil Columns of Leninakan and Kirovakan's Zone 2

in the two cities. Few neighboring cities in the world are likely to have as similar structures as Leninakan and Kirovakan did [see Yegian et al. (1994a) for details]. There is also no doubt that Kirovakan was shaken by weaker incident seismic waves: rock-outcrop PGA in Kirovakan was persuasively estimated to be only 1/2 to 2/3 the corresponding value in Leninakan. Alternative hypotheses for the underlying causes (seismological/geologic/topographic) of such unusually small intensity of seismic motions in Kirovakan have been presented in the beginning of the present paper.

Of equal importance is that the soil conditions in most parts of Kirovakan (mostly 10–30 m stiff deposits) are more favorable than in Leninakan. However, in one location in Kirovakan (zone 2), underlain by a basin of up to 150 m of stiff clay (with stiffness very similar to the clays found in Leninakan), the percentage of collapsed buildings significantly surpassed the Leninakan number. Fig. 11 compares the spectra computed by 1D amplification analysis for Leninakan and for Kirovakan's zone 2. The building-damage statistics presented in Fig. 5 indicate that of the four- to five-story structures with periods 0.25–0.40 sec (Yegian et al. 1994b) (the predominant type in Zone 2 in Kirovakan) about 62% collapsed, but only 21% of the similar structures collapsed in Leninakan. Yet, the computed response spectra shown in Fig. 11 predict almost the opposite trend. This leaves little doubt that for zone 2 in Kirovakan 1D amplification analysis substantially underpredicts the ground surface motions—consistent with the earlier conclusion stemming from the comparison of the spectra calculated for zones 2 and 4.

### THREE-DIMENSIONAL VALLEY EFFECTS

A north-south section across Kirovakan's zone 2, depicted in Fig. 12(a), reveals that the bedrock-soil interface is not horizontal (as 1D analysis

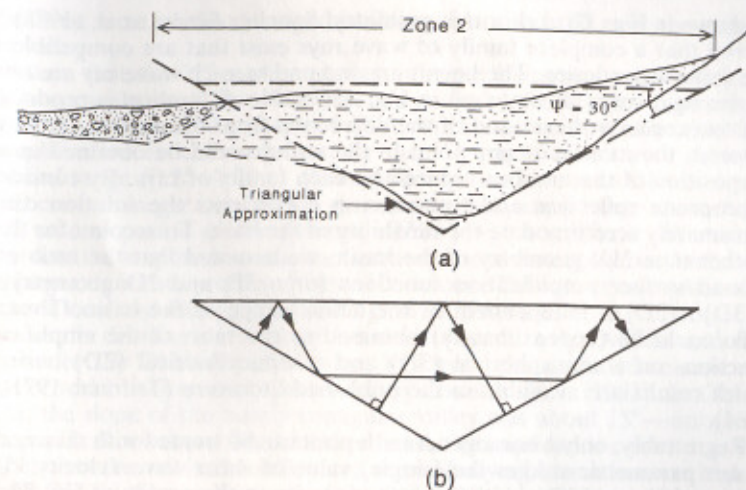


FIG. 12. Zone 2 in Kirovakan: (a) North-South Section and its Triangular Approximation; (b) Families of Wave Rays in Valley

implicitly assumes) but dips at an angle of about 30°. An east-west section through zone 2, not shown here, looks similar to that of Fig. 12(a), although its boundaries have not been as firmly established. Evidently, the sedimentary basin of zone 2 is relatively narrow and deep.

Empirical and theoretical evidence shows that earthquake ground motions on the surface of such valleys are stronger and longer than the motions predicted with 1D wave-propagation theories or recorded/experienced on top of very wide plains (such as the Shirak Valley of Leninakan). Several wave-propagation phenomena, akin to the 3D geometry, have been recognized as producing these deleterious effects: wave focusing tends to amplify the motion primarily near the center of the valley; surface waves, generated at the (steep) edges, propagate back and forth across the valley; and trapping of obliquely incident body waves amplifies the motion experienced near the edges of the valley. One or more of these phenomena were evident in several earthquakes. In Caracas, Venezuela, the high concentration of damage in the area of Palos Grandes during the 1967 earthquake was attributed to the steep slope (dip of about 35°) of the supporting bedrock at the northern boundary of the 3 km long sedimentary valley (Seed et al. 1970; Papageorgiou and Kim 1991).

One can qualitatively argue that some of the aforementioned phenomena must have taken place in the sedimentary basin of zone 2 in Kirovakan. On the other hand, a rigorous quantitative analysis of the 3D seismic response of this valley is a formidable task that goes beyond the objectives of the present paper. An estimate, however, of the likely valley effects on the shaking at the ground surface could be obtained through an approximate analysis using a simple geometric solution developed by Sanchez-Sesma et al. (1988).

Their solution applies to a 2D, triangularly shaped homogeneous valley, the sides of which dip at an angle  $\Psi = 90^\circ/N$  ( $N = 1, 3, 5, \dots$ ), and that is supported by a rigid base. In our case,  $N = 3$  and  $\Psi = 30^\circ$  would result in an idealized geometry that matches well the shape of the actual valley,



as shown in Fig. 12(a). For this geometry, Sanchez-Sesma et al. (1988) have shown that a complete family of wave rays exist that are compatible with the valley boundaries. The beginning and end of each wave ray are normal to the rigid base, as sketched in Fig. 12(b). No diffraction is produced at the two corner vertices and, if the diffraction from the central vertex were ignored, the motion at any point in the valley could be obtained as a superposition of the motions induced by each family of rays. By considering appropriate reflection and transmission coefficients the solution can approximately accommodate the flexibility of the base. To account for the 3D (rather than 2D) geometry of the basin, we assumed that the ratio of the ground surface amplification functions for a 3D and 2D geometry, i.e.  $A(3D)/A(2D)$  is independent of the actual shape of the basin. Thus, this ratio could be (approximately) obtained as the ratio of the amplification functions on a semispherical (3D) and a semicylindrical (2D) basin, for which results are available in the published literature (Trifunac 1971; Lee 1984).

Regrettably, only a homogeneous deposit can be treated with this method. In our parametric studies the (single) value of shear wave velocity  $V_s$  was chosen either as 560 m/s (the average velocity in the profile of Fig. 7) or as 280 m/s (giving more weight to the velocity of the top layers and accounting for some softening due to the moderately large developing shear strains). Characteristic results are presented in Fig. 13 for the Fourier amplification ratio (AR) as a function of period. AR is defined as the ratio of the amplitude of the steady-state motion at a particular point on the valley surface to the amplitude of motion that would be recorded at the surface of the free field (i.e. at the rock outcrop); this definition of amplification is also known as elastic rock amplification (Roesset 1977) and is a function of the "acoustic impedance" ratio,  $\alpha = \rho_s V_s / \rho_r V_r$ , between soil and rock. The continuous line in Fig. 13 is for the center point of the 3D valley; the dashed line is for a 1D homogeneous soil column of the same properties and thickness of  $H = 140$  m. The middle of the valley was selected for comparison because of

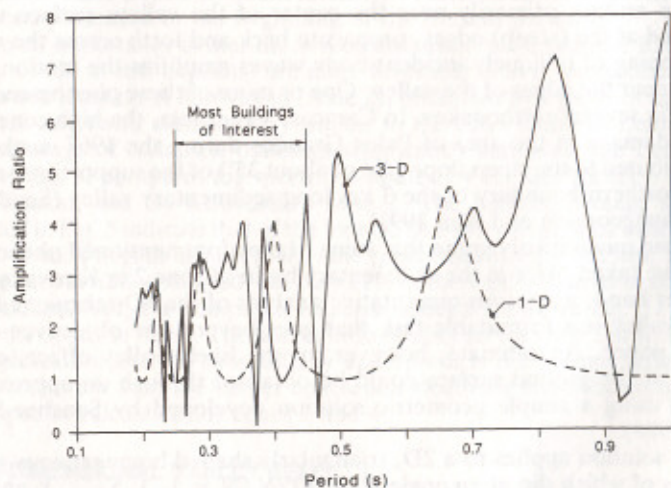


FIG. 13. Comparison of Approximate 3-D and 1-D Amplification Results for Zone 2 in Kirovakan

the fact that most of the damaged buildings were located near the center of the valley.

It is seen that the 3D motion contains (in the frequency range studied) many more peaks than the widely spaced peaks of the 1D curve—an outcome of the complicated pattern of waves in the valley. It is clear that the 3D amplification exceeds substantially the 1D amplification over most of the period range (0.25–0.40 s) of the buildings in this zone of Kirovakan. The 1D curve is larger only over a very narrow frequency range around the second natural period of the column,  $4H/3V_s \approx 0.4$  s. These differences suggest that the amplitude of the motion atop the sedimentary basin of zone 2 was larger than that predicted from 1D theory. This can then explain the enormous localized damage to buildings in Kirovakan.

It is worth drawing an analogy between zone 2 in Kirovakan and the valley under the Ohba-Ohashi bridge, in Japan, the recorded seismic response of which was recently presented by Gazetas et al. (1993). In Ohba-Ohashi, the slope of the nearly triangular valley was about  $15^\circ$ —only half as steep as in Kirovakan. On the other hand, the impedance contrast,  $\rho_s V_s / \rho_r V_r$ , between the soil in the valley and the underlying formation was higher in Ohba-Ohashi than in Kirovakan. In Ohba-Ohashi, the recorded surface and base motions resulted in amplification functions having a large number of substantial peaks, as opposed to the two relatively narrow peaks of the 1D wave-amplification theory. In fact, the observed differences are quite similar to those shown in Fig. 13. The result: in Ohba-Ohashi, the recorded ground-surface accelerogram had 70% higher amplitudes than those predicted with 1D theory using the recorded base accelerogram as excitation. Thus, there is strong reason to believe that similarly higher accelerations developed in the center of zone 2 in Kirovakan.

In zone 1 where the alluvial valley is not so steep, 3D effects are expected to have had an intermediate impact.

## SUMMARY AND CONCLUSIONS

The smaller degree of damage in the city of Kirovakan (10 km from the fault) compared to Leninakan (25 km from the fault) was primarily the result of the unusually small intensity of the incident seismic wave motions. Such motions have resulted in rock outcrop accelerations with estimated peak values of only 0.10–0.15 g in Kirovakan. At least three possible factors have been identified that could have contributed to the reduction in the intensity of seismic excitation in the city.

1. The segment of the fault closest to Kirovakan cuts to a depth of 2 km through soft rock (chalk) and would thus have released smaller seismic energy than a similar fault through competent rock.
2. Along the transmission path from the fault to Kirovakan, one observes the presence of fractured rocks with many secondary faults; this would have increased the overall damping and produced larger attenuation of the propagating waves.
3. The geology along the transmission path is such that the seismic waves initially propagating in soft rock are subsequently entering hard rock with reduced amplitudes ("impedance-contrast" effect).

None of these factors were present in the relevant fault segment or the transmission path to Leninakan.



To assess the influence of local soil conditions in the extent and distribution of damage in the two cities, this and the companion paper (Yegian et al. 1994c) have presented results of 1D and 3D soil amplification analyses. The computed response spectra for the different regions in the two cities were systematically compared and the following conclusions were reached:

1. 1D soil amplification analyses of the Leninakan profile, where the sedimentary basin width-to-maximum-soil-thickness ratio is 55, yield realistic results (if reliable soil parameters are used as input). In fact, many of the patterns in building-damage distribution and various key field observations could be adequately confirmed with such analyses.

2. 1D wave-propagation analyses of shallow (20–30 m) and stiff soil profiles in Kirovakan have also yielded reasonable estimates of ground motions, consistent with the observed building-damage statistics.

3. In Kirovakan, buildings with six stories or more, founded on 20–30 m of dense alluvium, experienced 0.20–0.30 g elastic spectral accelerations and suffered little damage. Therefore, these buildings, despite the poor quality of construction materials and the seismically vulnerable bearing system, still had some level of inherent seismic capacity.

4. For the regions in Kirovakan where valley width-to-soil-thickness ratio is about 5 to 7, 1D soil amplification results seem to grossly underestimate the experienced level of shaking.

5. Compared to simple 1D analysis, 3D soil amplification analysis, for a triangular basin in Kirovakan (zone 2), having a width-to-soil-thickness ratio of about 5, results in ground-surface motions that provide a better explanation of the observed building damage.

#### ACKNOWLEDGMENTS

This research was made possible through a grant from the National Science Foundation (NSF). The support of NSF and of Clifford Astill, director of the program is greatly appreciated. In addition we appreciate the contributions to this research of our numerous colleagues in the United States, Armenia, Iran, Russia, Greece, and the United Kingdom. In particular we acknowledge the invaluable technical and logistical assistance provided by the following individuals and institutions: Rouben Harutiunyan of ARM-NIISA, Stepan Zargaryan of Yerevan Polytech. Inst., Lenser Aghalovyan and Arkady Karakhanian of Armenia Academy of Sciences, Vartkes Avetisyan of Univ. of Yerevan, Hakob Aloyan of Architectural and Civil Engineering Institute of Yerevan, Vincent Murphy of Weston Geophysical Corp., and Dean Paul King of Northeastern University.

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