#3

Ground-Motion and Soil-Response Analyses for Leninakan, 1988 Armenia Earthquake

By M. K. Yegian,[1] V. G. Ghahraman,[2] and G. Gazetas,[3] Members, ASCE

Abstract: Two earlier papers by the writers, appearing in the preceding issue of the journal, presented an overview of the seismological and engineering aspects of the 1988 Armenia earthquake and examined building damage statistics contrasted to geologic and geotechnical soil profiles. Possible regions of appreciable soil amplification effects were identified in the cities of Leninakan and Kirovakan. The present paper and companion paper, in the same issue of the journal, present results from analytical soil amplification studies using actual soil profiles from Leninakan and Kirovakan, and investigate whether or not current state-of-practice methods could adequately explain the damage statistics and their local and geographical distribution in the two cities. The present paper deals with Leninakan, which is located in the center of a very wide flat valley, having a width-to-maximum-soil-thickness ratio of about 55. Results indicate that, when using proper laboratory and field measurements of soil properties, one-dimensional soil amplification analyses can explain well not only the trends observed in the intensity and distribution of damage to buildings, but also observations made of response of various structures in Leninakan. The companion paper describes the one- and three-dimensional soil amplification analyses and valley effects in Kirovakan and summarizes the overall conclusions drawn from this research related to soil effects during the Armenia earthquake.

INTRODUCTION

On December 7, 1988, an earthquake of surface wave magnitude M_s = 6.8 struck Northwestern Armenia destroying over 1,000 buildings and causing over 40,000 fatalities. Fig. 1 shows a map of the damage zone and points of interest. Fig. 2 summarizes the building damage statistics for the three major cities of interest, Leninakan (later renamed Kumayri), Spitak, and Kirovakan, all in Armenia. Questions were raised regarding the reasons for such a high level of damage from a moderately strong event, as well as for the considerable difference between damage in Kirovakan (which is closer to the ruptured fault) and Leninakan. The writers have performed extensive investigation on many aspects of the earthquake. An overview of the earthquake and many of the factual data related to seismological, geological, geotechnical, and structural engineering aspects of the earthquake can be found in Yegian et al. (1994a).

Yegian et al. (1994b) focused on ground motions and building damage statistics. Upper and lower bounds were established for peak ground acceleration on the basis of the observed performance of grave markers in the cemeteries of Spitak, Leninakan, and Kirovakan, as well as other key observations of building performance. Detailed building damage statistics were contrasted to geological and geotechnical profiles in Leninakan (which

[1]Prof. and Chmn., Dept. of Civ. Engrg., Northeastern Univ., Boston, MA 02115.
[2]Dept. of Civ. Engrg., Northeastern Univ., Boston, Mass.
[3]Prof. of Civ. Engrg., State Univ. of New York at Buffalo, Buffalo, NY 14260; and National Technical Univ., Athens, Greece.

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 0733-9410/94/0002-0330/$1.00 + $.15 per page. Paper No. 4624.

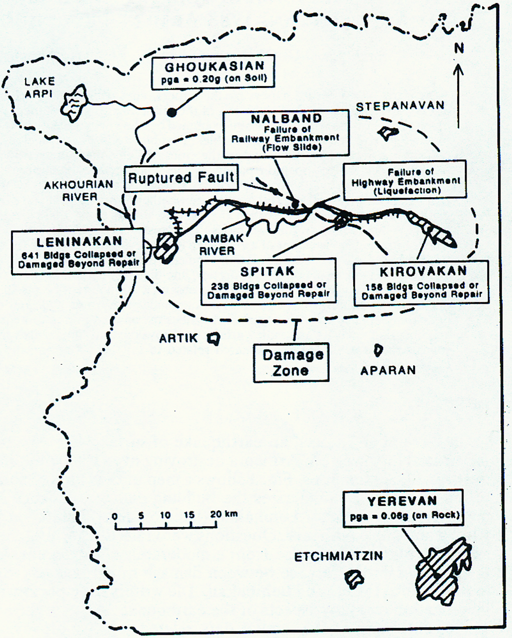


FIG. 1. Map of Damage Region and Points of Interest

is founded in the center of a wide flat basin) and in Kirovakan (where the soil profile varies considerably within the city). Spitak, located very close to the ruptured fault experienced very large ground motions, destroying 90% of its multistory buildings. Therefore, it would be very difficult to assess the effect of soil amplification on building damage in Spitak.

The present paper and companion paper (Yegian et al. 1994c) present extensive results of wave-propagation (soil amplification) analyses for Leninakan and Kirovakan using soil properties obtained from laboratory and field measurements. The dual objective of this theoretical study is:

- To analytically assess the role of soil amplification on the extent and geographic distribution of damage in the Armenia earthquake.
- To find out whether current state-of-practice methods could have predicted the foregoing effects, had the location and magnitude of the event been known.

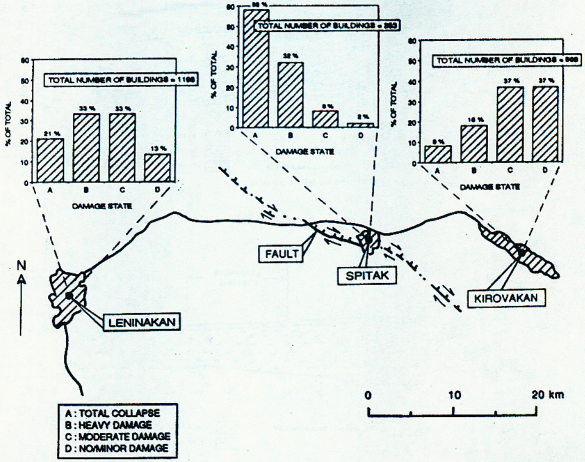


FIG. 2. Overall Building Damage Statistics in Leninakan, Spitak, and Kirovakan

OVERVIEW OF DAMAGE STATISTICS CONTRASTED TO SOIL PROFILES

The city of Leninakan is located in the center of the flat and wide (20 km by 16 km) Shirak Valley. Fig. 3 displays a cross section of the valley, which is of volcanic and tectonic origin. The soil deposits in this basin consist of a top 35–50 m of stiff silty-sandy clays occasionally containing layers of sand and tuff, underlain by about 300–350 m of very stiff lacustrine clays. Yegian et al. (1994b) have contrasted these soil conditions to building damage statistics and have made the following qualitative conclusions:

- Variations in the composition of the surficial (top 35–50 m) soils (i.e. presence or absence of volcanic tuff and of river sands) had no apparent effect on building damage. Buildings with similar characteristics had the same likelihood of collapse or damage regardless of where they were located in the city.
- There was no predominant orientation for building damage in Leninakan. Identical buildings with different orientations experienced similar level of damages.
- The horizontal peak ground-surface acceleration (PGA) must have exceeded 0.30 g, as evidenced by the response of grave markers.

A detailed discussion of the evidence for the preceding conclusions is presented by Yegian et al. (1994b).

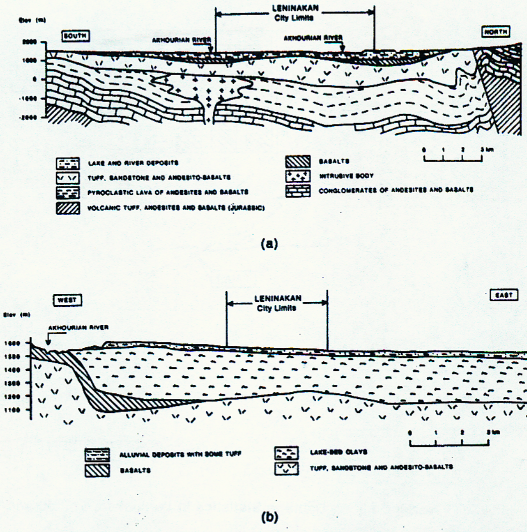


FIG. 3. Geologic Cross Section through Shirak Valley: (a) 3,000 m Deep; (b) 500 m deep (from Avetisian, personal communication, 1990)

SOIL AMPLIFICATION STUDIES

One-dimensional wave propagation analyses were performed, assuming that the seismic waves were exclusively vertically propagating S-waves. This is believed to be a reasonable approximation since Leninakan, covering an area of roughly 3 km by 7 km, is in the center of the 20 km wide and flat Shirak Valley, consisting of stiff and very stiff soils down to a depth of about 350–400 m from the surface [Fig. 3(*a*)]. The "aspect" (width-to-depth) ratio of the sedimentary basin is thus about 55, and all available empirical and theoretical evidence (e.g. Bard and Gariel 1986; Silva 1989; Sanchez-Sesma et al. 1989) suggests that any two-dimensional (2-D) effects would have been of marginal importance for structures in the center of the valley. In addition, due to the proximity of the fault, directly arriving Rayleigh and Love waves would also be of secondary, if any, importance, especially at the relatively low period range of interest for the Leninakan structures (Gazetas and Yegian 1979).

The analyses to compute ground-surface motions and the corresponding 5% damped response spectra were performed using the computer program SHAKE (Schnabel et al. 1972). In all of the analyses the nonlinear behavior of stiff clays was characterized (in an equivalent linear approximation) by the shear modulus reduction curves given by Vucetic and Dobry (1991). The modulus reduction curves for silty sandy layers and the damping versus shear-strain relationships of all other soils were taken from Seed and Idriss (1970).

SOIL PROFILES AND PROPERTIES

Two geologic profiles (at different scales) describing the overall subsurface conditions in Leninakan are shown in Fig. 3. The top 35–50 m of the deposits generally consists of silty-sandy stiff clays with occasional presence of 4–6 m thick volcanic tuff or of river-deposited dense sands. Beneath this layer one finds a 300–350 m thick deposit of very stiff lake-bed (lacustrine) clays. To confirm the specific locations of these soils and to present their prop-

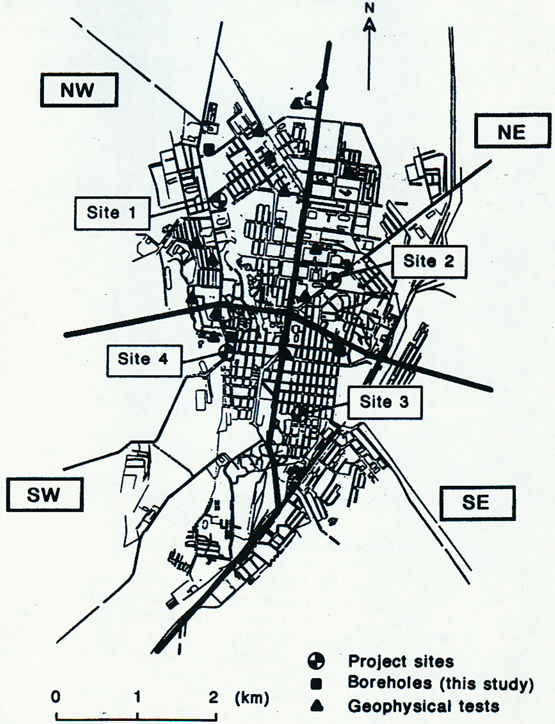


FIG. 4. City of Leninakan with Location of Project and Field Investigation Sites

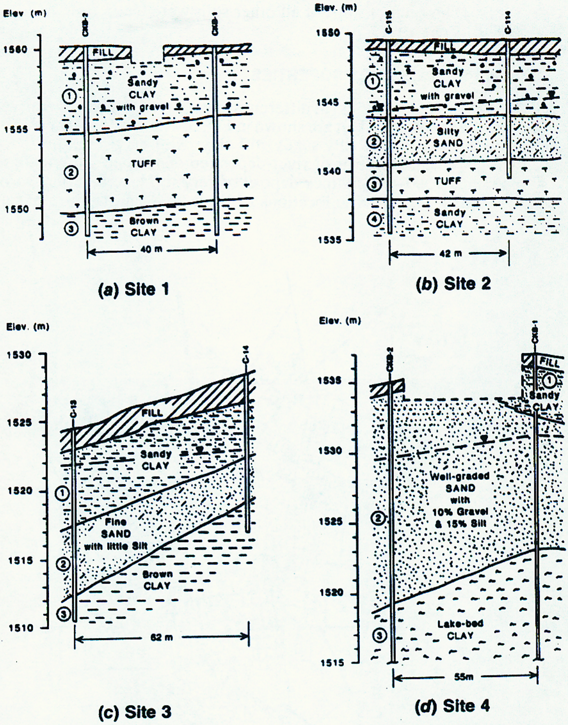


FIG. 5. Geotechnical Cross Sections for Four Project Sites in Leninakan

erties, four project sites, one in each of the four quadrants into which we subdivided Leninakan, are selected and presented. Fig. 4 shows the plan view of the city and the location of the project sites. Typical profiles and the properties of the soils encountered at the four selected sites are shown, respectively, in Fig. 5 and Table 1 [Research Institute for the Ministry of Construction in Armenia (ARMNIISA), personal communication, 1989]. The values of the soil parameters shown in Table 1 have been confirmed with additional data from over 200 boreholes. Table 2 gives the range and the average values of the measured physical, index, and mechanical parameters for each of the four general types of soils encountered in Leninakan.

To independently confirm these site conditions and the soil properties compiled by Armenian engineers, the writers transported standard pene-

TABLE 1. Soil Properties for Four Selected Project Sites in Leninakan

Soil layer number (1)	W_n (percent) (2)	W_p (percent) (3)	W_l (percent) (4)	e (5)	ρ_t t/m³ (6)	C kPa (7)	ϕ (degrees) (8)
(*a*) Site 1: (NW Section)							
1	29.2	27.3	43.2	—	1.74	29	19
2	—	—	—	—	1.49	—	—
3	35.4	30.5	48.8	—	1.83	35	27
(*b*) Site 2: (NE Section)							
1	25	25	46	0.92	1.70	23	29
2	27	25	29	0.91	1.70	—	—
3	—	—	—	—	1.49	—	—
4	29	31	42	0.92	1.80	—	—
(*c*) Site 3: (SE Section)							
1	30	25	38	0.90	1.80	—	—
3	40	26	48	1.22	1.72	—	—
(*d*) Site 4: (SW Section)							
1	26	22	37	0.85	1.86	22	22
3	37	34	56	1.06	1.83	36	14

tration test (SPT) and cone penetration test (CPT) equipment and ran selected tests in different cities and locations in Armenia. Fig. 4 shows the locations of the boreholes made by the writers in Leninakan. Table 1 includes the additional data obtained by the writers, which are generally consistent with the results made available by Armenian engineers.

In addition to geotechnical field investigations, geophysical tests using shear wave velocity downhole measurements were performed by the U.S.S.R. Ministry of Construction. Fig. 4 shows the locations of the geophysical test holes in Leninakan. The shear wave velocities for each major soil type encountered in Leninakan are also summarized in Table 2 (ARMNIISA, personal communication, 1989).

The generated soil profiles in Leninakan together with the properties presented in Table 2 were utilized to establish the soil columns for the soil amplification analyses (Fig. 6). Since the silty-sandy clays (soil type 1) and the sand layer (soil type 2) have very similar shear wave velocities, no differentiation between these two soil types and their shear modulus and damping properties were deemed necessary. Hence, essentially two typical idealized soil columns were used to describe all Leninakan sites; one without tuff and the other with tuff, as shown in Fig. 6. The range of values for the shear wave velocity for the top approximately 50 m of the profile, shown in Fig. 6, were obtained from measured geophysical data. The average velocities shown in Fig. 6 correspond to average values of the upper and lower bounds. The shear wave velocities of the lake-bed clay at depths below 50 m were estimated from the values measured within the top 50 m. These estimates were made considering an increase in shear wave velocity as a function of overburden stress as given by Seed and Idriss (1970).

GROUND MOTIONS

Yegian et al. (1994b) discussed the strong ground motion record obtained and the site condition at the recording station in the town of Ghoukasian,

TABLE 2. Soil Properties in Leninakan

Parameter (1)	Value (2)	Average (3)	Number of sample points (4)
(*a*) Soil Type 1: Silty, Sandy Clay with Occasional Gravel (Medium–Stiff)			
W_n	20–38%	27.2%	83
W_p	19–34%	26.2%	89
W_l	26.6–53.2%	42.8%	89
P.I.	16.6%	—	89
G_s	2.68–2.72	2.70	83
e	0.73–1.0	0.88	83
ρ_t	1.74–1.9 t/m³	1.79	83
C	12–38 kPa	25 kPa	6
ϕ	18°–31°	20°	6
V_s	275–325 m/s	300 m/s	18
q_c	17.7–43.2 MPa[a]	—	—
(*b*) Soil Type 2: Sands and Gravelly, Silty Sands (Medium Dense–Dense)			
G_s	2.64–2.73	2.68	6
ρ_t	1.82–2.03 t/m³	1.93	7
ϕ	30°–40°	35°	8
V_s	240–390 m/s	310 m/s	14
q_c	66.4–97.5 MPa	80.5[c]	—
q_c	57.4–131.7 MPa (gravelly sands)	92.2[d]	—
SPT-N_{field}	25–28 blows (clean sands)	27[e]	—
(*c*) Soil Type 3: Tuff			
G_s	2.50	—	—
ρ_t	1.49–1.51 t/m³	1.50 t/m³	16
V_s	370–570 m/s	446 m/s	6
(*d*) Soil Type 4: Brown Clay/Lake-Bed Clay (Very Stiff)			
W_n	27–63%	41.5%	28
W_p	22.3–50%	33.7%	29
W_l	39.7–79%	56.2%	31
P.I.	24.1%	—	29
G_s	2.71–2.73	2.72	5
e	0.93–1.0	0.97	5
ρ_t	1.68–1.83 t/m³	1.77 t/m³	5
C	30–36 kPa	33 kPa	6
ϕ	14°–16°	15°	6
V_s	300–400 m/s[b]	350 m/s	12

[a]At 2–3 m deep.
[b]At 10–12 m deep.
[c]At 3 m deep.
[d]At 5.5 m deep.
[e]At 2–4.5 m deep.

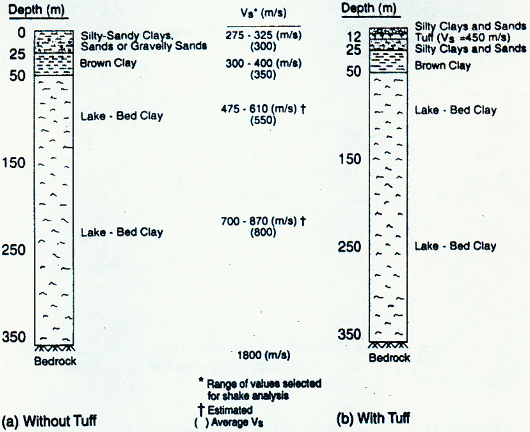


FIG. 6. Soil Columns with Shear Wave Velocities Used in One-Dimensional Amplification Analyses for Leninakan: (*a*) without Tuff; (*b*) with Tuff

Armenia (Fig. 1). Peak horizontal ground accelerations were about 0.20 g in the two horizontal components (A. Der-Kiureghian, personal communication, 1989), but the frequency characteristics, the significant duration, and the details of the two components were quite different. Using an inverse procedure ("deconvolution"), rock outcrop acceleration time-histories were deduced having peak values of about 0.25 g in the north-south (N-S) direction and 0.14 g in the east-west (E-W) direction.

Strong motion records that must have been recorded in Leninakan were lost as they were located in buildings that were destroyed during the earthquake. But single-pendulum and multipendulum seismoscopes did survive, having recorded relative displacements. Unfortunately, the motions of the long-period pendulums tended to be excessive and were restricted by impact on the glass encasement. Fig. 7 displays a pair of useful seismoscope recordings. It is noted that both seismoscopes (period = 0.25 s) exhibit a single major pulse in the direction 30° E-W, which is approximately parallel to the direction of the segment of the fault closest to Leninakan. In the N-S direction, the pulses are of slightly smaller amplitude but are greater in number. This is consistent with the two components of the Ghoukasian record, described by Yegian et al. (1994b). It is also noted that both Ghoukasian and Leninakan are located about the same distance from the northwestern segment of the activated fault (Fig. 1). Hence, the frequency characteristics of two components of the computed Ghoukasian rock motion were utilized to approximate the characteristics of motion in Leninakan. As is discussed later in the present paper, this assumption is further supported by comparing the one-dimensional (1-D) soil amplification results for Leninakan—using, as excitation, the Ghoukasian rock-outcrop motions (prop-

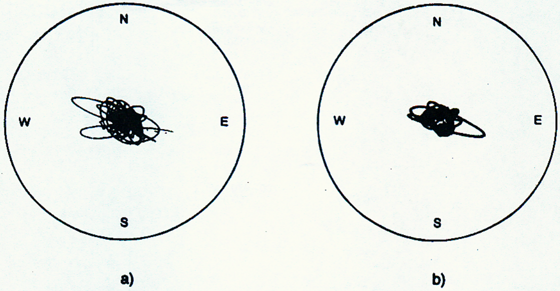


FIG. 7. Seismoscope Records in Leninakan (T = 0.25 s): (*a*) in Institute of Geophysics and Engineering Seismology; (*b*) in Central Part of City (from Martirossian et al. 1989)

erly scaled for distance)—and the corresponding amplification results using the Santa Cruz rock record from 1989 Loma Prieta, Calif., earthquake, which was of similar magnitude and distance-to-source as Leninakan.

The question remains: what are the likely values of PGA for the two components of motion at rock outcrop in Leninakan? One approach would be to assume the estimated peak acceleration of the rock outcrop motion in Ghoukasian to be applicable in Leninakan, after correcting for the somewhat smaller attenuation in the latter (25 versus 30 km from the center of the northwestern part of the activated fault). However, Ghoukasian is in a direction parallel to the fault, while Leninakan is in a perpendicular direction. Potentially significant azimuthal effects on PGA would then be overlooked. The alternative engineering approach that was followed involved calculating (by trial and error) the PGA of each of the two components of the Ghoukasian rock motions, so that when these scaled motions were propagated upward through the soil profiles (using 1-D wave propagation theory) yielded results in accord with three key observations on the ground surface in Leninakan. These three observations are as follows.

Observation 1: Toppled Cemetery Blocks

We observed that few cemetery blocks in Leninakan toppled during the earthquake. These grave markers, facing approximately the E-W direction, were in cemeteries founded on the deep alluvium and lake-bed deposits. Shaking-table test results on model blocks (conducted at Northeastern University), representative of fallen cemetery grave markers, show that the ground-surface acceleration in Leninakan in the E-W direction must have exceeded 0.30 g, but only slightly, since many of the less slender blocks had survived the ground motions (Yegian et al. 1994b). Results from soil amplification analyses performed with the average values of shear wave velocities shown in Fig. 6 indicate that the peak ground acceleration on rock outcrop in Leninakan must have exceeded 0.20 g in the E-W direction to have caused a ground-surface acceleration of 0.30 g or higher.

Observation 2: Overturning of St. Astvatzatzin Church Steeple

During the earthquake, the steeple of St. Astvatzatzin in Leninakan toppled in the N-S direction, yet remained intact. Hamasian (1990) thoroughly investigated the dynamic response of the church and that of the rigid steeple. He calculated that the acceleration on the ground surface in the N-S direction must have exceeded 0.30 g. Once again, soil-response analyses would indicate that the rock outcrop motion in Leninakan in the N-S direction must have been about 0.25 g.

Observation 3: Seismoscope Records

For each typical value of peak ground acceleration of rock outcrop motion, the spectral displacements at ground surface for the periods and damping ratios of the multipendulum seismoscopes were calculated and compared with the actual seismoscope records. Fig. 8 (a and b) portrays these comparisons in the N-S and E-W directions, respectively, for the rock motions that yielded (in the trial-and-error search) the best match between calculated and observed values. The computed displacements in both N-S and E-W directions corresponding to 0.25 g rock motion (in both directions) are in reasonable agreement with the recorded seismoscope data. The computed displacements in the E-W direction are slightly larger than those in the N-S direction, which is in accord with the observations of the single-pendulum seismoscope records shown in Fig. 7. It is also worth noting that the arrows pointing vertically up on the data points corresponding to seismoscopes with periods of 0.5, 0.7, and 0.9 s indicate that the actual displacements were clearly larger, since these pendulums had been restricted by their glass encasements.

Thus, the seismoscope data along with the results of soil-response analyses lead to the following conclusions:

1. Peak ground accelerations on rock outcrop in Leninakan were about 0.25 g in both N-S and E-W directions, resulting in peak horizontal accel-

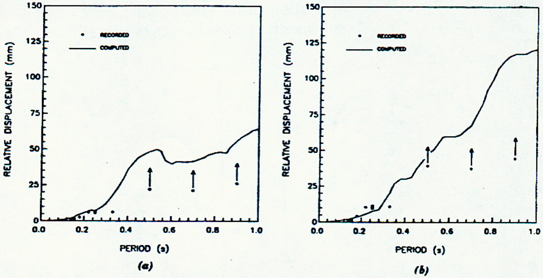


FIG. 8. Comparison of Seismoscope Records with Results Calculated from Soil Amplification Analyses for Leninakan (Arrows Indicate that Actual Displacements Would Have Been Larger if Pendulums Were Not Restricted by Their Glass Encasements): (*a*) North-South; (*b*) East-West

erations on the ground surface of 0.32 g and 0.39 g, respectively. These surface acceleration values are consistent with observations 1 and 2.

2. Unlike the back-estimated rock outcrop motion for Ghoukasian, where acceleration amplitudes in the E-W direction are smaller than in the N-S direction, in Leninakan the two rock outcrop components appear to have had comparable values of peak horizontal acceleration. This difference may be attributed to azimuthal effects. Note that strong azimuthal effects have been found in records of the 1989 Loma Prieta earthquake (Campbell 1991; Idriss 1990), 1986 Kalamata, Greece, earthquake (Gazetas et al. 1990), 1985 Michoacan (Mexico City) earthquake (Finn and Nichols 1988), and 1971 San Fernando, Calif., earthquake (Arnold et al. 1976).

In summary, the existing evidence suggests that in Leninakan rock motion characteristics (e.g. duration and general frequency content) of the N-S and the E-W components are similar to respective components of the Ghoukasian record. Rock outcrop PGA values are estimated to have been about 0.25 g in both directions.

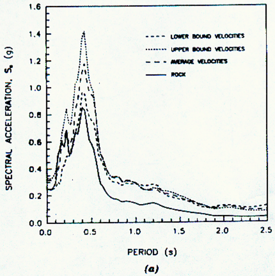
SOIL-RESPONSE RESULTS

Analyses of 1-D soil-response were made using the soil columns depicted in Fig. 6, for the shown range of shear wave velocities. The rock motions were assigned to outcrop, and ground-surface motions were calculated. The 5%-damped acceleration response spectra of the calculated ground-surface motions are summarized in Fig. 9 for the N-S and E-W components. Fig. 10 plots the corresponding spectral ratios between ground surface and rock outcrop. From these figures, several trends are worth noting:

1. The effect of uncertainties in the shear wave velocity measurements on the soil amplification ratios is not very important.

2. Considering the range of shear wave velocities, peak horizontal accelerations are soil-amplified by a factor ranging between 1.0 and 1.8.

3. The peak spectral amplification ratio occurs at a period of about 2 s, or slightly greater, in both components. This value corresponds to the natural



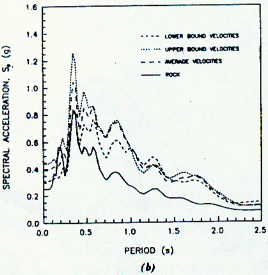


FIG. 9. Acceleration Response Spectra (5% Damping) For Leninakan Using Range of Shear Wave Velocities: (*a*) North-South; (*b*) East-West

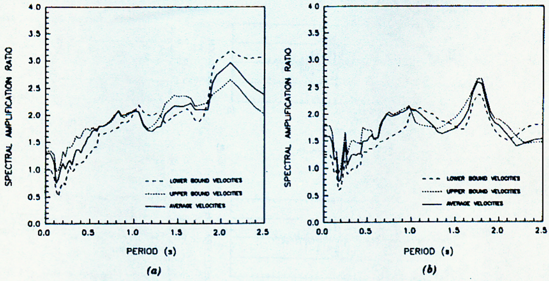


FIG. 10. Ratio of Spectral Accelerations (Soil/Rock) for Leninakan Using a Range of Shear Wave Velocities: (a) North-South; (b) East-West

period of the soil deposit and is in general agreement with the 2–2.5 s fundamental period estimated from microtremor and aftershock records in Leninakan by Borcherdt et al. (1989). It is noted that, in the soil amplification the potential effect of soil nonlinearity was minimal, due to the stiff nature of Leninakan profile. Thus, the estimated fundamental period from soil amplification is comparable with that from study of microtremors. The fundamental period of Leninakan soil is about 2 s, while all buildings had estimated natural periods falling between 0.25 to 0.90 s. Therefore, in Leninakan, there was no "resonance" between buildings and soil profiles, although ground motions were somewhat amplified.

4. In the period range of 0.25–0.40 s, typical of 4- to 5-story buildings (category 2 according to Yegian et al. 1994b), soil amplification effects were marginal (ratio generally less than 1.5). In the period range of 0.5–0.9 s, corresponding to buildings with 6 stories and higher (category 3, Yegian et al. 1994b), soils are predicted to have had some effects on ground motions, with amplification ratios of less than 2. Thus, one could not persuasively attribute the enormous earthquake damage (where 641 buildings, about 54% of the total, either collapsed or were heavily damaged) to soil effects alone.

Fig. 11(*a*) displays the time histories of the N-S and E-W components of the soil ground motions in Leninakan, computed using the average values of shear wave velocities shown in Fig. 6. Fig. 11(*b*) shows the time histories of the inferred rock motions used in the soil-response analyses. The general frequency characteristics of these computed ground motion records are consistent with the seismoscope records that exhibit essentially only one pulse in the E-W direction but several pulses of smaller amplitude in the N-S direction. As stated earlier, soil amplification analyses show little softening taking place in the stiff soil profiles (moderately nonlinear soil behavior). Hence, both components of the calculated ground-surface time histories show no significant increase in the fundamental period of the motions. Fig. 12 compares the corresponding elastic response spectra of the N-S and E-W components. One may draw the following conclusions:

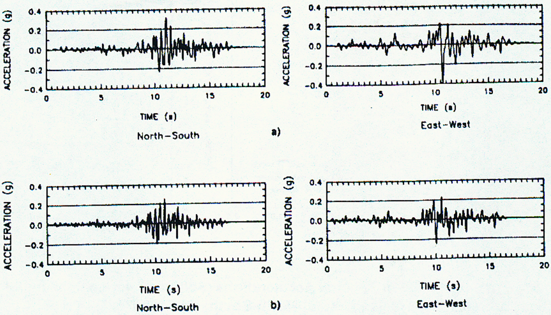


FIG. 11. Calculated Acceleration Records on: (*a*) Ground Surface; (*b*) Inferred Rock; for Leninakan

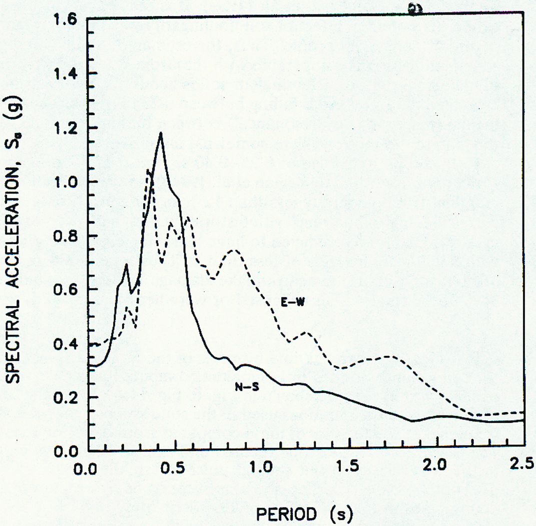


FIG. 12. Acceleration Response Spectra (5% Damping) for the Calculated Ground Surface Motion in Leninakan Using Average Shear Wave Velocities

1. In the period range of 0.25–0.4 s (4- to 5-story structures), the elastic spectral response in the two directions are comparable. Thus, both components of motion have probably caused similar levels of damage.
2. In the period range of 0.5–0.9 s (6 stories and higher buildings), the N-S component produces smaller spectral accelerations than the E-W component. However, for inelastic structures, as were the damaged buildings during the earthquake, this is probably counterbalanced by the larger number of pulses in the N-S direction.
3. The spectral values in the range of the fundamental period of the Leninakan profile (2–2.5 s) are small. Thus, in the analyses of soil effects of the deep stiff profile in Leninakan, it was not the fundamental period of the profile that was of importance, but rather what the site effect was in the period range of the buildings (up to 1.0 s).

Nevertheless, as was mentioned earlier, there is some uncertainty as to what were the exact characteristics of the two components of the rock outcrop motion (amplitude, frequency composition, number of significant pulses). To ensure that our conclusions are not sensitive to any realistic variations in the input ground motions, 1-D amplification analyses were repeated using as input a seismologically similar rock outcrop motion from the Loma Prieta earthquake. The accelerogram of Santa Cruz (Housner et al. 1990), located 20 km from the fault of this M_s = 7.1 event (compared to Leninakan's 25 km and M_s = 6.8), was scaled down by a (constant) factor of 0.61. This factor was derived from the Joyner and Boore (1988) attenuation relationship for PGA. Fig. 13(*a*) shows the rock motion spectra of the Santa Cruz record and the Ghoukasian N-S and E-W components. In Fig. 13(*b*) the spectral amplification ratios (soil/rock) corresponding to these records are compared. The results show that the ground-surface spectra and soil amplification ratios from both Santa Cruz and Ghoukasian rock motions are quite similar. Thus, our conclusions regarding soil amplification in Leninakan do not contain any bias from the utilized Ghoukasian outcrop motions.

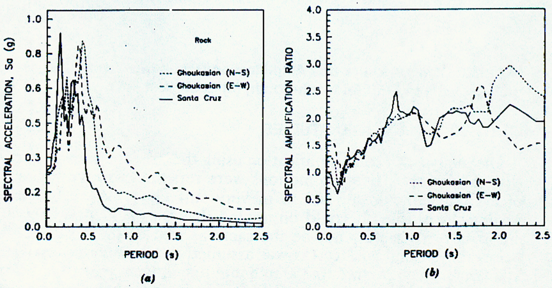


FIG. 13. Comparison of Soil Amplification Results for Leninakan Using Inferred Ghoukasian and Santa Cruz (Loma Prieta) Records after Scaling to (Common) PGA = 0.25 g; (*a*) Response Spectra on Rock Outcrop (5% Damping); (*b*) Ratio of Response Spectra (Soil/Rock).

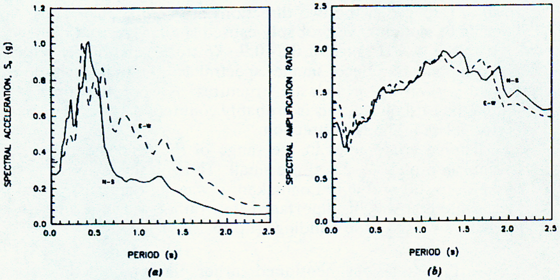


FIG. 14. Soil Amplification Results Using Only Top 150 m of Leninakan Soil Profile: (*a*) Acceleration Response Spectra (5% Damping); (*b*) Ratio of Response Spectra (Soil/Rock)

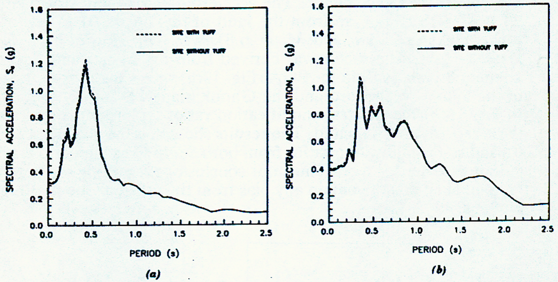


FIG. 15. Comparison of Soil Amplification Results for Leninakan Using Profiles with and without Tuff: (*a*) North-South; (*b*) East-West

FURTHER PARAMETRIC STUDIES

The analyses of soil amplification using the average shear wave velocities (Fig. 6) and rock outcrop motions were repeated to investigate the effect of excluding the lower 200 m of very stiff clays (V_s = 800 m/s) in the Leninakan profile. It could be argued that the incident waves at an outcropping of rock may not be the same as that of the base rock at 350 m below the ground surface (as was assumed in all previous analyses). Rock at an outcrop compared to 350 m depth may not only be of a different type but it may have lower shear wave velocities because of weathering and lower confining stresses. For this reason soil amplification analysis was repeated considering only the top 150 m of the Leninakan soil profile.

Fig. 14 shows the response spectra and the soil amplification ratios for the N-S and E-W components. Compared with the results of Figs. 10 and 12, the plots of Fig. 14 suggest that:

1. The response spectra in the period range of buildings in Leninakan (0.25–0.9 s), are not significantly influenced by the omission of the bottom 200 m stiff layer in the soil amplification analyses.

2. The fundamental period of the profile is smaller (about 1.3) when the bottom 200 m is not included in the amplification analysis. Analyses of microtremors and aftershock records by Borcherdt et al. (1989), show a fundamental period of 2.0–2.5 s. It is concluded that including the entire deep soil profile in soil amplification analyses results in a better estimate of the fundamental period of the profile. This may be of importance for long-period structures, founded on deep soil profiles through which the propagating incident waves are rich in long periods. Such may have been the case in Mexico City, but not in Leninakan.

Finally, soil-response analyses were performed considering the presence of a layer of tuff within the surficial soils (Fig. 6). Fig. 15 plots the response spectra for the two components and compares them with the respective spectra of the soil profiles without tuff. It is clear that the presence of (5–6 m thick) tuff in the 350 m of stiff profile in Leninakan had no appreciable effect on the calculated ground-surface motions. This conclusion agrees with the records of Borcherdt et al. (1989): microseismic motions on soil profiles with and without tuff were similar.

CONCLUSIONS

In summary, the 1-D soil amplification studies, considering the uncertainties involved in the soil properties and the ground motion characteristics in Leninakan, appear to provide reasonable results and lead to conclusions of practical significance, the most important of which are as follows:

- Values of peak ground accelerations, spectral displacements/accelerations and fundamental periods of the profiles are consistent with the level and distribution of damage, the seismoscope records and other postearthquake observations/measurements.
- The general characteristics of the computed ground-surface motions are consistent with the seismoscope records. In the E-W direction, the computed record exhibits a single major pulse whereas in the N-S direction, the pulses are smaller in amplitude but are greater in number. Hence, the two components of the ground-surface motion are predicted to have had similar effect on building damage, in accord with the damage statistics that reveal that collapse and heavy damage were independent of building orientation (Yegian et al. 1994b).
- Variations in the soil profile at shallower depth is predicted to have exerted little effect on the calculated soil amplification ratios, again in accord with the damage statistics, showing that the level of damage was not affected by the small local variations in the upper 35–50 m of this deep (350 m) stiff soil profile.
- The effect of soil amplification on the performance of the multistory buildings in Leninakan is predicted to have been small. In fact, these effects were probably even smaller since the buildings must have experienced slight nonlinearity due to cracking and yielding. The soil profile in Leninakan is very deep, but the constituent soils are

very stiff. Soil had only a limited effect on the ground motions and, thereby, cannot be solely responsible for the extensive building damage. Other factors, including the high overall level of seismic shaking and the high seismic vulnerability of the vast majority of buildings, must have been important contributors to the destruction of Leninakan.

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 ARMNIISA, Stepan Zargaryan of Yerevan Polytech. Inst., Lenser Aghalovyan and Arkady Karakhanian of Armenia Academy of Sciences, Vartkes Avetisian of Univ. of Yerevan, Hakob Aloyan of Architectural and Civil Engrg. Inst. of Yerevan, Vincent Murphy of Weston Geophysical Corp., and Dean Paul King of Northeastern University.

APPENDIX. REFERENCES

Arnold, P., Vanmarcke, E. H., and Gazetas, G. (1976). "Frequency content of ground motions during the 1971 San Fernando earthquake." *Res. Rep. R76-3*, Mass. Inst. of Tech., Cambridge, Mass.

Bard, P. Y., and Gariel, J. C. (1986). "The two-dimensional resonance of sediment-filled valleys," *Bull. Seism. Soc. Am.*, 76, 343–346.

Borcherdt, R. D., ed. (1989). "Results and data from seismologic and geologic studies following earthquake of December 7, 1988, near Spitak, Armenia S. S. R.," *Open File Rep. 89-163A*, 1, U.S. Geological Survey, Menlo Park, Calif.

Campbell, K. W. (1991). "An empirical analysis of peak horizontal acceleration for the Loma Prieta earthquake of 18 October 1989." *Bull. Seism. Soc. Am.*, 81(5), 1838–1858.

Finn, W. D. L., and Nichols, A. M. (1988). "Seismic response of long period sites: lessons from the September 19, 1985 Mexico earthquake." *Can Geotech. J.*, 128–137.

Gazetas, G., and Yegian, M. K. (1979). "Shear versus Rayleigh waves in soil dynamics." *J. Geotech. Engrg. Div.*, ASCE, 105(12), 1455–1470.

Gazetas, G., Dakoulas, P., and Papageorgiou, A. S. (1990). "Local-soil and source-mechanism effects in the 1986 Kalamata (Greece) earthquake." *Earthquake Engrg. Soil Dyn.*, 19, 431–456.

Hamasian, R. H. (1990). The parameters of seismic influence in Leninakan during the Spitak earthquake of December 7, 1988 in Armenia." *Proc., 7th European Earthquake Engrg. Conf.*, 9, U.S.S.R. Ministry of Construction, Moscow, Russia, 85–90.

Housner, G. W., Chairman (1990). "Competing against time." *Report to Gov. George Deukmejian from the Governor's Board of Inquiry on the 1989 Loma Prieta earthquake*, Thiel, C. C., ed., Office of the Planning and Research Services, State of California, North Highlands, Calif.

Idriss, I. M. (1990). "Response of soft soil sites during earthquakes," *Proc. H. B. Seed Memorial Symp.*, Vol. 2, BiTech Publishers, Vancouver, British Columbia, Canada, 273–289.

Joyner, W. B., and Boore, D. M. (1988). "Measurement, characterization, and

prediction of strong ground motion." *Proc. Earthquake Engrg. and Soil Dyn.*, J. L. Von Thun, ed., ASCE, New York, N.Y., 43–102.
Martirossian, R. P., Mkhitarian, L. A., Tonoyan, K. A., and Grigorian, F. K. (1989). "Analysis of the instrumental observations of the Spitak December 7, 1988 earthquake." *Journal Earth Sciences, Bulletin, Academy of Sciences*, Yerevan, Armenia, 42(4), 67–73 (In Russian).
Sanchez-Sesma, F. J., Campillo, M., Bard, P. Y., Gariel, J. C., and Aki, K. (1989). "The great 1985 Michoacan earthquake: a unified approach considering source, path, and site effects." *Engineering Seismic and Site Response*, Computational Mechanics Publishers, Southampton, U.K., 43–75.
Schnabel, P. B., Lysmer, J., and Seed, H. B. (1972). "SHAKE: a computer program for earthquake response analysis of horizontally layered sites." *Rep. No. EERC 72-12*, Earthquake Engineering Research Center, Univ. of California, Berkeley, Berkeley, Calif.
Seed, H. B., and Idriss, I. M. (1970). "Soil moduli and damping factors for dynamic response analysis." *Rep. No. EERC 70-10*, Earthquake Engineering Research Center, Univ. of Calif, Berkeley, Berkeley, Calif.
Silva, W. J. (1989). "Site geometry and global characteristics," *Proc. NSF/EPRI Workshop on Dyn. Soil Prop. and Site Characterization*, EPRI, Palo Alto, 1, 6.1–6.79.
Vucetic, M., and Dobry, R. (1991). "Effect of soil plasticity on cyclic response," *J. Geotech. Engrg.*, ASCE, 117(1), 89–107.
Yegian, M. K., Ghahraman, V. G., and Gazetas, G. (1994a). "1988 Armenia earthquake, I: seismological, geotechnical and structural overview." *J. Geotech. Engrg.*, ASCE, 120(1), 1–20.
Yegian, M. K., Ghahraman, V. G., and Gazetas, G. (1994b). "1988 Armenia Earthquake, II: damage statistics versus geologic and soil profiles." *J. Geotech. Engrg.*, ASCE, 120(1), 21–45.
Yegian, M. K., Ghahraman, V. G., and Gazetas, G. (1994c). "Seismological, soil and valley effects in Kirovakan, 1988 Armenia earthquake." *J. Geotech. Engrg.*, ASCE, 120(2), 349–365.