1988 ARMENIA EARTHQUAKE. II: DAMAGE STATISTICS VERSUS GEOLOGIC AND SOIL PROFILES

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ABSTRACT: This is a companion paper dealing with engineering aspects of the surface-wave magnitude $M_s = 6.8$ 1988 Armenia earthquake. The first paper, by the same writers and in the same journal issue, provides an overview of the seismological, geological, geotechnical, and structural aspects of the earthquake. The present paper offers building-damage statistics in the cities of Leninakan and Kirovakan, Armenia. These statistics are qualitatively correlated to the soil profiles to assess the potential importance of any soil amplification effects. The results indicate that in Leninakan, located in a very wide valley, the soil had some effect but could not have been solely responsible for the tremendous damage in the city. In Kirovakan, the soil profiles vary significantly within the city. Damage was primarily within a limited region where there is a valley filled with stiff clays and having width-to-maximum-depth ratio of approximately 5:1. In this region, 74% of the buildings collapsed or were heavily damaged. Two subsequent papers by the present writers, in the following month's issue of the journal, describe theoretical analyses of soil amplification in Leninakan and Kirovakan. The results of these analyses are used to determine if current state-of-practice procedures could explain the damage statistics and their local and geographic distribution described in the present paper.

INTRODUCTION

In the first paper of this series (Yegian et al. 1994a), the writers presented an overview of the seismological, geological, geotechnical, and structural aspects of the 1988 Armenia earthquake. The earthquake destroyed over 1,000 buildings in the cities of Spitak, Leninakan, and Kirovakan, Armenia; and leveled thousands of single family dwellings in small villages scattered within 40 km of the earthquake fault.

The extensive destruction of engineered buildings and the variations in the distribution of damage from city to city and, particularly, from region to region within the city of Kirovakan, raised many questions. No single factor could alone adequately explain the extent and spatial variation of the seismic damage; geological, topographic, geotechnical, and structural conditions have all played a role and must be viewed together to understand why things happened the way they did.

The present paper starts with an analysis of the recorded seismic ground motions, followed by an evaluation of the potential geologic and soil effects on the observed building damage. Detailed damage statistics are presented for Leninakan and Kirovakan and are related to the local geological and soil profiles, for a first qualitative assessment of potential soil effects.

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GROUND MOTIONS

Ground motions during the Armenia earthquake were recorded only in two stations: in Ghoukasian, Armenia (25–30 km from the main fault rupture), and in the capital city of Yerevan, Armenia (85 km from the fault). The Ghoukasian record was analyzed and used in subsequent studies of ground motion attenuation and soil amplification. The two components, north-south (N-S) and east-west (E-W) of the main shock record have peak ground accelerations of about 0.20 g and 0.19 g, respectively. Fig. 1 shows the digitized portion of the two recorded time histories (A. Der-Kiureghian, personal communication, 1989). Note that the N-S component is rich in higher frequencies and contains significantly more pulses than the E-W component of the motion. These differences are reflected in the acceleration response spectra of the two components, which are plotted in Fig. 2. Indeed, the E-W component exhibits an unusually long predominant period (for what was initially believed to be a rock motion). Questions raised by the writers were resolved by subsequent geological and geotechnical subsurface investigation that revealed the recording station at Ghoukasian was on a deposit of 35–40 m of alluvium and lake-bed clays. Fig. 3 portrays the geologic profile of Ghoukasian. Notice the intermittent layers of alluvium and lake-bed clays overlying bedrock. Fig. 4 and Table 1 show the geotechnical profile and properties, respectively, at the recording-station site.

Since the Ghoukasian record is the only good-quality strong-motion record of the Armenia earthquake, it was important to remove any of the soil amplification effects from the recorded motions and obtain a reference rock motion. As the ratio of width of the valley to soil thickness in Ghoukasian is about 80:1, one-dimensional (1-D) wave propagation analyses were performed with the computer program SHAKE (Schnabel et al. 1972) to obtain a possible rock-outcrop motion, by deconvolution. The shear modulus and damping ratio versus shear strain curves presented by Seed and Idriss (1970) for the gravelly sandy alluvium and by Vucetic and Dobry (1991) for the silty low-plasticity clays (plasticity index ≈20) were used.

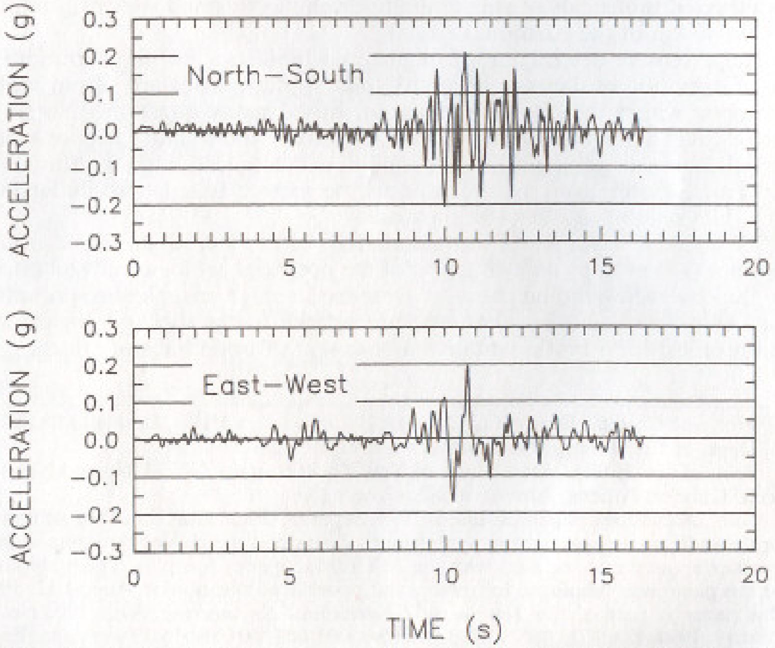


FIG. 1. Two Horizontal Components of Ground Motion Recorded in Ghoukasian

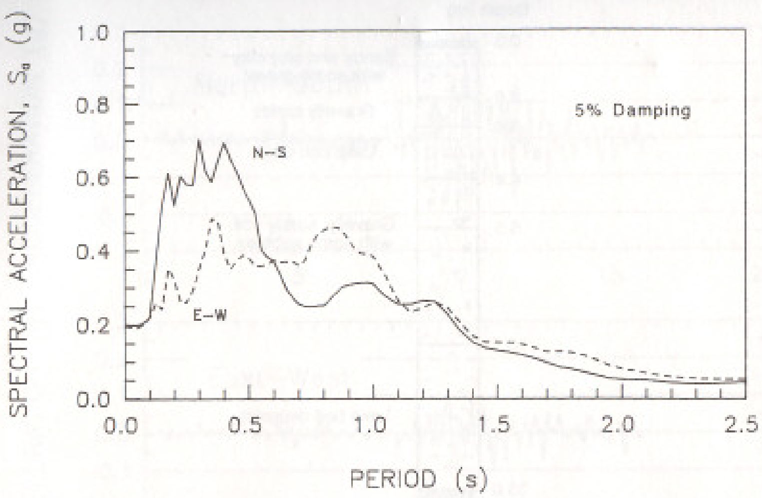


FIG. 2. Response Spectra of Ground Motion Recorded in Ghoukasian

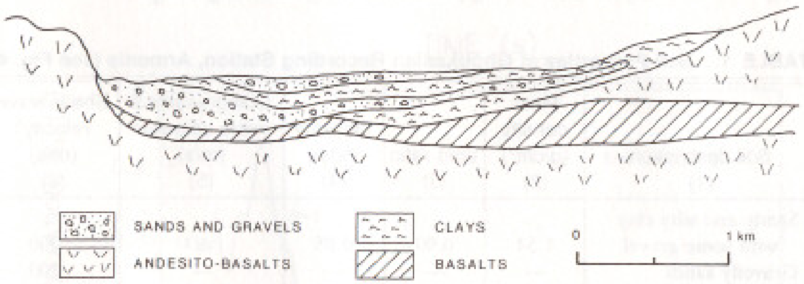


FIG. 3. Geologic Section of Ghoukasian Valley (Vertical Scale Is Exaggerated 10 Times)

Fig. 5 shows the computed outcrop rock time histories and their respective response spectra for the N-S and the E-W components. Fig. 6 plots the ratios of each response spectrum at the ground surface divided by the corresponding calculated response spectrum at the rock outcrop. Note in this figure that the Ghoukasian site has a relatively long calculated fundamental period, ranging between 0.8 s and 1.2 s, which is arguably responsible for the presence of high-period pulses in the surface recordings of Fig. 2.

Fig. 7 compares the normalized average spectrum computed for rock at Ghoukasian with the mean and mean-plus-standard-deviation spectral shapes obtained by Seed et al. (1976) from other rock motions recorded mainly in the Western U.S. Also shown are the recent recordings on rock at similar distances in the 1989 Loma Prieta (Housner et al. 1990), and the 1990 Manjil,

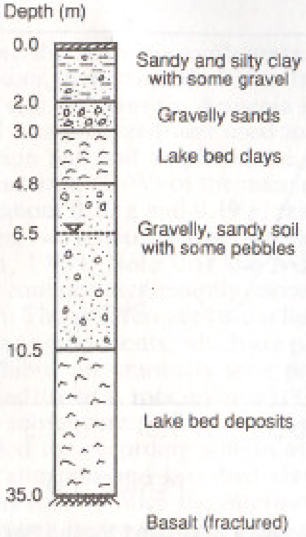


FIG. 4. Soil Profile at Ghoukasian Recording Station

TABLE 1. Soil Properties at Ghoukasian Recording Station, Armenia (see Fig. 4)

Soil description (1)	Mass density (g/cm³) (2)	Void ratio (3)	Liquidity index (4)	Compressional wave velocity[a] (m/s) (5)	Shear wave velocity[b] (m/s) (6)
Sandy and silty clay with some gravel	1.54	0.99	0.85	600	200
Gravelly sands	—	—	—	—	200
Lakebed clays	1.77	1.05	0.7	—	200
Gravelly, sandy soil with some pebbles	1.8	1.01	—	1,000	300
Lakebed deposits	1.77	1.05	0.85	1,220	300
Basalt	2.6	—	—	2,500	1,000

[a] Measured.
[b] Estimated.

Iran (A. Naderzadeh, personal communications, 1991), earthquakes. (Recall that the latter occurred in the same tectonic region as Armenia.) Notice the overall similarity in shape of all these rock spectra.

Fig. 8 plots the peak ground accelerations (PGA) recorded on rock in Yerevan, on soil in Ghoukasian, and the computed PGA on rock in Ghoukasian, as a function of the closest horizontal distance to surface trace of the fault. They are compared with the attenuation relationships of Idriss (1990), Joyner and Boore (1988), and a rock motion recorded during the 1990 Manjil earthquake. The Ghoukasian and Yerevan points seem to be consistent with worldwide attenuation relationships; but they are not sufficient to fully define the attenuation of PGA in Armenia. To augment the

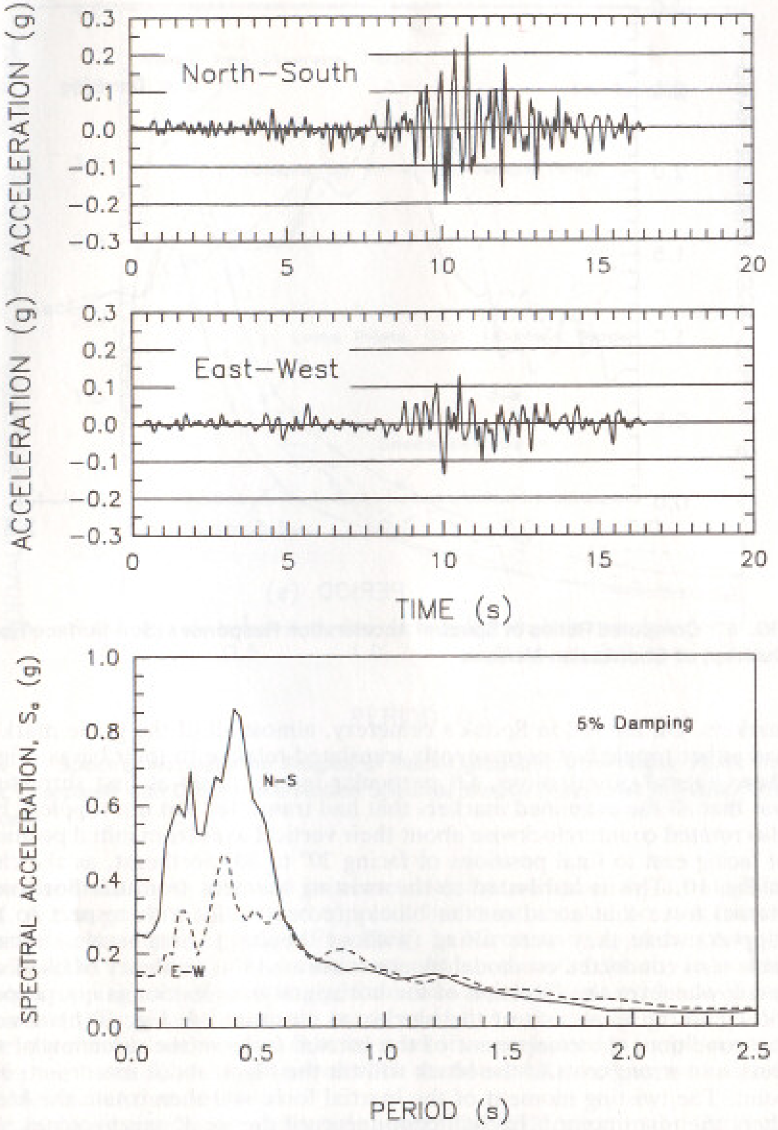


FIG. 5. Time Histories and Response Spectra of Back-Calculated Rock Outcrop Motion in Ghoukasian

PGA data, the writers investigated and analyzed the response of grave markers in cemeteries in Armenia.

Response of Grave Markers

During their trip to Armenia, the writers visited the cemeteries in Spitak, Leninakan, and Kirovakan and observed the seismic behavior of the grave

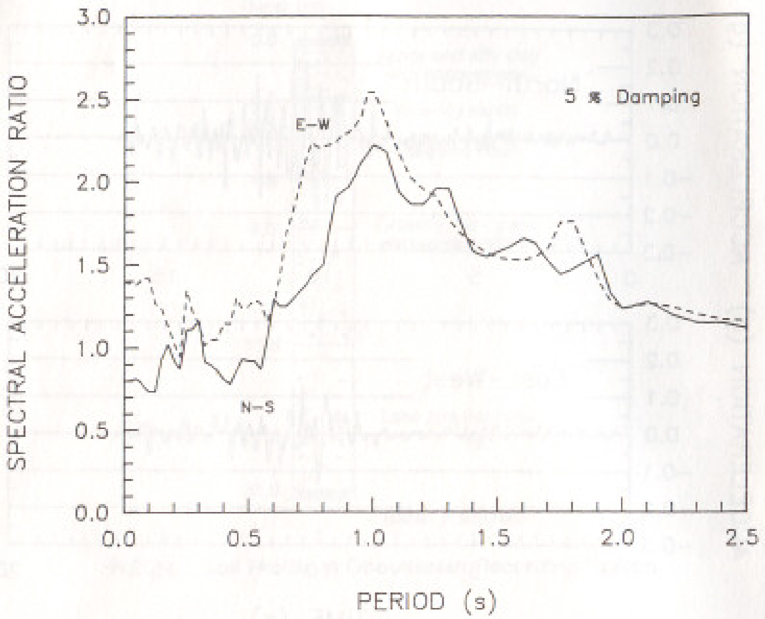


FIG. 6. Computed Ratios of Spectral Acceleration Responses (Soil-Surface/Rock-Outcrop) of Ghoukasian Motions

markers. On the hill in Spitak's cemetery, almost all of the grave markers had either toppled or permanently translated relative to their bases. Fig. 9 shows typical observations. Of particular interest, and at first surprising, was that all the examined markers that had translated but not toppled, had also rotated counterclockwise about their vertical axes from initial positions of facing east to final positions of facing 20° to 30° northeast, as sketched in Fig. 10. This is attributed to the twisting moment from the horizontal inertial force that acted on the blocks (eccentrically with respect to the support) while they were tilting (without toppling). Small-scale shaking-table tests conducted on model blocks confirmed this tendency of blocks to rotate whenever the direction of the horizontal base motion is not perpendicular to the weak axis of the blocks, as illustrated in Fig. 10(*b*). Under this condition, the component of the inertial force in the direction of the weak and strong axes of the block will tilt the block about its corner pivot point. The twisting moment of the inertial force will then rotate the block about the pivot point. This will continue until the weak axis becomes perpendicular to the direction of base motion. Then, due to symmetry, the block will simply rock.

From such model tests it was concluded that the direction of the axis perpendicular to the faces of the markers in their final positions in the cemeteries must essentially coincide with the direction of the predominant motion. In Spitak, this direction was found to be nearly perpendicular to the nearby segment of the thrust fault. This suggests a strong azimuthal variation of the ground motions in the near field during the Armenia earthquake. A similar observation was made by Arnold et al. (1976) with the 1971 San Fernando earthquake ground motions.

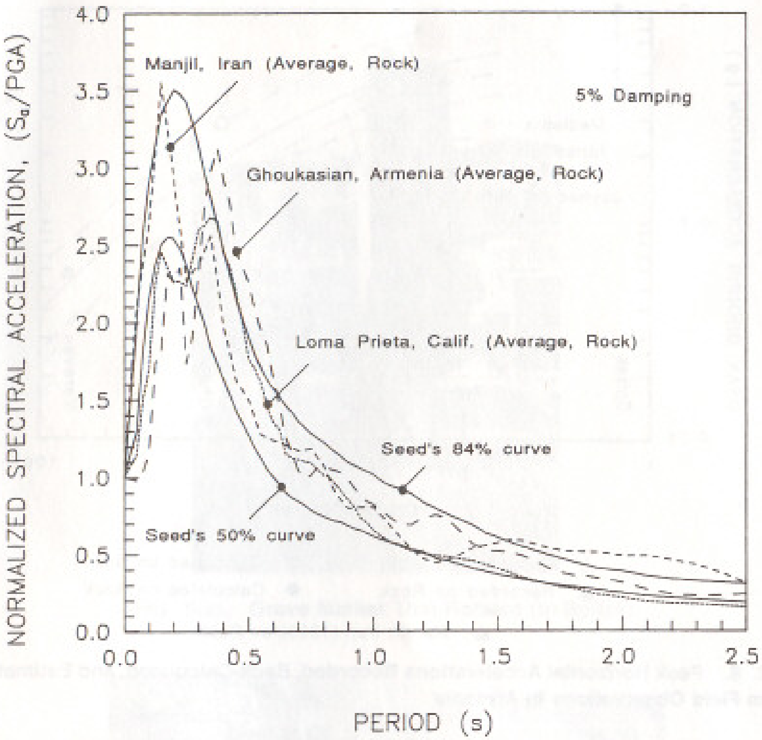


FIG. 7. Spectral Acceleration Shapes of Back-Calculated Ghoukasian Rock Motion, Compared with Other Rock-Motion Spectral Shapes (Recorded at Similar Distances)

In Leninakan, the city and its cemeteries are underlain by an old lake bed. A few grave markers had toppled; but most showed no movements relative to their granite bases [Fig. 9(*c*)]. In Kirovakan, approximately 10 km from the causative fault, an old cemetery northeast of the city is located on outcropping rock. Surprisingly, there was absolutely no evidence of any permanent displacements of the markers of this cemetery [Fig. 9(*d*)]. We carefully checked and verified that the markers were indeed in simple contact with their bases. This suggests that rock motions in Kirovakan were significantly smaller than in Spitak.

Valuable (even if somewhat crude) quantitative information on the most likely levels of ground excitation at the three cemetery sites can be extracted from the observed patterns of behavior of their grave markers. To this end, we conducted a series of parametric shaking-table tests on scaled-model blocks, and derived lower and upper bounds for the values of PGA. These limiting accelerations correspond to the response of different size model blocks that toppled or rotated. The results indicate that in Spitak the PGA must have exceeded 0.40 g to topple certain slender blocks [Fig. 9(*b*)], but was less than 1.0 g otherwise the less slender blocks that rotated would have toppled [Fig. 9(*a*)]. In Leninakan the grave markers that toppled indicate that the PGA on the soil surface must have been in the range of 0.30 g–

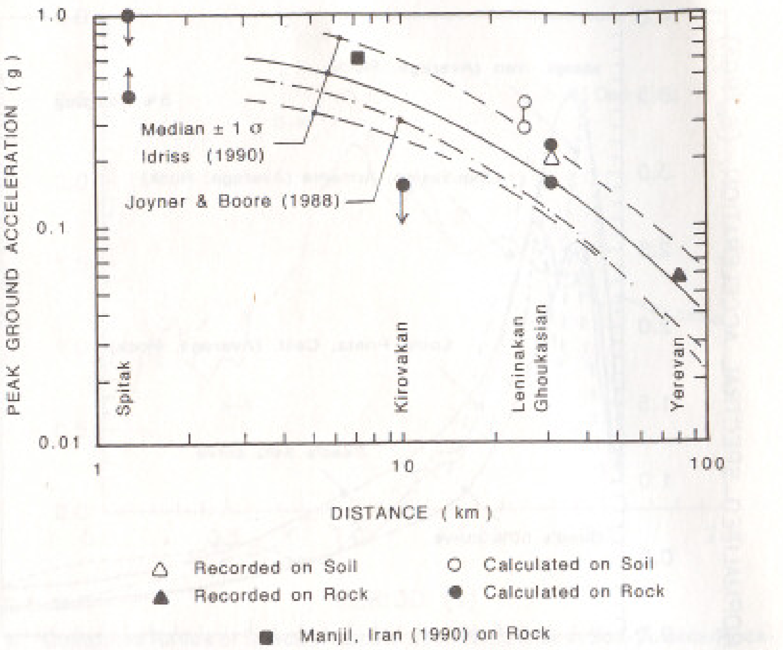


FIG. 8. Peak Horizontal Accelerations Recorded, Back-Calculated, and Estimated from Field Observations in Armenia

0.35 g. In Kirovakan, where no grave marker experienced any relative movement with respect to its base, the acceleration was estimated to have been less than 0.15 g. On the other hand, however, since buildings founded on rock and shallow stiff soils in Kirovakan did experience some cracking and other minor damage, PGA must have exceeded 0.10 g. The fact that seismic excitation in Kirovakan was about one-half of that in Leninakan is consistent with the observed differences in degree of damage in the two cities, as will be shown in Yegian et al. (1994a, b).

These calculated peak ground accelerations are depicted in the attenuation graph of Fig. 8. Notice that the Spitak and Leninakan PGA values from analysis of grave-marker response and from the records are consistent with the data from the 1990 Manjil earthquake and with the worldwide attenuation relationships of Idriss (1990) and Joyner and Boore (1988). However, it is evident that Kirovakan experienced much smaller acceleration levels than expected based on available attenuation relationships. The causes of such small acceleration levels in Kirovakan are not known; alternative hypotheses are developed in Yegian et al. (1994c).

DAMAGE STATISTICS

The Armenia earthquake inflicted heavy casualties, having occurred in a densely populated area, with three major cities in which hundreds of residential multistory structures collapsed or were damaged. Village houses, typically single-story unreinforced stone-masonry structures, were also damaged or collapsed. Because of the enormity of the numbers and variability

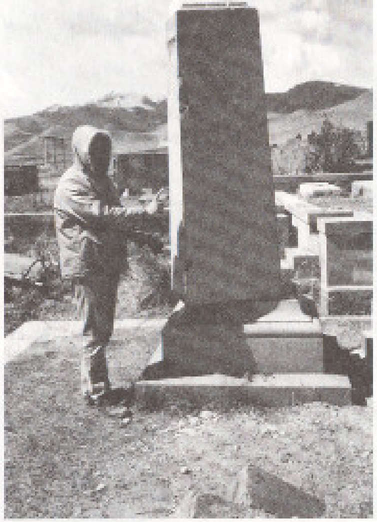


FIG. 9(*a*). Grave Marker That Rotated (in Spitak)

FIG. 9(*b*). Grave Marker That Toppled (in Spitak)

in construction type and quality of such single-story residential houses, these structures were excluded from the analysis of damage statistics. The present study considers almost all of the multistory structures including residential, commercial, industrial, school, and hospital buildings in Spitak, Leninakan, and Kirovakan. The engineers and scientists of Research Institute for the Ministry of Construction in Armenia (ARMNIISA) compiled detailed large scale maps (2 m by 4 m) for each city. Depending on the level of damage each building was assigned to one of four damage states (A, B, C, or D) ranging from worst to least damage.

In the former Soviet Union, of which Armenia was part, only a limited number of types of buildings were constructed, using standardized proce-

FIG. 9(*c*). Grave Marker That Toppled (in Leninakan)

FIG. 9(*d*). Grave Marker That Did Not Topple (in Kirovakan)

dures for both design and construction. The main types of buildings common in the earthquake region of Armenia are described in Yegian et al. (1994a). For presenting damage statistics, these buildings were categorized by their height as follows:

- Category 1: one- to three-story reinforced or unreinforced stone or concrete structures including residential (except single-story houses), commercial, and industrial buildings of various types
- Category 2: four- to five-story structures, predominantly unreinforced and partially reinforced masonry structures of the series 450 and 451 type (Yegian et al. 1994a)
- Category 3: six-story and higher buildings, predominantly prefabricated concrete-frame buildings (series 110, 111, and 112); this group includes a few of series 450 and 451, and two lift-slab buildings.

An overview of the damage statistics in Spitak, Leninakan, and Kirovakan is depicted in Fig. 12 of the companion paper [Yegian et al. (1994a)]. In Spitak almost 90% (238 buildings) of the total 263 buildings either collapsed or were damaged beyond repair. In Leninakan, which is about 25 km from the fault, about 54% (641 buildings) of the total 1,198 buildings collapsed or were heavily damaged. Surprisingly, in Kirovakan, which is only about 10 km from the fault, 26% (158 buildings) of the total 598 buildings collapsed or were heavily damaged.

These overall damage statistics for the three major cities raise the questions: Why so much destruction? and why was total damage in Kirovakan (despite its closer proximity to the fault) so much less than in Leninakan?

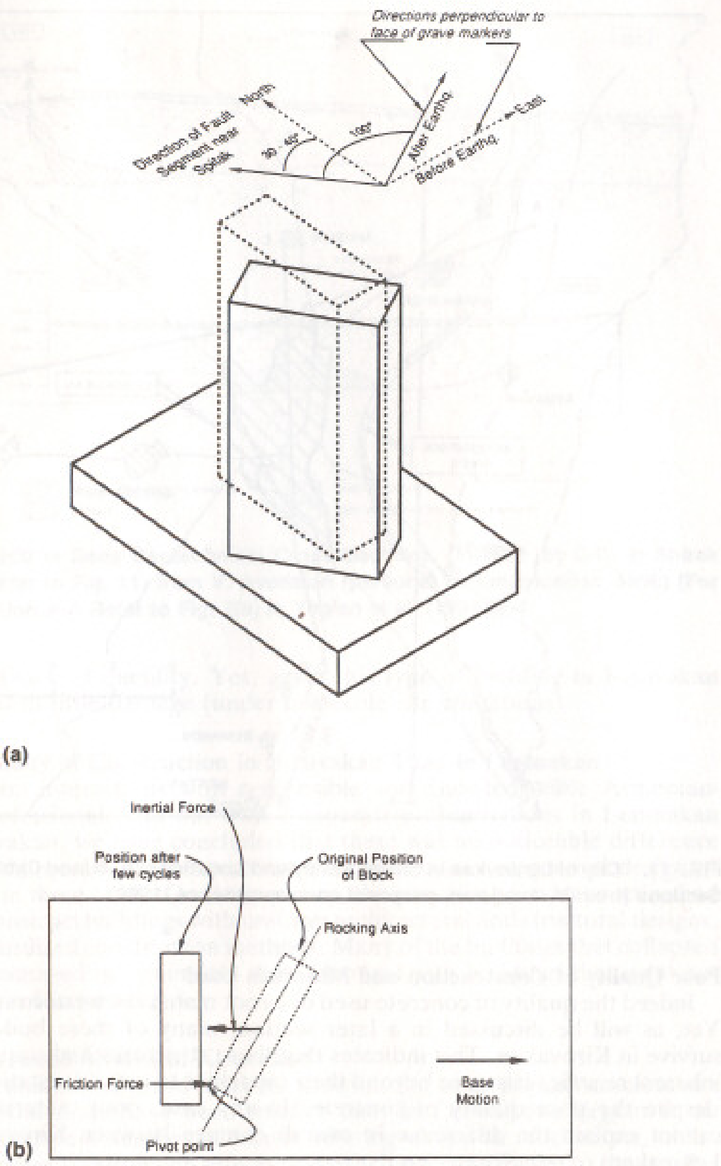


FIG. 10. Illustration of Response of Grave Markers: (*a*) in Spitak Cemetery; (*b*) on Shaking Table

Soviet engineers, local Armenian government officials and various investigators from around the world who traveled to Armenia after the earthquake suggested a number of possible factors that may have contributed to the destruction. A list of four factors and the writers' opinion on their likely roles follows.

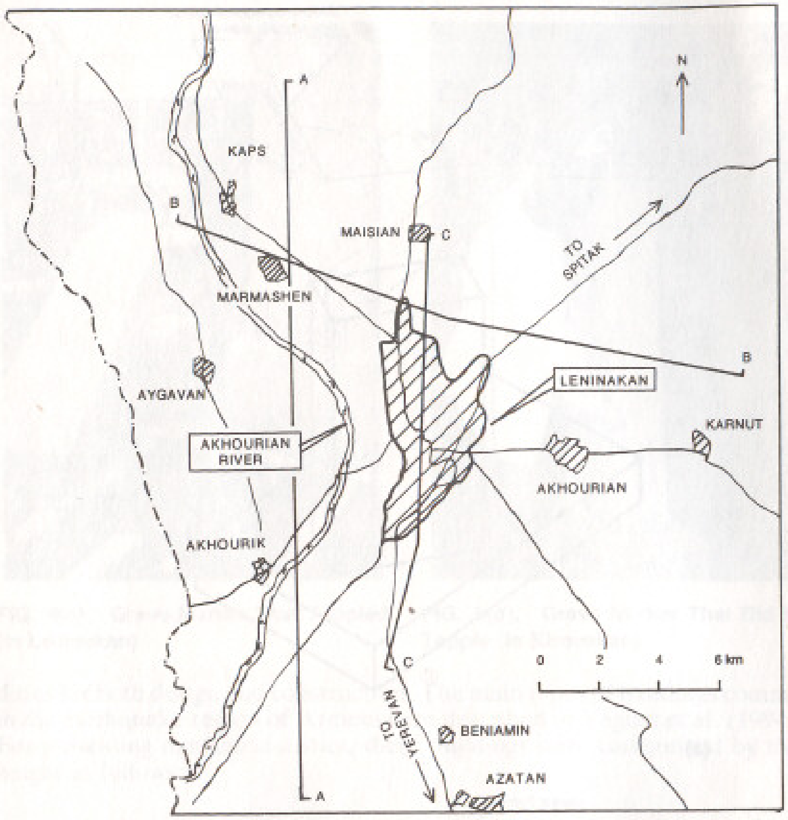


FIG. 11. City of Leninakan in Shirak Valley and Locations (A, B, and C) of Geologic Sections (from V. Avetisian, personal correspondence, 1990)

Poor Quality of Construction and Materials Used

Indeed the quality of concrete used does not match the western standards. Yet, as will be discussed in a later section, many of these buildings did survive in Kirovakan. This indicates that these structures had some level of inherent seismic resistance beyond their capacities to resist the static loads—despite the poor quality of concrete. In any case, poor material quality cannot explain the difference in overall damage between Kirovakan and Leninakan.

Deficiencies of Structural System

The seismic code of the former Soviet Union was clearly deficient. Given the historic seismicity of the region (Yegian et al. 1994a), the design base shear coefficients of 0.025 for Spitak and Kirovakan and 0.05 for Leninakan were unrealistically small. In addition, the utilized structural design concepts did not reflect seismic considerations. For example, the precast concrete frame buildings (of the type referred to as series 110–112) lack the proper seismic provisions, and their design had many deficiencies including poor

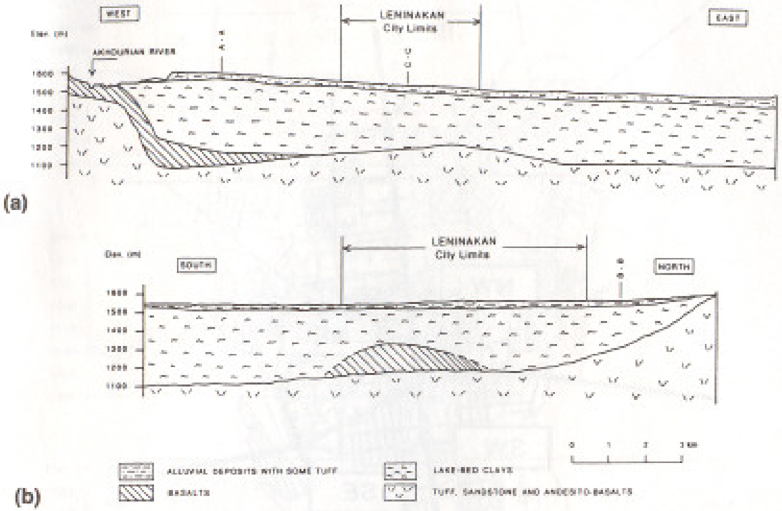


FIG. 12. 500 m Deep Geotechnical Cross Sections: (*a*) B-B; (*b*) C-C; in Shirak Valley—Refer to Fig. 11; from V. Avetisian (personal communication, 1990) [For Cross Section A-A Refer to Fig. 7(*a*) in Yegian et al. (1994a)]

joints and lack of ductility. Yet, again this type of building in Kirovakan survived with little damage (under favorable site conditions).

Better Quality of Construction in Kirovakan Than in Leninakan

Based on interactions with responsible and knowledgeable Armenian/Soviet professionals and our own comparative observations in Leninakan and Kirovakan, we have concluded that there was no noticeable difference either in the quality of construction materials, or in the general design of buildings in these cities. On the contrary, the prevailing Soviet practice had been to construct buildings with uniform architectural and structural designs, and standardized construction methods. Many of the buildings that collapsed or were damaged in Leninakan were identical with buildings that were not damaged in Kirovakan.

Smaller Ground Motion in Kirovakan

As the analysis of grave markers showed, the peak ground acceleration in Kirovakan must have been smaller than in Leninakan. Yegian et al. (1994c) describe a number of factors relating to source mechanism, radiation, and wave transmission effects that may have contributed to the smaller rock acceleration, thus lesser damage, in Kirovakan than in Leninakan.

Soil Amplification Effects

Soil conditions in Spitak, Leninakan, and Kirovakan were different. Spitak, located in the Pambak Valley, is on 120 to 150 m of alluvium. Because of its close proximity to the fault it has certainly experienced very large accelerations, resulting in the destruction of 90% of its multistory buildings. This is also confirmed by the previously described analysis of the response of grave markers. Thus, it would be extremely difficult to assess the effect

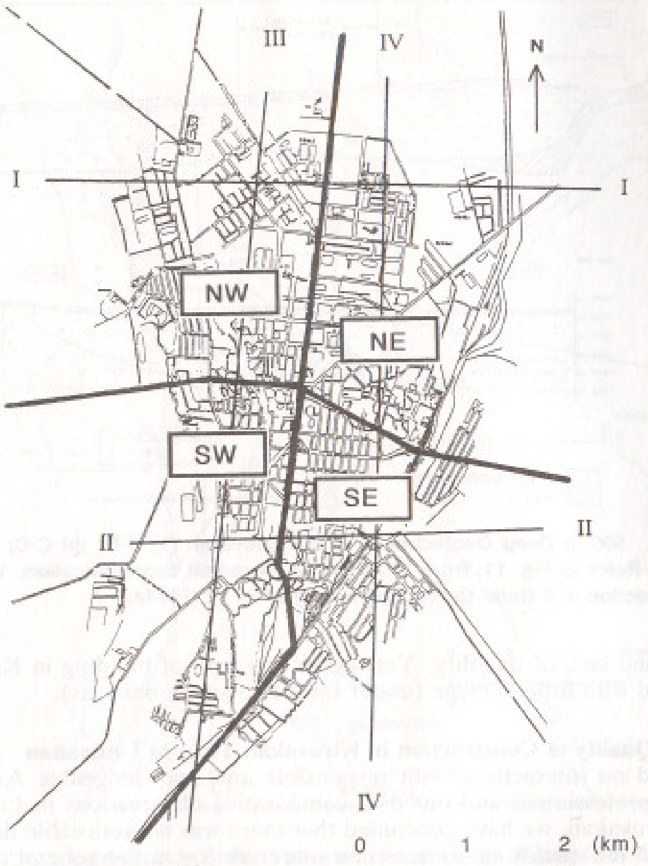
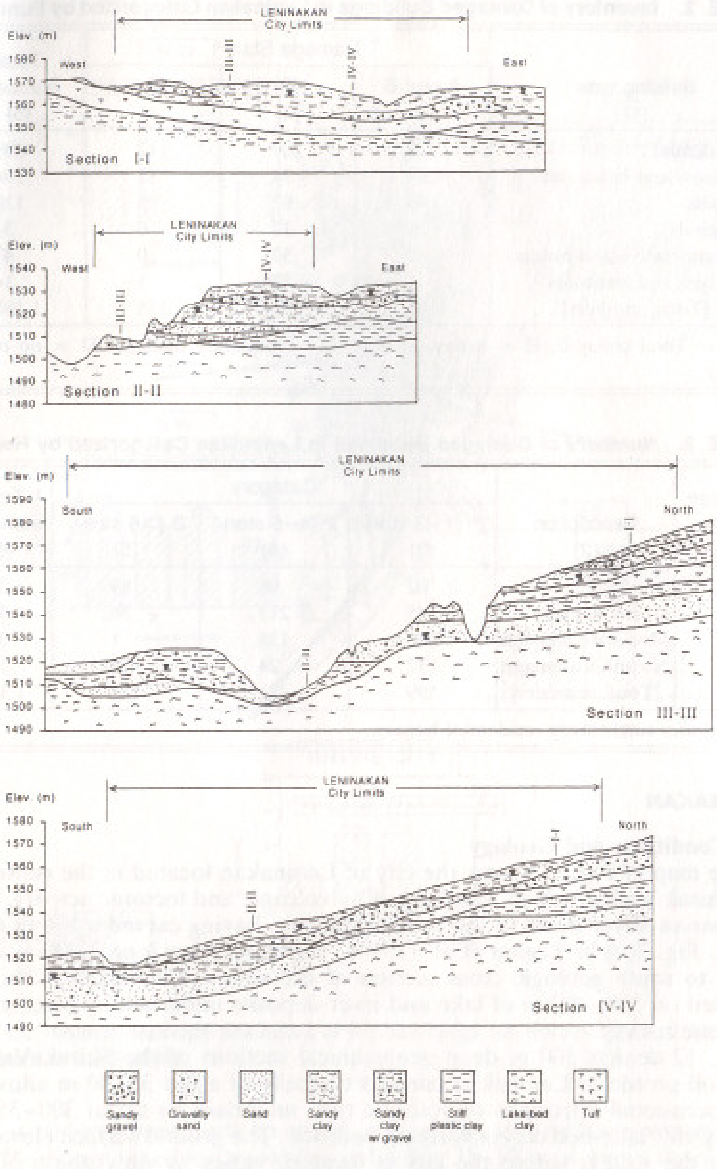


FIG. 13. Leninakan Divided into Four Quadrants and Location of Geotechnical Profiles

of the soil conditions in Spitak. However, the degree to which soil conditions were responsible for the extent and the distribution of damage in Leninakan and Kirovakan remains an important question.

The writers have expended a major research effort aimed at answering these questions. The various investigations made for this purpose include:

1. Geologic and geotechnical exploration and characterization of numerous subsurface profiles in Leninakan and Kirovakan.
2. Detailed comparative studies to reconcile building damage statistics with site conditions in Leninakan and Kirovakan.
3. Theoretical analyses of (1-D and 3-D) soil amplification to provide explanations for the observed extent and geographic distribution of damage and to show whether current state-of-practice methods are capable of predicting such effects.



Note: Vertical scale is exaggerated 25 times.

FIG. 14. Geotechnical Profiles through Leninakan Along Lines I, II, III, and IV—Refer to Fig. 13 (from Avetisian 1990)

The remainder of this paper presents results from 1 and 2, while the papers by Yegian et al. (1994b, c) describe the soil amplification studies for Leninakan and Kirovakan, respectively.

TABLE 2. Inventory of Damaged Buildings in Leninakan Categorized by Function

Building type (1)	Damage State[a] A and B (2)	C (3)	D (4)	Total numbers (5)
Residential	378	209	112	699
Business and industrial	199	74	11	284
Schools	40	62	18	120
Hospitals	16	12	6	34
Administrative and hotels	7	30	10	47
Colleges and institutes	1	12	1	14
[Total numbers]	641	399	158	1,198

[a] A = Total collapse; B = heavy damage; C = moderate damage; D = no minor damage.

TABLE 3. Numbers of Damaged Buildings in Leninakan Categorized by Height

Damage state (1)	Description (2)	Category 1[a] (1–3 story) (3)	2 (4–5 story) (4)	3 (>6 story) (5)	Total numbers (6)
A	Total collapse	62	98	89	249
B	Heavy damage	145	211	36	392
C	Moderate damage	260	138	1	399
D	No/minor damage	132	24	2	158
—	[Total numbers]	599	471	128	1,198

[a] Excludes single story residential houses.

LENINAKAN

Site Conditions and Geology

The map of Fig. 11 shows the city of Leninakan located in the center of the Shirak Valley, which was formed by volcanic and tectonic activity. The Akhourian River flows to the west of the city, having carved a 100 m deep gorge. Fig. 7(*a*) in Yegian et al. (1994a) shows a 20 km long 3,000 m deep north to south geologic cross section of the valley. Leninakan is shown, founded on 300–400 m of lake and river deposits underlain by basalts and Neocene rocks.

Fig. 12 depicts 500 m deep geotechnical sections of the Shirak Valley. The soil profile in Leninakan consists typically of a top 35–50 m alluvium with occasional intrusions of volcanic tuff, underlain by about 300–350 m of very stiff lake-bed clays overlying bedrock. The ground surface elevation within the valley, where the city is located, varies by only about 50 m. Outcropping of rock can only be observed in 10 km from Leninakan.

Extensive geotechnical investigations, performed prior to and after the earthquake, provided valuable data for describing the soil conditions in Leninakan. Numerous shallow and deep boreholes were used to capture the variability in surficial (top 35–50 m) soils within the city. The results clearly show that soil profiles do vary from north to south, and from east to west. To investigate the effects of such differences in local soil profiles on distribution of damage, the city map was subdivided into four regions as shown in Fig. 13. The figure also shows the locations of four geotechnical sections (two extending from east to west and two from north to south), the profiles of which are portrayed in Fig. 14, showing the local variations in the top 35–50 m of soil in the city. In general, this deposit consists of alluvium with intrusions of volcanic tuff and sands. The 5–10 m thick tuff is found near the ground surface in the western part of the city; in the east, it becomes thinner and penetrates deeper in the profile. In the southern region of the city, the tuff disappears and is replaced by sands deposited by meandering of old and present rivers. Ground water in Leninakan flows from the east to the west into the Akhourian River. The depth of the ground-water table ranges between 4 and 8 m.

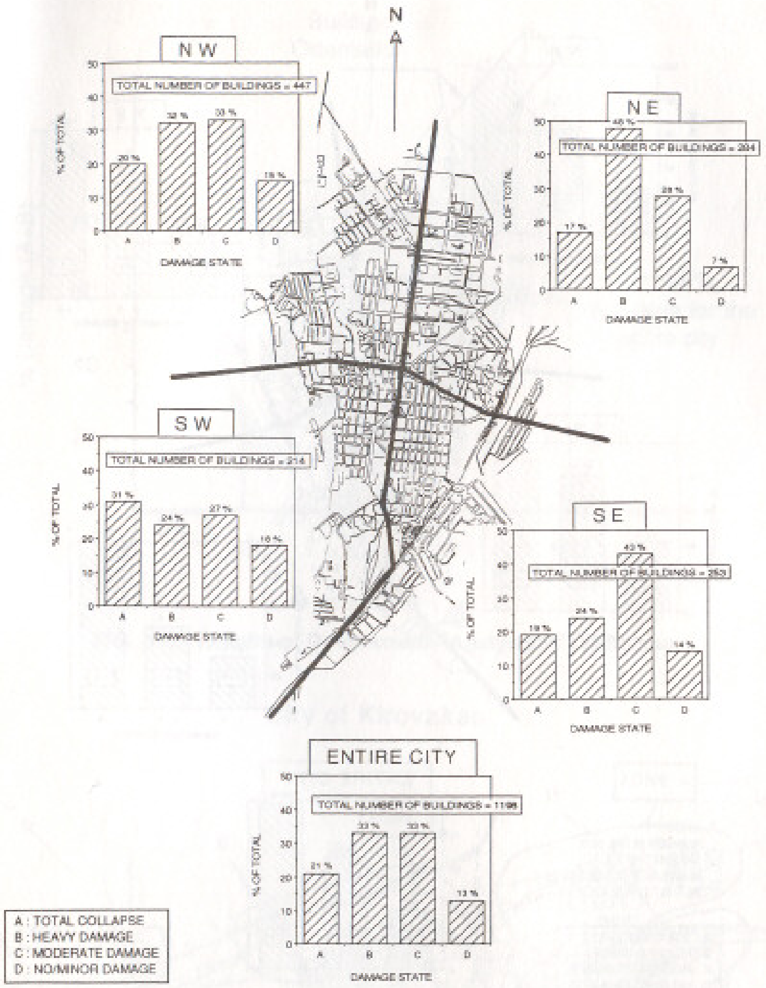


FIG. 15. Overall Damage Statistics of All Buildings for Entire City and for Each Quadrant in Leninakan

In summary, there are some variations in the site conditions within the top 35–50 m of the soil profile in Leninakan. Did they have any significant

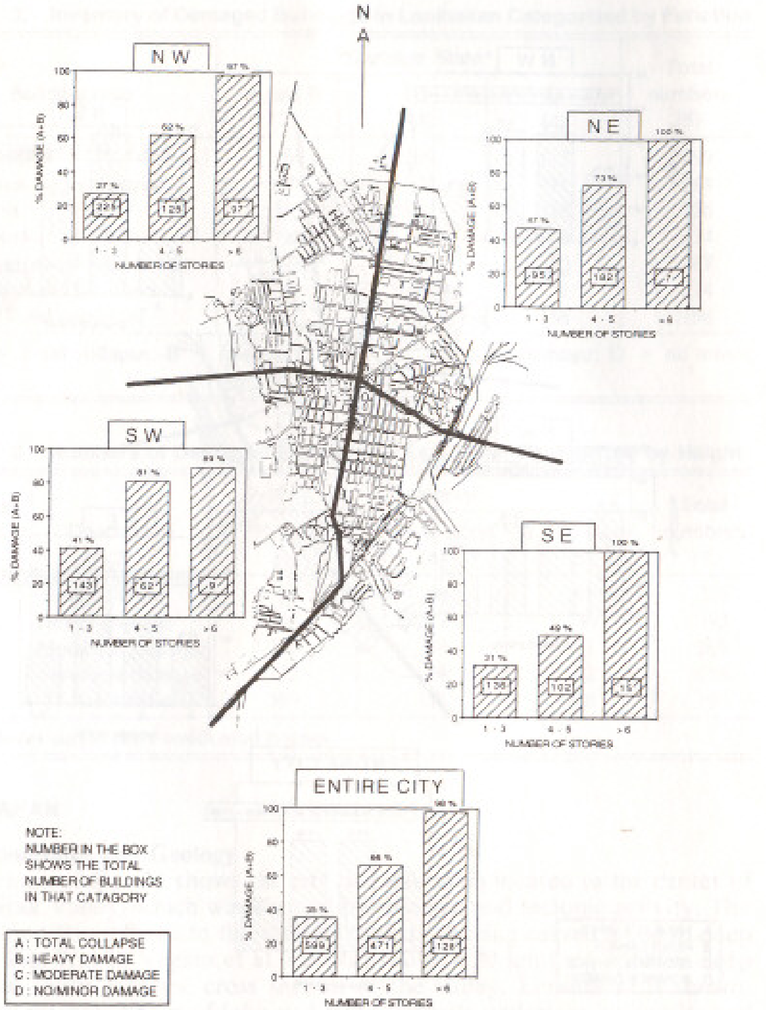


FIG. 16. Damage Statistics (A and B) for Three Categories of Buildings (with 1–3, 4–5, and 6 or More Stories) in Leninakan

effect on the distribution of damage among the four regions of Leninakan? This is investigated next.

Damage Statistics

Table 2 presents an inventory of the buildings in Leninakan. A total of 1,198 buildings (excluding single-story residential houses) were surveyed by the Research Institute for the Ministry of Construction, and 641 were found in the heavily damaged states (A and B). Table 3 presents the damage statistics for the entire city, categorized by building height as described earlier.

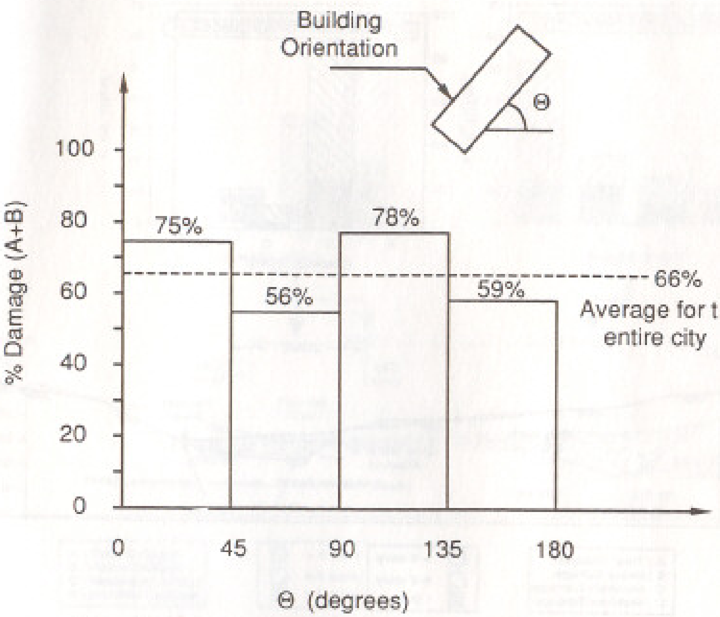


FIG. 17. Results of Directionality Analysis in Leninakan

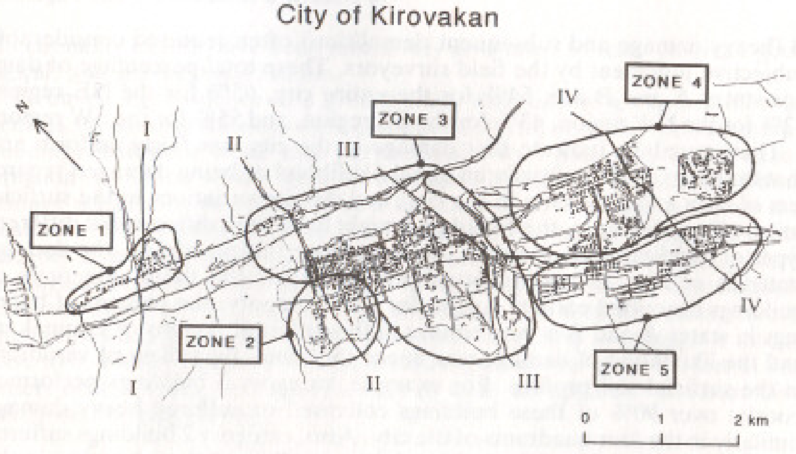


FIG. 18. Map of Kirovakan Subdivided into Five Zones, and Lines across Which Geotechnical Sections Are Shown (I, II, III, and IV)

The damage statistics given in Table 3 were subdivided for each of the four regions of Leninakan (namely NE, NW, SE, and SW) and are plotted in Fig. 15. Notice that the distribution of damage in the four regions is quite similar, especially if one combines damage states A and B. It is important to remember that the distinction between state A (total collapse) and state

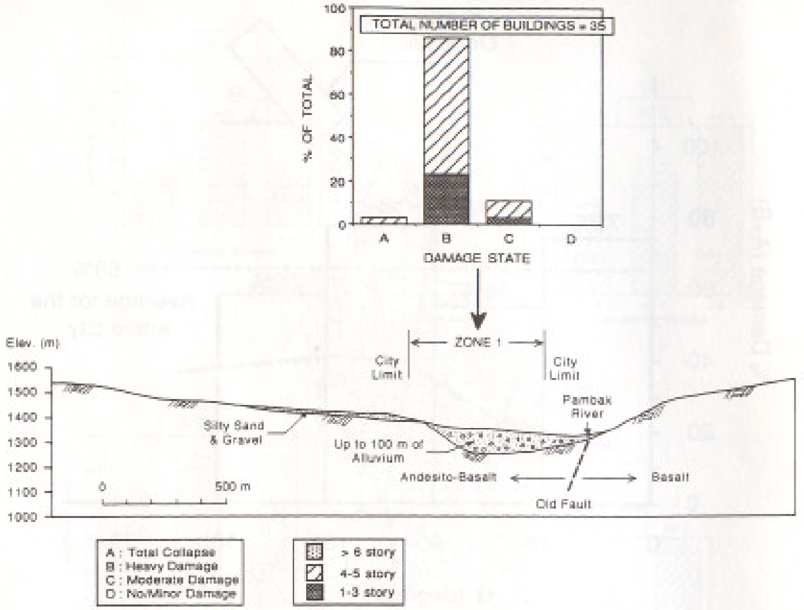


FIG. 19. Geotechnical Section I-I through Zone 1 in Kirovakan, and Corresponding Damage Statistics by Building Category

B (heavy damage and subsequent demolition) often required considerable subjective judgment by the field surveyors. These total percentage of damage states A and B are: 54% for the entire city, 65% for the NE region, 52% for the NW region, 43% for the SE region, and 55% for the SW region.

These numbers indicate that damage in the city was fairly uniform and that buildings had essentially an equal likelihood of being damaged regardless of their exact location in the city, and despite variations in the surficial soil profiles. However, this likelihood might have been different for different types of buildings in Leninakan. To investigate this possibility, the damage statistics of Fig. 15 are replotted in Fig. 16 for the three categories of buildings described earlier. Again, for each category, the percent of buildings in states A and B is very similar in the different regions of Leninakan, and the likelihood of damage was hence the same, regardless of variations in the surficial soil profiles. For example, category 3 buildings performed poorly: over 90% of these buildings collapsed or suffered heavy damage similarly in the four quadrants of the city. Also, category 2 buildings suffered less than category 3 buildings, but again regardless of their location in the city, over 60% either collapsed or were damaged beyond repair. Finally, category 1 buildings performed relatively well (about 35% damage), again essentially uniformly throughout the city.

Another aspect considered in the analysis of damage statistics was directionality of the ground motion in Leninakan. Finn and Nichols (1988) showed that the ground motions in Mexico City lake-bed deposits had a preferred E-W orientation. Idriss (1990) observed that ground surface motions in the Loma Prieta earthquake also exhibited a preferred orientation, and so did the motion in the 1986 Kalamata earthquake (Gazetas et al. 1990). Such directionality effects have been tentatively attributed to seismological, geological, and geotechnical factors.

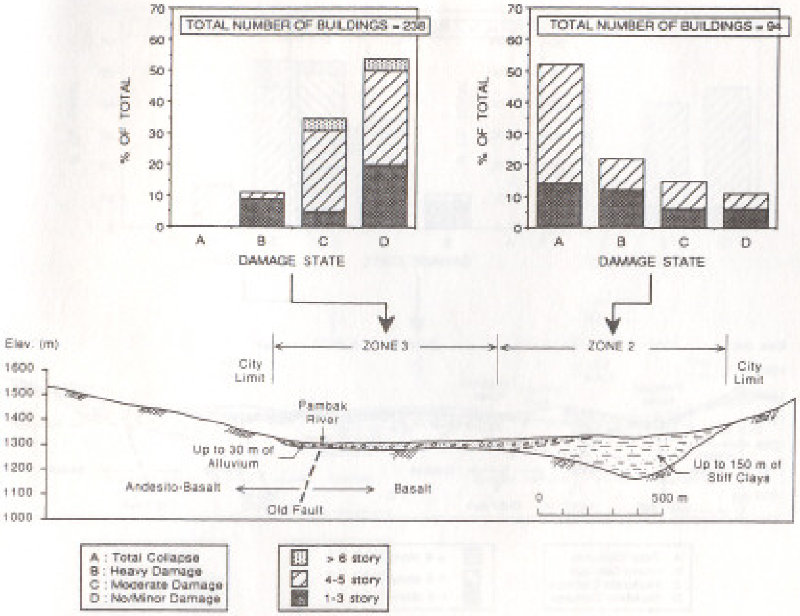


FIG. 20. Geotechnical Section II-II through Zones 2 and 3 in Kirovakan, and Corresponding Damage Statistics by Building Category (Notice Complete Reversal of Damage Pattern from Zone 2 to Zone 3)

To unveil any evidence of a predominant direction of ground motion in Leninakan, damage statistics were compiled in terms of building orientation. Buildings with their weak axes perpendicular to a potential predominant direction of motion would have an increased likelihood of damage. Thus, damage statistics were analyzed as a function of θ, the angle between the weak axis of a building, and the E-W direction. For this investigation, only category 2 buildings were considered because most of these buildings were rectangular in plan section, allowing θ to be easily and reliably determined. Also, the data for this category was abundant. The resulting statistics are summarized in Fig. 17. Evidently, the extent of A and B damage is insensitive to θ, within, of course, the expected experimental scatter. Hence, the writers conclude that in Leninakan there were no apparent directionality effects on building damage.

KIROVAKAN

Site Conditions and Geology

In contrast to Leninakan, Kirovakan is located in a mountainous region in the narrow Pambak River Valley. Fig. 18 shows the city divided into five zones that consider the variations in local soil conditions and building-damage statistics. Also shown are the locations of four geotechnical sections across the five zones, the results of which are given in Figs. 19–22. It can be seen that soil conditions in Kirovakan vary significantly, and are described

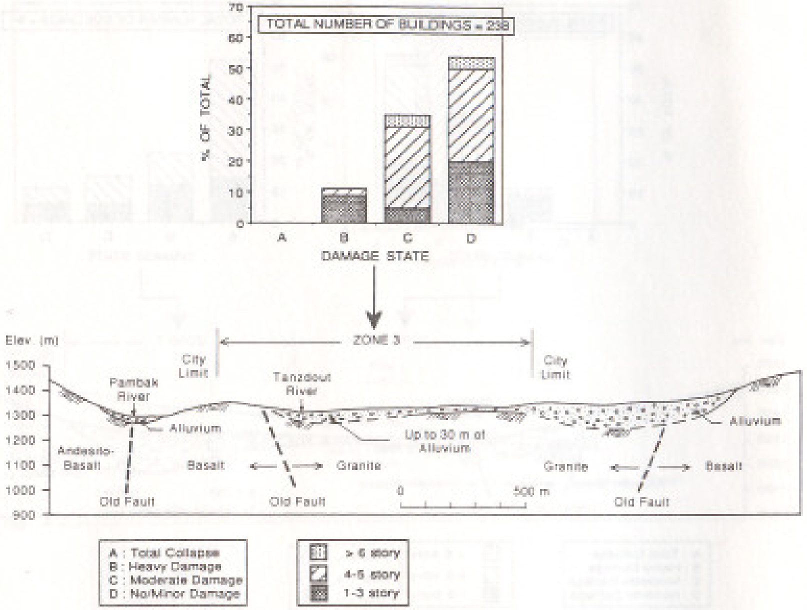


FIG. 21. Geotechnical Section III-III through Zone 3 in Kirovakan, and Corresponding Damage Statistics by Building Category

for each zone as follows:

- Zone 1: Up to 100 m generally very dense alluvial sands and gravels with pebbles and boulders
- Zone 2: Localized 150 m deep deposit consisting of a top very stiff silty sandy clay followed by very stiff, low-plasticity clay of lacustrine origin
- Zone 3: Up to 30 m of very dense alluvium with cobbles and boulders
- Zone 4: About 6–20 m of silty, sandy clay
- Zone 5: About 10–30 m of alluvium, similar to zone 3

The nature of bedrock in the region varies, and includes granite, andesite, basalt, and tuff. Also, there is evidence of faulting in the Pambak River Valley (Figs. 19–22). Hence, unlike Leninakan, the soil profiles within Kirovakan vary dramatically. The impact of such variations on building damage distribution is described next.

Damage Statistics

In Fig. 12 of Yegian et al. (1994a), the damage statistics for Leninakan and Kirovakan are compared. Whereas in Leninakan, damage statistics for the entire city are also representative of the different city subregions, the statistics in Kirovakan vary significantly from one zone to another. The damage statistics for the entire city of Kirovakan are given in Table 4. Note that only 50 of the total 598 multistory buildings collapsed and most of them were of category 2 buildings. Figs. 19–22 depict the damage statistics in each individual zone, for the three studied building categories. The following trends are worthy of note:

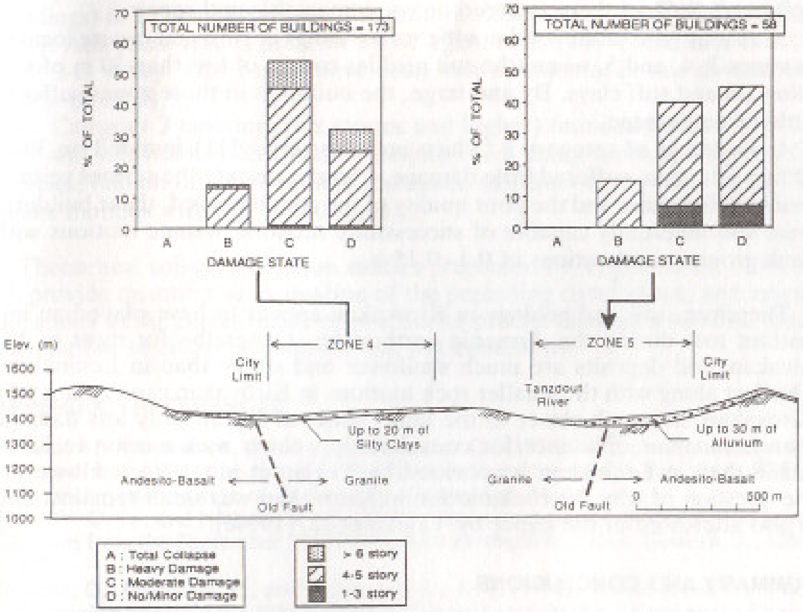


FIG. 22. Geotechnical Section IV-IV through Zones 4 and 5 in Kirovakan, and Corresponding Damage Statistics by Building Category (Natural Scale)

TABLE 4. Numbers of Damaged Buildings in Kirovakan Categorized by Height

Damage state (1)	Description (2)	Category			Total numbers (6)
		1 (1–3 story) (3)	2 (4–5 story) (4)	3 (>6 story) (5)	
A	Total collapse	13	37	0	50
B	Heavy damage	40	67	1	108
C	Moderate damage	25	168	26	219
D	No/minor damage	59	140	22	221
—	[Total numbers]	137	412	49	598

[a] Excludes single story residential houses.

1. Almost all the collapsed buildings were in zone 2, where 150 m of stiff clays are deposited in a narrow valley. Also, in this zone, 36% of category 1 and 62% of category 2 buildings collapsed—percentage values significantly larger than the 10% and 20% observed in Leninakan for the respective categories. Using analytical procedures, Yegian et al. (1994c) attribute this unusually higher damage to 3-D valley effects of the sedimentary basin in zone 2.
2. In zone 1, where there is up to 100 m of alluvium, although no building

collapsed, 86% of them suffered heavy damage beyond repair.

3. About 78% of the total number of buildings in Kirovakan were located in zones 3, 4, and 5, where the soil profiles consist of less than 30 m of stiff alluvium and stiff clays. By and large, the buildings in those zones suffered little or no damage.

4. Buildings of category 3 (which includes series 111) founded on 30 m of firm alluvium, suffered little damage. Clearly, despite the serious seismic design deficiencies and the poor quality of the concrete used, these buildings were still inherently capable of successfully resisting seismic motions with peak ground accelerations of 0.1–0.15 g.

Therefore, soil and geology in Kirovakan appear to have played an important role during the Armenia earthquake. Generally, for most of Kirovakan, soil deposits are much shallower and stiffer than in Leninakan. This fact along with the smaller rock motions in Kirovakan can explain why Kirovakan, although closer to the fault, suffered significantly less damage than Leninakan. Evidence for considerably weaker rock motion in Kirovakan than in Leninakan is provided by Yegian et al. (1994c). However, the question of why the rock motion in Kirovakan was small remains, and is also addressed in the paper by Yegian et al. (1994c).

SUMMARY AND CONCLUSIONS

A detailed comparative study of ground-motion intensity and distribution of damage from the Armenia earthquake is presented. Damage statistics for different category buildings are correlated with geologic and soil profiles in Leninakan and Kirovakan. The following conclusions are drawn:

1. One-dimensional wave propagation analysis of the recorded ground-surface motions on soil in Ghoukasian, where the width of the valley to soil thickness ratio is about 80:1, produces rock-outcrop motions having spectral shapes consistent with those on rock from other earthquakes.

2. Ground-motion attenuation in Armenia, established from the recorded data and acceleration values estimated from observations of grave markers, agree in general with data from the 1990 Manjil earthquake that occurred in the same tectonic region, as well as with the data from similar-magnitude 1989 Loma Prieta earthquake at similar distances.

3. One significant exception: motions in Kirovakan were significantly smaller (by a factor of at least 2) than anticipated from worldwide attenuation relations. This is attributed to potential seismic source mechanism, and wave transmission path effects, as explained by Yegian et al. (1994c).

4. Leninakan, located on a deep deposit and in a wide valley, suffered uniformly. Buildings of different categories experienced different degrees of damage; yet, for each category, damage was uniform across the entire city. Hence, local variations in the composition of the surficial (top 35–50 m) stiff soils had no apparent influence on building damage. Also, there was no apparent predominant direction of motion on the ground surface. Analytical studies by Yegian et al. (1994b) provide quantitative confirmation of these findings.

5. In Kirovakan, soils vary drastically from place to place. Collapse and heavy damage was confined in a small region where up to 150 m of stiff silty sandy clays fill a very narrow valley (ratio of width to soil thickness is about 5:1). Despite the fact that the rock motion in Kirovakan was smaller, damage in this region is significantly higher than (for the same category buildings) in Leninakan (where the ratio of width to soil thickness is about 55:1). Analytical results presented by Yegian et al. (1994c) indicate that 2-D or 3-D valley effects must have been very substantial in this devastated region (zone 2).

6. Category 3 buildings (six stories and higher) founded on 20–30 m of very stiff alluvium in Kirovakan, despite their many seismic design deficiencies, had an inherent seismic resistance sufficient to survive the earthquake motions with PGA 0.10–0.15 g.

Theoretical soil-amplification studies presented by Yegian et al. (1994b, c), provide quantitative evaluation of the preceding conclusions, and assess the ability of the current state-of-practice to predict damage levels and their correlations to different geologic and soil conditions.

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