1988 ARMENIA EARTHQUAKE. I: SEISMOLOGICAL, GEOTECHNICAL, AND STRUCTURAL OVERVIEW

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ABSTRACT: This is the first in a sequence of five papers dealing with engineering aspects of the surface-wave magnitude $M_s \approx 6.8$, 1988 Armenia earthquake, the devastating effects of which are still being felt in Armenia. Although the central theme of our three-year study has been to assess the role of local soil conditions on the magnitude and geographic distribution of damage, we have come to recognize that a close link exists among seismological, geological, geotechnical, and structural aspects of the Armenia earthquake. Our field investigations and analysis of various geologic and engineering aspects of the earthquake have culminated in a series of five papers. This and the companion paper present mostly factual information pertaining to: (1) The mechanics of the fault and its surface breakout; (2) some potentially significant topographic, geologic, and geotechnical features; and (3) the statistics of damage in cities of Spitak, Leninakan (now called Kumayri), and Kirovakan, Armenia, correlated to geologic and soil profiles. In the third and fourth papers of this series, which will appear in a subsequent issue of the journal, theoretical analysis of soil amplification in Leninakan and Kirovakan are described. The fifth paper, also in a later issue of the journal, presents data and analysis of liquefaction-induced embankment failure case histories.

INTRODUCTION

It was called the worst natural disaster of the decade. The surface-wave magnitude $M_s \approx 6.8$ earthquake that shook northern Armenia on the 7th of December 1988 left about 40,000 dead and half a million homeless as hundreds of multistory buildings were reduced to rubble in villages, towns and cities of the epicentral region. The social and economic consequences of the event were equally grave and attracted worldwide public attention and sympathy.

The interest of the scientific-engineering community has been no less captivated. International research teams surveyed the earthquake-stricken region and have reported on seismological and engineering aspects of the disaster. Preliminary damage statistics (Der-Kiureghian 1989a, 1990; Eisenberg 1990) were published and speculative arguments were advanced to explain what caused such enormous damage. Questions were raised regarding historic seismicity, seismic codes, structural defects, construction quality, and soil effects. The report of a 14-member U.S. team, published in a special issue of *Earthquake Spectra* (Wyllie and Filson 1989) eight months after the earthquake, contains much of this preliminary data. Useful information can also be found in an article in *Nature* by Cisternas et al. (1989) focusing on the seismotectonic aspects of the December event, and in a report by Bommer and Ambraseys (1989) that provides additional information on the surface expressions of the faulting process.

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With support from the National Science Foundation, the writers of the present paper embarked on a comprehensive research program aimed at gathering all the necessary data and information to permit evaluation of the geotechnical aspects of the earthquake. The result of this research provides some definitive answers to the questions posed earlier, raises a number of new questions, and brings forward issues that could not be resolved within our understanding of the current state of earthquake engineering knowledge.

The objectives of this research have been:

- To compile and assess the reliability of the available seismological, geological, geotechnical, and structural evidence from all possible Armenian and international sources
- To perform additional field observations focusing on, but not limited to, geotechnical performance and seismic ground motions and case histories
- To conduct standard penetration and cone penetration tests in as many soil sites as possible, and to calibrate the results with available geophysical and geological boring-log data
- To investigate analytically the possible role of the local soil conditions on the extent and distribution of damage to structures
- To document and discuss the possible roles of geologic heterogeneities and of nonuniform fault-rupturing process versus the effects of local soil conditions on some surprising aspects of this earthquake

Throughout the course of this investigation it became evident that a close link existed among seismological, geological, geotechnical, and structural aspects of the earthquake, and hence that no single factor could alone convincingly explain the extent and, especially, the geographic peculiarities of the disaster. Our efforts have thus been directed toward a comprehensive understanding of all facets of the earthquake.

The present paper offers primarily background factual information on all key aspects of the earthquake, and sets the stage for the analysis of building damage and its correlations with geologic and local soil profiles, and liquefaction-induced embankment failure case histories presented in the companion papers (Yegian et al. 1994a–d).

OVERVIEW

Several values have been reported for the surface-wave magnitude, M_s, of the 7 December 1988 Armenia earthquake, ranging from 6.7 (Institut de Physique du Globe, Strasburg, France) to 7.0 (Institute of Physics of the USSR) and averaging about 6.8 (Cisternas et al. 1989, Wyllie and Filson 1989). The reported body-wave magnitude, m_b, averaged about 6.3. A strong aftershock 4 min 20 s after the main shock was assigned an $m_b \approx 5.9$ and, no doubt, finished up the damage triggered by the main shock. The location of the earthquake fault along with additional relevant geographic information is given in Fig. 1.

The occurrence of the 1988 Armenia earthquake should not have been a surprise. Historical seismicity records dating as early as 139 A.D. show high levels of seismic activity in the region. Fig. 2 shows the epicenters of the historic events plotted from a comprehensive list that the writers have compiled from the following sources: Armenia Academy of Sciences (unpublished catalog, 1987); Ambraseys and Adams (1989); Berberian (1976); Ambraseys and Melville (1982); Karapetian (1991); Armen (1983); and Armen (unpublished notes, "Seismicity and Anti-Seismic Building Traditions in Asia Minor," 1989). In June 1990, a similar earthquake ($M_s \approx 7.7$) devastated northwest Iran near Manjil (Fig. 2), causing nearly identical surface faulting to that observed in Armenia, and in March 1992, an identical magnitude earthquake ($M_s = 6.8$) struck eastern Turkey near the town of Erzincan. It may also be noted that in 1926 a magnitude 5.8 earthquake (Babayan 1984) struck Leninakan causing serious damage. Hence, the 1988 earthquake could have been anticipated, and similar large events in the region are likely to occur in the future.

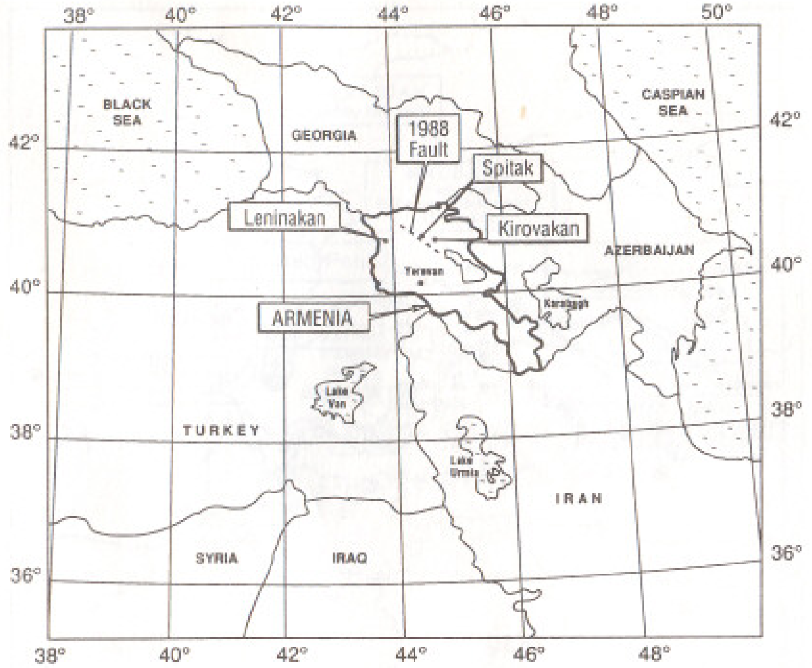

FIG. 1. Geographic Map of Armenia and Surrounding Region

Surface breakouts of the ruptured fault, in the form of either narrow bands of pressure ridges within the soil cover, or clear scarps in outcropping rocks, were initially found by surveying expeditions along a 10 km slightly curved line, starting at the outskirts of Spitak and treading northwest (at an average azimuth of about N 50° W) just past the village of Nalband, Armenia (Fig. 3). Subsequent field investigations revealed an additional 10 km of extensive, albeit intermittent, surface breakouts southeast of Spitak treading at a bearing of about N 30° W, as well as some 7 km of less-intense breakouts extending northwest of Nalband (Karakhanian 1989).

Three main cities were affected by the 1988 earthquake: Spitak (pre-earthquake population of 30,000), Leninakan (population of 300,000), and Kirovakan (population of 200,000). Sitting right next to the surface breakout of the fault, Spitak experienced a devastating shock: 238 (90% of the total) of its two-story or taller buildings either collapsed or were damaged beyond

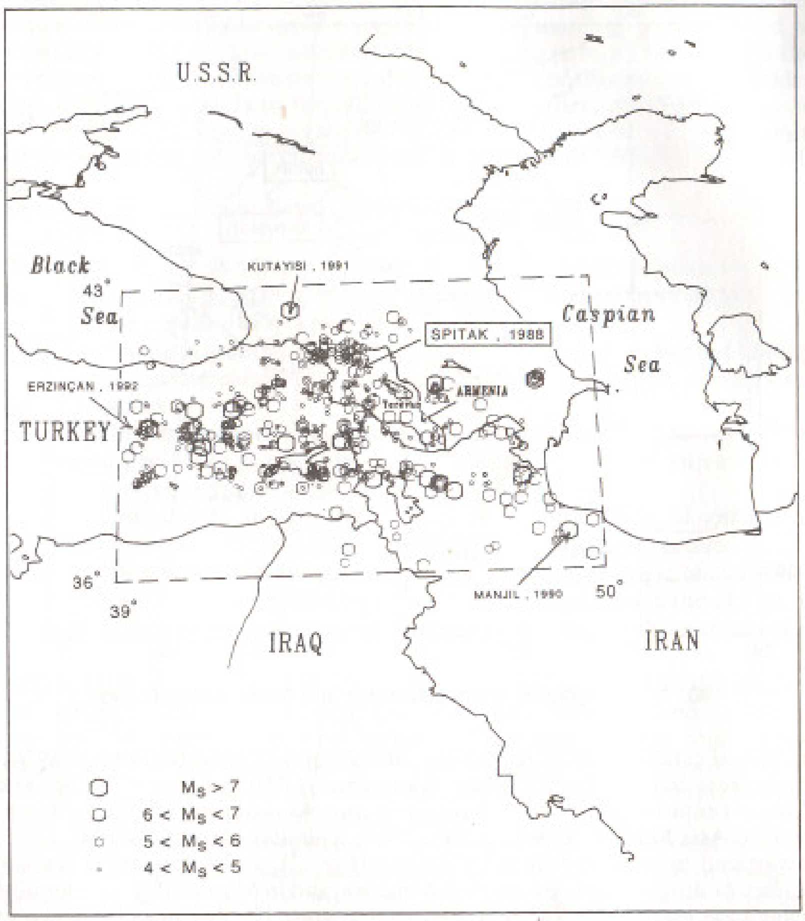

FIG. 2. Historical Earthquakes in Armenian Highlands and Neighboring Regions from 139 to 1992

repair and were later demolished. In Leninakan, about 25 km from the fault, the toll of collapsed/demolished (two-story and taller) buildings reached a surprisingly high 641 buildings (or 54% of the total). By contrast, although at a mere 10 km distance from the fault, Kirovakan sustained a relatively moderate degree of damage: only 158 of its buildings (26% of the total) collapsed or were demolished. Possible explanations for this apparent inconsistency will be discussed subsequently.

Early reports on geotechnical failures (O'Rourke 1989) focused on the numerous landslides and rockfalls that were observed throughout the affected region, and on the failures of gravity retaining walls in and around Spitak. Persistent surveying by the writers (after the melting of the snow cover) revealed two fascinating cases of liquefaction, one involving level ground scarred by sand boils, the other a railway embankment that experienced a devastating liquefaction flow failure. Both sites were within 1–2

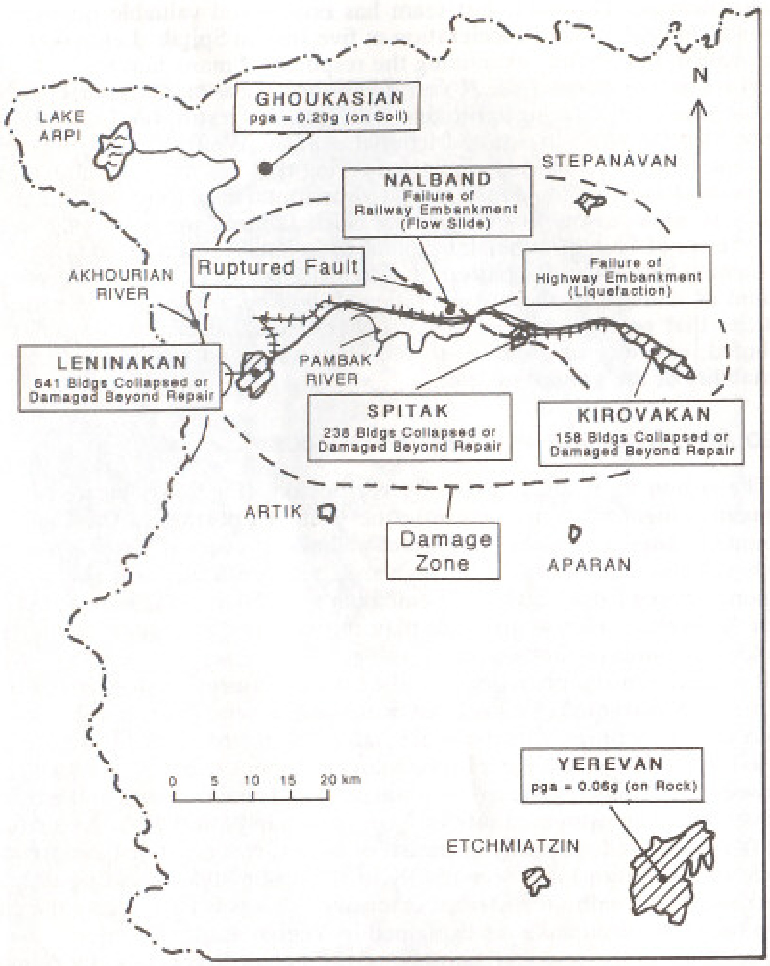

FIG. 3. Map of Damaged Region with Points of Interest

km from the fault breakout (Fig. 3) and in both cases the liquefied layers were gravelly sands; documented analysis of these failures is presented by Yegian et al. (1994d).

An important strong-motion accelerogram was recorded in Ghoukasian, Armenia, located 25 km from the northwestern tip of the fault's surface breakout, along the direction of the fault (Fig. 3). The two components of this record exhibit horizontal peak ground acceleration (PGA) of about 0.20 g (Der-Kiureghian, personal communication, 1989).

Another accelerogram, recorded in the capital city of Yerevan, 80 km south of the fault, had a PGA ≈ 0.06 g (Khachian 1990). Single-pendulum and multipendulum seismoscopes gave a few recordings in the city of Leninakan; however, as explained in Yegian et al. (1994b), their functioning during this event was hardly faultless and their value is thus limited.

Regrettably, strong-motion accelerograms were not recorded on sites of major damage. However, our team has established valuable quantitative bounds on peak ground acceleration at five sites in Spitak, Leninakan, and Kirovakan, by carefully examining the response of many hundreds of grave markers in five cemeteries. A vast number of these markers were slender rectangular blocks, facing approximately East, and resting on the underlying embedded flat tomb in simple frictional contact. We traced the movement of some of these blocks: asymmetric rocking that has led to rotation about the vertical axis (torsional response), to horizontal displacement, and, eventually in some cases, to overturning. Such failures were the rule in the cemeteries of Spitak, rather infrequent in Leninakan, and practically nonexistent in Kirovakan—a pattern that to a large degree echoes the aforesaid extent of damage in these three cities. It will be argued in this series of articles that geologic, topographic, and geotechnical factors have all contributed, one way or another, to the magnitude and spatial (geographic) variability of the ground motion.

GEOLOGY, TOPOGRAPHY, AND GEODYNAMICS

The region most affected by the earthquake (Fig. 4) is located in the Armenian highlands that constitute the southern portion of the Caucasus mountain range. Formed as a result of millions of years of tectonic activity, both volcanic and seismic, the highlands reach altitudes (in the studied region) ranging from 1,500 m in Leninakan to 2,530 m in the mountain crest near Kirovakan. Figs. 4 and 5 display the key topographic, tectonic, and geologic features of this region.

It is seen that the prevailing trend of these features (including the fault of the 1988 earthquake) runs from northwest to southeast, parallel to the main Caucasus range. On the other hand, the tectonics of the region are fueled by a north-south compression, arising from the continental collision between the Arabian plate in the south and the Eurasian plate in the north, converging at an estimated rate of 3 cm/yr (Philip et al. 1989). As a result, the faults are predominantly of thrust, or better, reverse style (compressive mode of dislocation) and secondarily of strike-slip style (shearing dislocation) associated with an east-west extension. This was also clearly the case with the 1988 earthquake, as explained in Yegian et al. (1994a).

As shown in the regional map (Fig. 3), Pambak River, initially running in a west-east direction, crosses the fault near Nalband at an angle of about 30°, flows through Spitak and traverses a narrow valley in Kirovakan (Fig. 4). The mountains surrounding this valley consist of volcanic rocks such as andesites, basalts, and tuffs, while the thickness of the deposited alluvia varies from a few meters up to 150–200 m in one or two locations. A characteristic geologic/topographic section across the valley at Kirovakan is shown in Fig. 6. Most of the city is built on rock outcrop or on very stiff shallow alluvium, but a small part near the city center is underlain by very deep stiff clays.

On the other side of the fault zone, Leninakan is located at the center of the Shirak Valley—a flat, very wide and very deep plain, drained by Akhourian River (Fig. 4). Alluvial and lake-bed deposits reach depths of about 400 m, and sedimentary rock formations about 3,000 m. Two characteristic regional geologic and geotechnical profiles across the valley are displayed in Fig. 7. Detailed geotechnical soil profiles are presented and utilized in Yegian et al. (1994a, b).

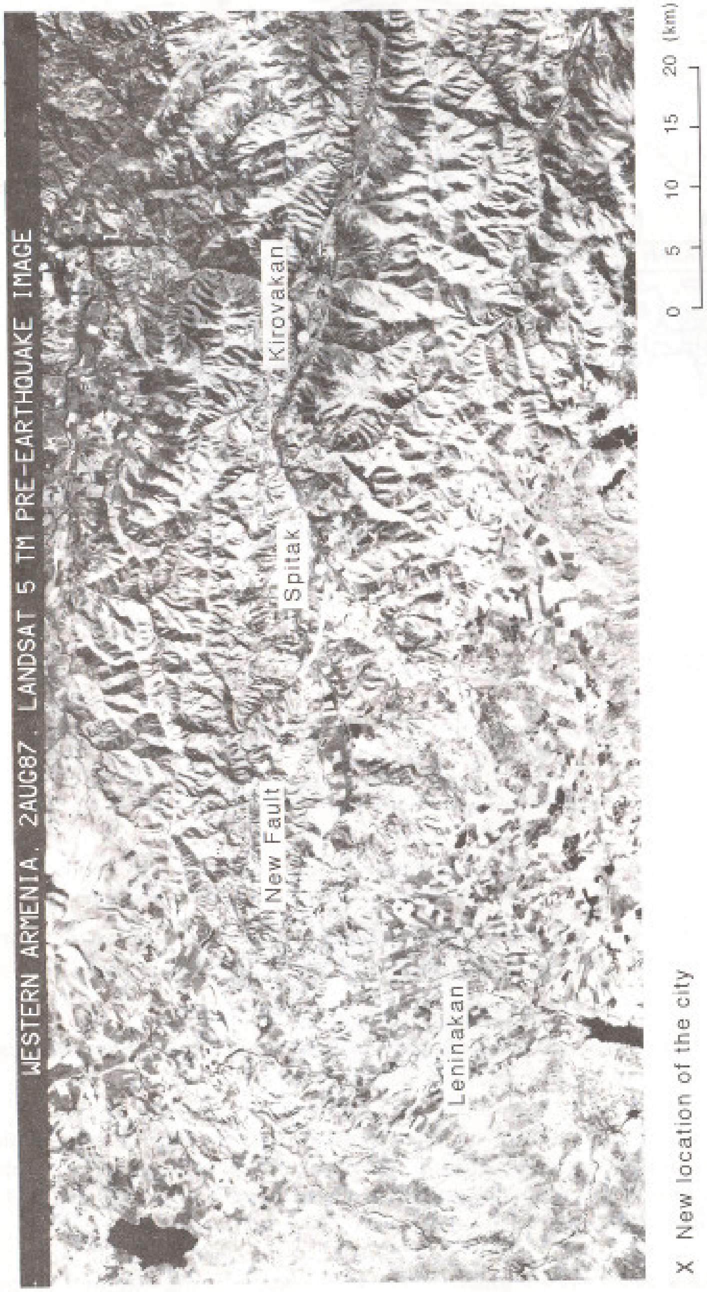

FIG. 4. Landsat Photograph of Earthquake Region Showing: Leninakan, in Plains of Shirak Valley; Spitak, Adjacent to Ruptured Fault; and Kirovakan, Nestled in Mountainous Region (Courtesy of EOSAT)

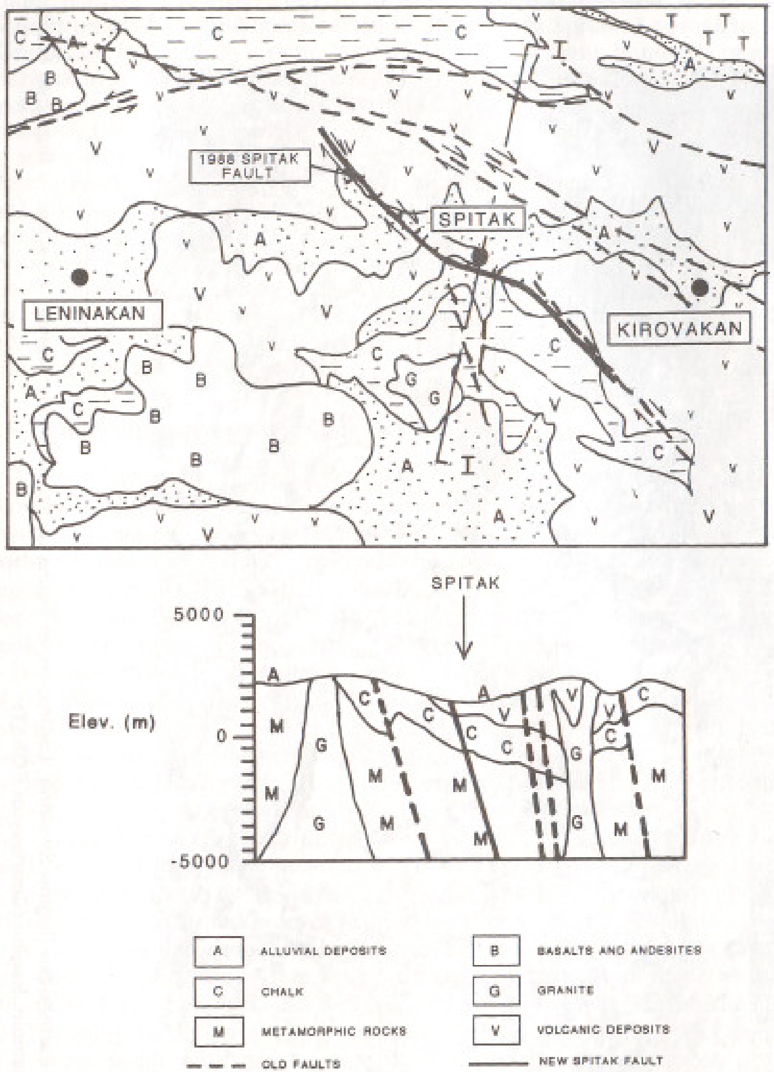

FIG. 5. Geologic Map and Cross Section of Devastated Region [from Baghdasarian (1961)]

This section is concluded with three observations that will later provide the basis of qualitative arguments for explaining the differences in the extent of damage between Leninakan and Kirovakan. Specifically, from Figs. 4–7 it is evident that:

- The southeastern segment of the fault, being parallel to, and 10 km away from, Kirovakan, cuts through at least a few kilometers of chalk (Fig. 5)—a rock substantially softer than granite, basalt, and

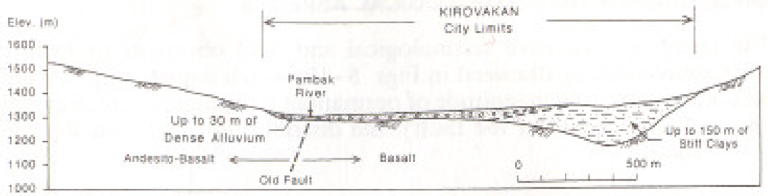

FIG. 6. Typical Geologic Cross-Section through Kirovakan [from Avetisian, Personal Communication, (1990)]

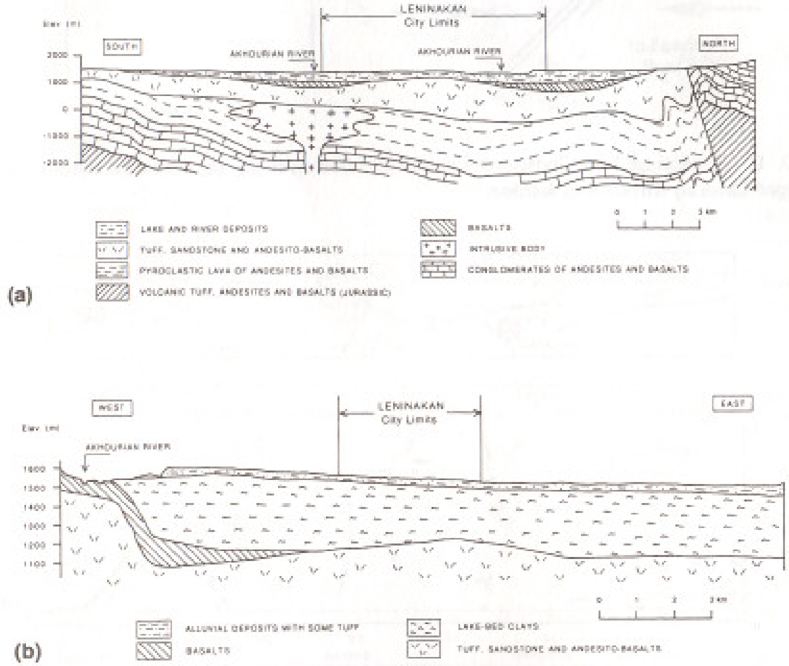

FIG. 7. Geologic Cross Sections through Shirak Valley: (*a*) 3,000 m Deep; (*b*) 500 m Deep [from V. Avetisian, Personal Communication, (1990)]

other igneous rocks through which the segments of the fault northwest of Spitak (the closest to Leninakan) penetrate
- Some high mountain peaks lie between Kirovakan and its nearest fault segment; by contrast, we notice mostly valleys between the fault and Leninakan (Fig. 4)
- The earth crust between the fault and Kirovakan has apparently been fractured (over the centuries) by tectonic forces and contains several secondary faults; no such secondary faults seem to exist between the fault and Leninakan, where the rocks appear to be intact—a difference reminiscent of the dissimilarity (at a much larger scale) between Californian and eastern North American basement rocks (e.g. Jacob and Turkstra 1989).

SOURCE MECHANISM: SEISMOLOGICAL ASPECTS

The results of extensive seismological and field observations from numerous sources are synthesized in Figs. 8–10, which depict, respectively: a sketch of the sense and magnitude of permanent movement (hereafter called "slip" or "dislocation" at the fault); the distribution of vertical slip along

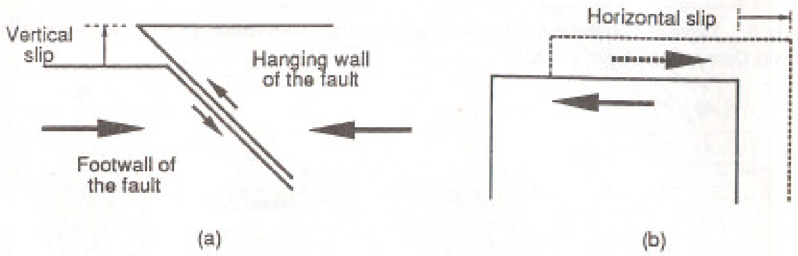

FIG. 8. Sketch of Two Components of Fault Dislocation: (*a*) Reverse Motion; (*b*) (Right-Lateral) Strike-Slip Motion

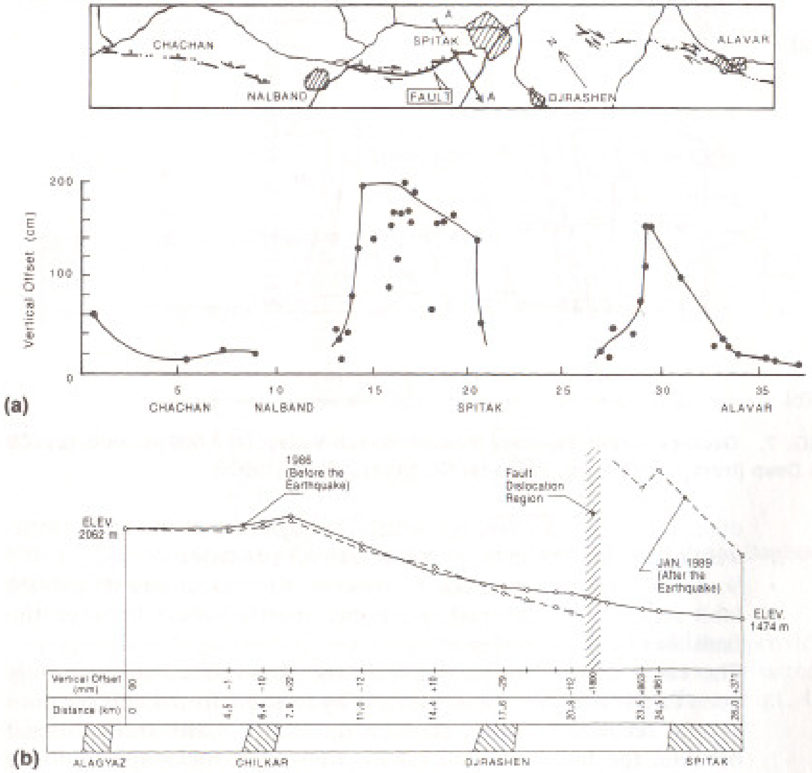

FIG. 9. Details of Ruptured Fault: (*a*) Distribution of Slip along the Surface Breakout of the Fault [from Trifonov et al. (1989)]; (*b*) Geodetic Triangulation across Fault along A-A (from Karakhanian 1989)

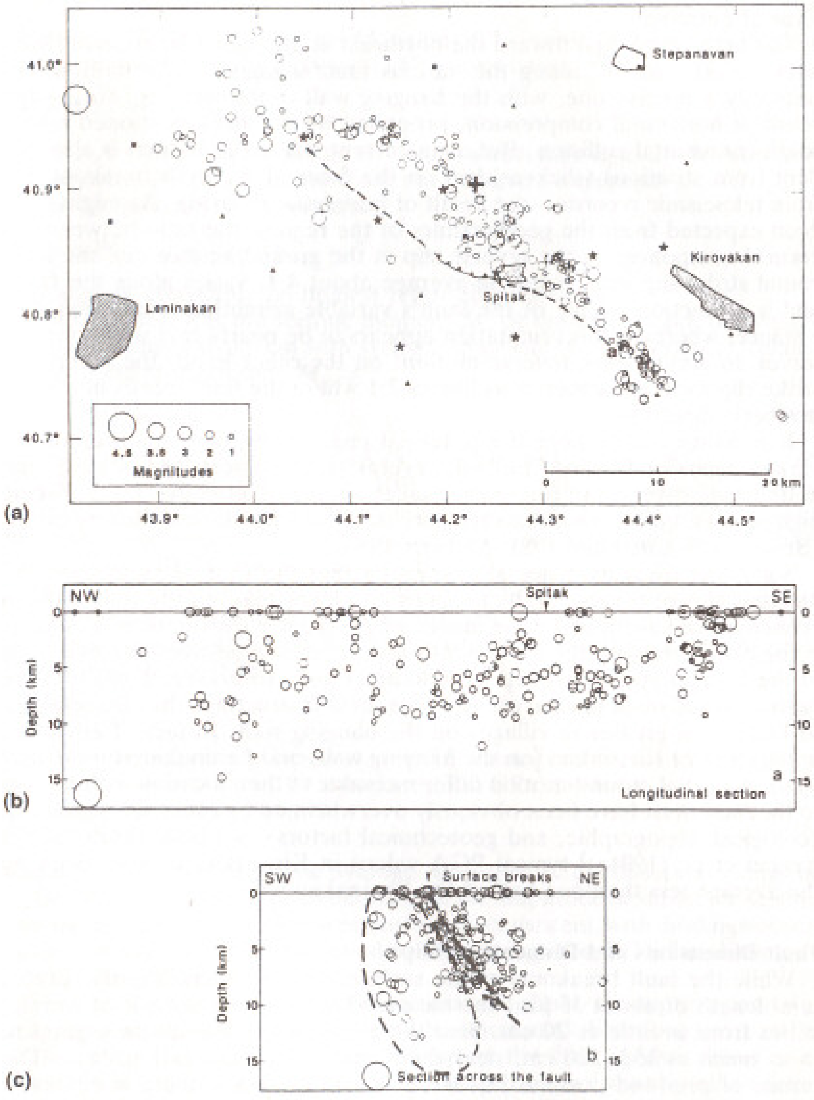

FIG. 10. Distribution of Main Shock and Aftershocks: (*a*) Location of Epicenters of Main Shock (Cross) and Aftershocks (Circles); (*b*) Projection of Hypocenters on Fault Plane; (*c*) Hypocenters on Section Across Fault [from Cisternas et al. (1989)] (Stars, Triangles, and Squares Show Location of Seismic Recording Stations)

the surface breakout of the fault; and the location of the epicenters and hypocenters of the main event and its aftershocks. Important conclusions drawn from these figures and the related studies are as follows.

Type of Faulting

The fault plane dips toward the northeast at an angle that seems to vary between 50° and 70° along the various fault segments. The motion was primarily a reverse one, with the hanging wall upthrown [Fig. 8(*a*)]—the result of horizontal compression, propelled by the aforementioned north-south continental collision. But a concurrent strike-slip motion is also evident from striations (slickensides) on the faces of the fault breakout and from teleseismic records—the result of horizontal shearing. As might have been expected from the geodynamics of the region, the ratio between the vertical component of the reverse slip at the ground surface and the horizontal strike-slip one, being on-average about 4:1, varies along the fault, and is a function mainly of the fault's variable azimuthal orientation. For instance, wherever this orientation appears to be nearly east-west, one observes an almost-pure reverse motion; on the other hand, the reverse to strike-slip ratio decreases to as low as 2:1 where the fault trends in a more northerly direction.

It is worth noting here the potential engineering consequences of the various types of faulting. Indeed, several seismological studies have suggested that reverse-faulting earthquakes are more effective in producing high peak ground accelerations than are strike-slip and normal-faulting events (Brune 1976; Campbell 1981; McGarr 1984).

Some empirical evidence also suggests that the ground motion on the hanging wall of reverse faults tends to be higher than on the foot wall. In Armenia, we have found no evidence of geographic distribution of damage being consistent with the aforementioned difference between the two walls of the fault, despite early reports (Bommer and Ambraseys 1989) that the destruction of small masonry houses (i.e. of stiff structures that are sensitive to PGA) was greater in villages on the hanging wall. In fact, if anything, in the cities of Kirovakan (on the hanging wall) and Leninakan (on the foot wall), potential ground-motion differences due to their location with respect to the fault must have been obviously overwhelmed by other seismological, geological, topographic, and geotechnical factors—we have estimated [in Yegian et al. (1994a)] typical PGA values in Kirovakan to have been on the average less than one-half of the Leninakan values.

Fault Dimensions and Dislocation (Slip)

While the fault breakouts at the surface extend (intermittently) over a total length of about 35 km, the measured vertical component of the slip varies from as little as 20 cm, near the edges of the two major segments, to as much as 150–200 cm, near their centers, as seen in Fig. 9(*a*). The results of pre- and post-earthquake geodetic surveys along a north-south axis passing through Spitak [Fig. 9(*b*)] are compatible with the observations of Fig. 9(*a*). In summary, then, the effective length L of the activated fault is equal to about 27 km and has experienced an average slip $\Delta\bar{u} = 70$ cm at the ground surface.

From the distribution with depth of the aftershock hypocenters [Fig. 10(*b*)] it appears that the rupture has extended down to depths of 16 km; hence the effective fault width W is about 16 km. This leads to an effective area of fault rupture A_f of about 400 km^2.

It is instructive to relate these values of L, A_f, and $\Delta\bar{u}$ to the surface and moment magnitude estimates, M_s and M_w, respectively, using empirical correlations from the literature. For instance, Slemmons' (1977) correlation

$$M_s \approx 2.02 + 1.14 \log L \tag{1}$$

where $L = 27{,}000$ m, gives an M_s value of 7—consistent with the highest of the reported M_s values. Wyss' (1979) correlation

$$M_s \approx 4.15 + \log A_f \tag{2}$$

where $A_f = 430$ km^2, results in $M_s \approx 6.8$, which falls right at the middle of the reported M_s range, while from the observed maximum slip, $\Delta u_{\max} \approx 1.9$ m, Slemmons (1977) predicts

$$M_s = 6.79 + 1.31 \log \Delta u_{\max} \approx 7.1 \tag{3}$$

only slightly exceeding the highest reported values.

Also of interest is the seismic moment M_o of the earthquake (expressed in C.G.S. units of dyne·cm with système international equivalents), related to the moment magnitude M_w as

$$M_w = (2/3)\log M_o - 10.7 \tag{4}$$

where in this case $M_w \approx M_s = 6.8$ (Kanamori 1983; Idriss 1985); hence $M_o \approx 1.8 \times 10^{26}$ dyne·cm (1.8×10^{19} N·m), a value consistent with the estimates derived from teleseismic long-period body and surface waves, and that fall in the range 1×10^{26} dyne·cm to 2×10^{26} dyne·cm (1×10^{19} N·m to 2×10^{19} N·m)(Cisternas et al. 1989).

In a more physical way, M_o is related to the average shear modulus of the material along the faulted plane, the effective fault area A_f undergoing slip, and the average slip $\Delta\bar{u}$ over the whole activated fault (Joyner and Boore 1988; Idriss 1985)

$$M_o = \mu A_f \Delta\bar{u} \tag{5}$$

Inserting the previously found A_f and M_o values and assuming the typical modulus value of 3.5×10^{11} dyne/cm^2 (350 GPa) leads to

$$\Delta\bar{u} \approx 120 \text{ cm} \tag{6}$$

which is nearly two times the average slip $\Delta\bar{u} \approx 70$ cm observed along the surface breakout. The implied decrease in the amplitude of slip as the seismic rupture process reaches the free surface is consistent with findings/observations in several other earthquake events, e.g. the 1971 San Fernando earthquake (Allen 1976).

From all the foregoing, we conclude that the slip in the rupture zone was of highly variable magnitude both in the horizontal direction, i.e. parallel to the strike (Fig. 9), and down the dip of the fault. (Also variable, as described in the previous section, was the direction of the slip or, in other words, the relative size of reverse versus strike-slip dislocation.) Although the distribution of slip on the fault plane has not as yet been backfigured through appropriate (inversion) procedures [such as in Wald et al. (1991) for the Loma Prieta earthquake], it can be argued that a plausible simplified slip-distribution model such as the one portrayed in Fig. 11 can be defended on seismological grounds. Fig. 11 sketches the most likely patches of slip concentration on the fault plane, where the slip magnitude could have been between 2 m and 4 m. The two slip regions shown in Fig. 11 cover areas

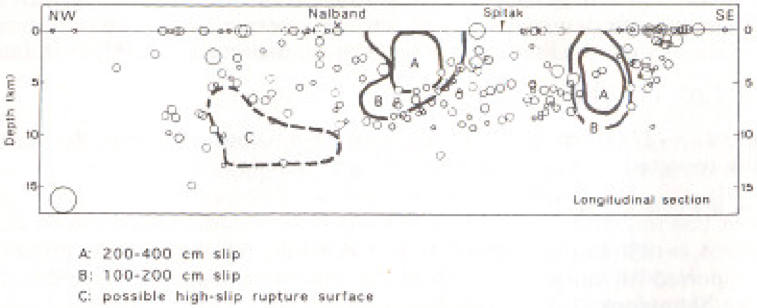

FIG. 11. Comparison of Distribution of Aftershock Hypocenters Projected onto Assumed Fault Plane with Two Plausible Regions (Patches) of High Slip Concentrations (Constructed Speculatively by Writers Based on Aftershock-Hypocenter Data and Recorded Surface Distribution of Slip)

of low aftershock activity and are consistent with both the recorded distribution of slip along the surface breakout (Fig. 9) and the anticipated decrease in slip magnitude near the ground surface ($\Delta \bar{u} > \Delta \bar{u}$). The significance of the location of these patches is further explored in the companion paper (Yegian et al. 1994a) in developing hypotheses for explaining certain peculiarities in the geographic distribution of damage. We note that the preceding arguments are somewhat speculative. It would have been possible to show other slip distributions by looking at aftershock segments in Fig. 11.

Aftershocks and Direction of Rupture Propagation

With the exception of the large $m_b = 5.9$ aftershock, 4 min 20 s after the main shock, the recorded (in local networks) aftershocks were mostly very small magnitude events. Furthermore, the distribution of hypocenters on the fault plane reveals large areas of low aftershock activity (gaps), most notably at shallow depths northwest and southeast of Spitak.

One may interpret these facts in terms of the barrier model proposed by Aki (1979) and Papageorgiou and Aki (1982), according to which few (if any) aftershocks are expected over a section of the fault that slips smoothly. On the contrary, areas that act as barriers to the rupture experience small amounts of slip and are stress concentrators. It is precisely such induced stress increases, combined with static fatigue, that would then trigger the sequence of aftershocks.

The foregoing two paragraphs lead to the conclusion that the rupture during the main event was relatively complete, and that large-amplitude slips must have taken place in the two shallow gaps of aftershock activity near Spitak. The corresponding two patches of slip concentration and the 200 cm slip contours (Fig. 11) are consistent with the observed distribution of slip along the surface breakout of the fault (Fig. 9).

The perpendicular to the fault cross section of Fig. 10(*c*) shows that, indeed, there is a concentration of aftershocks near the fault plane, which dips 50° to the NE near Spitak. However, in the northwestern part of the seismogenic region (northwest of Nalband) the distribution of aftershocks is diffused, both in plan [Fig. 10(*a*)] and at depth [Fig. 10(*c*)], and it extends far beyond the fault breakout. A hypothesis had been (preliminarily) advanced by Stein and Yeats (1989) and, independently, at the same time, by Cisternas et al. (1989) that this was partly a surface-folding earthquake. Such an earthquake would occur on a major blind fault under folded terrain (as is the region of the Lesser Caucasus Mountains) and would also activate several smaller reverse faults scattered throughout the seismogenic region, thereby producing a distribution of aftershocks that is diffused rather than aligned along the fault plane (as it appears to be the case in the area northwest of Nalband).

The subsequent discovery of the major fault breakout southeast of Spitak has largely reconciled the dimensions of the surface faulting with the magnitude of the 1988 event, as was illustrated in (1)–(4), and has thus cast some doubts on the validity of this theory.

We have so far addressed two aspects of the seismic source: (1) Fault-plane orientation and style of faulting; and (2) size and distribution of slip on the fault. A third important aspect of the mechanics of the source is the history of the seismic rupture, expressed through the direction and speed of rupture propagation.

The available evidence for determining the direction of rupture propagation in the Armenia earthquake is ambiguous. Mutually contradictory conclusions have been reached by Bommer and Ambraseys (1989) and Cisternas et al. (1989). The former claimed that the rupture propagated "south-eastwards," on the basis of the start-S time and a supposed evidence of Doppler effect (Aki and Richards 1980; Brune 1976; Joyner 1991) on the motion recorded in Ghoukasian. The latter argued that it propagated "north-westwards," since teleseismic records show the separation between the pulses to be larger in Chinese than in African, European, and American seismograms.

It may well be the case in Armenia that the rupture propagated simultaneously in two directions (as was the case with the 1989 Loma Prieta earthquake), or that the three segments of the fault ruptured independently and in different directions, or even that there was a reversal of rupture direction—as was found by Beroza and Spudich (1988) to be the case in the 1984 Morgan Hill earthquake. The fact remains that it is not known whether source directivity played any significant role.

STRUCTURAL DAMAGE: FINAL STATISTICS

The enormous destruction of engineered structures in Armenia has received considerable attention from the earthquake engineering community. Chapters 6 to 8 in the aforementioned *Earthquake Spectra* (Wyllie and Filson 1989), Der-Kiureghian (1990), as well as several other reports have provided useful preliminary information on this subject. This presentation aims at giving a more definitive account of the extent and distribution of damage. The damage statistics were prepared by the Research Institute for the Ministry of Construction of Armenia (ARMNIISA) through extensive field surveys and analyses of building conditions. This presentation focuses on the cities of Spitak, Leninakan, and Kirovakan, where multistory buildings were the rule. Heavy damage was, of course, also inflicted on single-story residential houses in several villages and the aforementioned three cities. But in the analysis of damage statistics such structures were not considered, in view of their unpredictably variable quality and the difficulty in reliably confirming their key characteristics once they had collapsed or been demolished.

A structural fact of great significance in these studies is that nearly all buildings in the three cities fall in one of five or six types (series) of standardized buildings. Generic designs for each series were furnished by the Soviet-government design institutes in Moscow, which were then slightly modified locally for seismic effects. Since 1971, the horizontal seismic base shear coefficient was merely about 0.025 g for buildings in Spitak and Kirovakan and 0.050 g for buildings in Leninakan (Der-Kiureghian 1989); these values were increased or decreased depending on soil type and depth to water table ("Seismic Design Provisions" 1987).

There were mainly four types of structures prevailing in the three cities:

1. One- to three-story structures include most of the commercial, educational, and industrial buildings and are constructed of all kinds of building materials (i.e. concrete, steel, varieties of masonry, and composite types). Their natural period is estimated between 0.15 s and 0.25 s (Khachian and Melkomian 1989; Eisenberg 1990).
2. Stone masonry bearing-wall and composite-frame stone buildings, mainly four- to five-story buildings (series type 450 and 451), are common in all large towns and cities in Armenia. The stone masonry blocks are of volcanic tuff, used both for interior and exterior walls, filled in with mortar. The composite frame buildings are constructed with precast-concrete frames infilled with interior and exterior stone-masonry walls. The floors consist of hollow-core precast-concrete planks, spanning between exterior and interior walls or between the precast beams. A large number of these buildings collapsed or were heavily damaged during the earthquake. Their estimated natural periods range between 0.25 s and 0.4 s (Khachian and Melkomian 1989; Eisenberg 1990).
3. Precast concrete-frame buildings are widely used in Leninakan. They are mainly six- to nine-story residential apartment buildings (series 110, 111, and 112) having three different floor plans, ranging from square to rectangular and T-shaped. In these buildings precast concrete columns and beams are connected to form moment-resisting frames in only one direction. Precast concrete hollow-core planks are placed on top of the beams for the floors. Poor beam-column connections and joints along with lack of adequate ties between the floor planks and the frame were the main deficiencies in their seismic resistance. In Leninakan, most of these buildings collapsed or were heavily damaged, and were the main contributor to the high human toll. The few existing buildings of this type in Spitak also collapsed. However, in Kirovakan, none of these buildings, which were all founded on 20–30 m of firm ground (Fig. 6), collapsed or suffered heavy damage. Their estimated natural periods range between 0.5 s and 0.9 s (Khachian and Melkomia 1989; Eisenberg 1990).
4. Precast large-panel buildings are 9-story bearing-wall buildings constructed of precast-concrete members. They have story-high segments of precast wall panels interconnected with cast-in-place vertical and horizontal concrete joints. Hollow-core floor planks are used as floors, spanning to the bearing walls on all four sides of the panel. The floor planks are properly connected to each other and to the walls to provide structural integrity. These buildings suffered minor damage in Leninakan. A five-story building of this type in Spitak was essentially the only standing tall structure after the earthquake.

In addition, there were also two "lift-slab" buildings in Leninakan that did not perform well in the earthquake. A 10-story double-core building completely collapsed and a single-core 16-story building was damaged beyond repair, to be subsequently demolished.

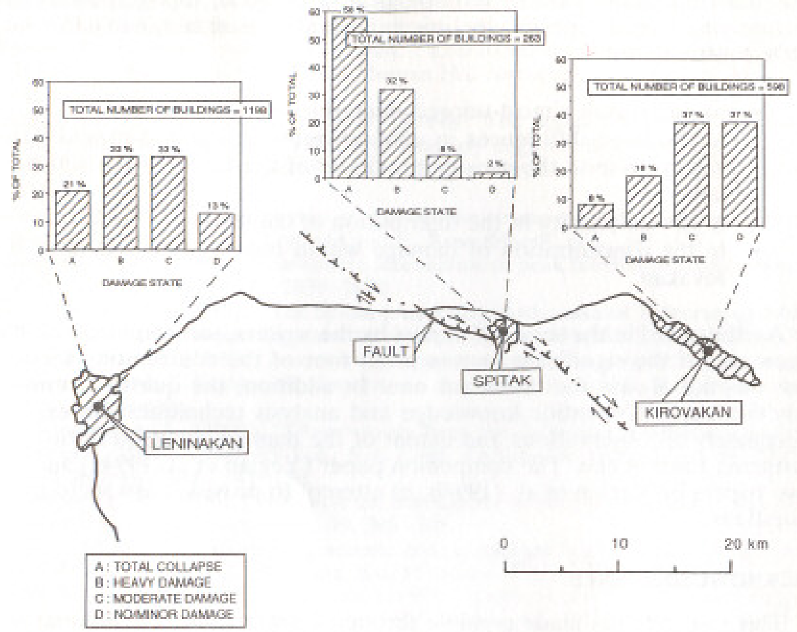

FIG. 12. Overall Building Damage Statistics in Leninakan, Spitak, and Kirovakan.

Engineers and scientists from the Research Institute for the Ministry of Construction of Armenia compiled comprehensive and large scale maps (2 m × 4 m) of the devastated cities of Leninakan, Spitak, and Kirovakan. They surveyed all the multistory buildings and, according to the level of damage, divided them into the following four damage states: A = total collapse; B = heavy damage/beyond repair; C = moderate damage/repairable; and D = no or minor damage.

Having excluded the single-story residential houses, we have arrived in the statistics of damage displayed in Fig. 12. This figure depicts the total number of buildings in each city and the distribution (in percent) of the different damage states. A detailed discussion on the building damage statistics and their correlation with subsurface soil conditions are presented in Yegian et al. (1994a).

The statistics of Fig. 12 restate the fact that damage reached catastrophic proportions in Spitak, was very substantial in Leninakan, and comparatively light in Kirovakan. A further finding to be addressed in the companion paper is that damage in Leninakan was uniformly distributed throughout the city. In contrast, nearly all (98%) of the collapsed buildings in Kirovakan were located in only one small part of the town (a few blocks), underlain by about 150 m of stiff clays (Fig. 6).

CONCLUSIONS: QUESTIONS RAISED

The extent and pattern of damage in Armenia pose a number of questions to geotechnical and structural earthquake engineers. For a complete answer one must take into account seismological, geological, topographical, and engineering factors. Specifically, it is important to ascertain the factors that have contributed:

- to the overall almost-unprecedented level of destruction
- to the large differences in damage between Leninakan and Kirovakan, despite the greater proximity of the latter to the activated fault
- to the uniformity in the distribution of damage in Leninakan
- to the concentration of damage within only a small region in Kirovakan

As illustrated in the series of papers by the writers, soil amplification has been one of the significant factors in all four of the contributing factors, but was not always the dominant one. In addition, the question remains whether current scientific knowledge and analysis techniques can explain adequately all observations and extent of the damage incurred during the Armenia Earthquake. The companion paper (Yegian et al. 1994a) and the two papers by Yegian et al. (1994b, c) attempt to provide answers to these questions.

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