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Soil Response During the 1988 Armenia Earthquake

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Synopsis: Building damage statistics from the 1988 Armenia earthquake are presented and discussed. These statistics are correlated to the local soil profiles in the two major cities of Leninakan and Kirovakan. The soil amplification effects on building damage during this earthquake are investigated. One-dimensional site response analysis results and valley effects are presented to explain the extent and pattern of damage in the two cities.

INTRODUCTION

The magnitude, $M_s=6.8$ earthquake that shook Northern Armenia on December 7, 1988, left about 40,000 dead, 20,000 injured, and over 500,000 people homeless. Over a thousand multi-story buildings in the town and cities of the epicentral region were reduced to rubble, and about 360 villages were destroyed. The social and economic consequences of the event were equally grave and attracted worldwide attention and support. Three major cities shown in Figure 1: Spitak (pre-earthquake population: 30,000), Leninakan (population: 300,000), and Kirovakan (population: 200,000) were the most affected by the 1988 earthquake. Sitting next to the surface breakout of the ruptured fault, Spitak experienced a devastating shock; 238 (90% of the total) of its 2 story or taller buildings either collapsed or were damaged beyond repair and were later demolished. In the City of Leninakan, about 25 km from the fault, the total number of collapsed/demolished, 2 story or taller, buildings reached a surprisingly high number of 641 (54% of the total). By contrast, Kirovakan, at a mere 10 km distance from the fault, sustained a relatively moderate degree of damage compared to Leninakan and Spitak; only 158 (26% of the total) of its buildings collapsed or were subject to demolition.

Figure 2 illustrates this closer proximity of Kirovakan to the seismogenic zone and summarizes the overall damage statistics for the two major cities of Leninakan and Kirovakan. Indeed, whereas about 54% of all buildings in Leninakan either totally collapsed or were damaged beyond repair and were later demolished (damage states A+B), the corresponding number for Kirovakan is 26%. Moreover, the percentage of totally collapsed buildings (damage state A) was nearly 3 times lower in Kirovakan. Furthermore, while the distribution of damage was quite uniform in Leninakan, this was not the case in Kirovakan. In particular, one region of Kirovakan

experienced extremely high degree of damage, even higher than Leninakan --- a clear reversal of the general trend.

Yegian and Ghahraman (1992) presented a comprehensive report on the seismologic, geologic and geotechnical aspects of the 1988 Armenia earthquake. This paper describes the possible soil amplification and valley effects upon the building damage in Leninakan and Kirovakan.

City of Leninakan

Leninakan is located in the center of a flat wide valley (20 km by 16 km) known as the 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 to 50 meters of stiff silty-sandy clays, occasionally containing layers of sand and tuff, underlain by about 300 to 350 meters of very stiff lacustrine clays. The authors have contrasted the local soil conditions to building damage statistics in different parts of the city. This has led to the conclusion that 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. The authors have also theoretically investigated the degree to which soil amplification was responsible for the extent of building damage in Leninakan.

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 valley, consisting of stiff and very-stiff soils down to a depth of about 350-

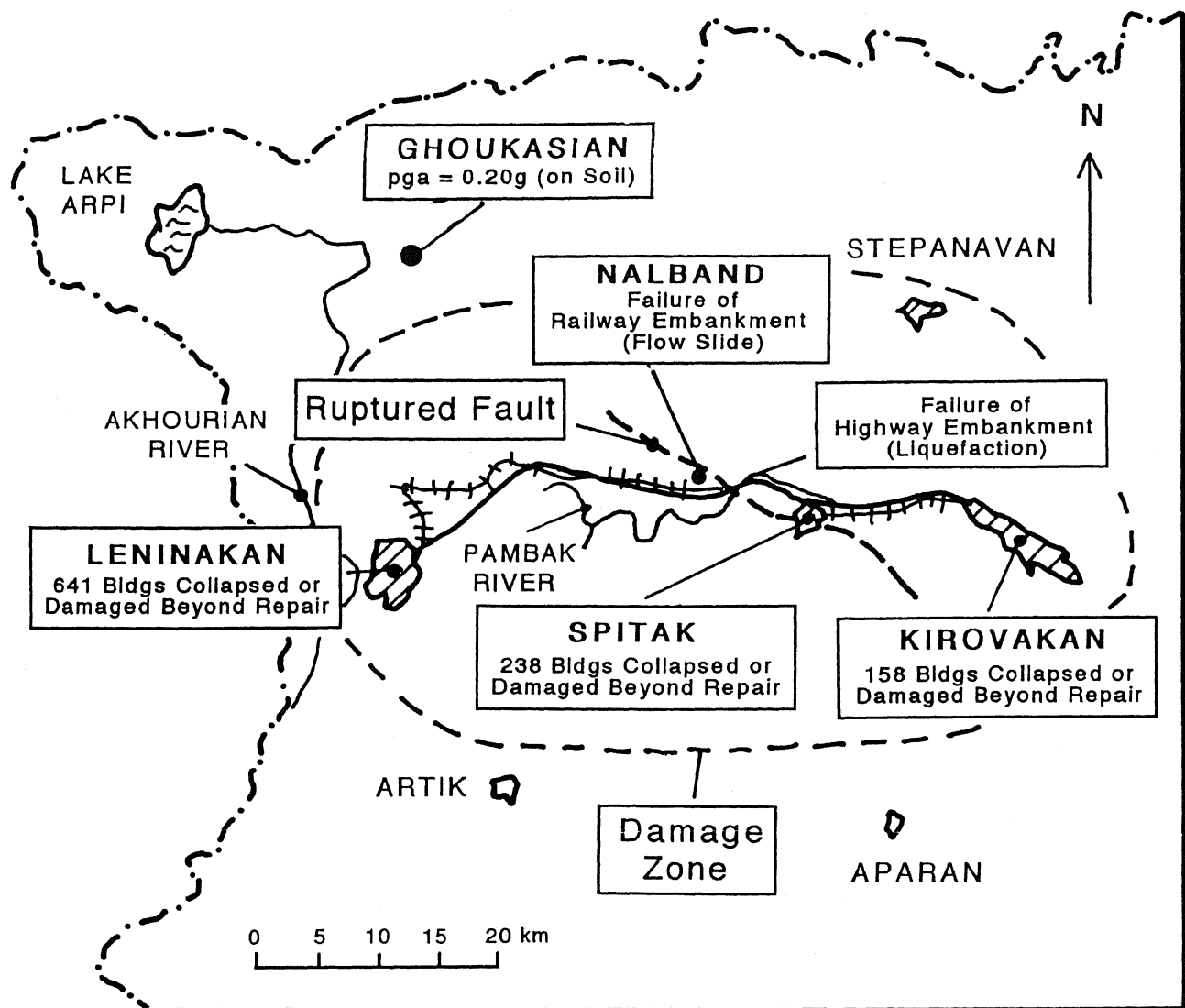


Fig. 1. Map of Northwestern Armenia and the Earthquake Damage Region

400 meters from the surface. 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) suggest that any 2-D effects would have been of marginal importance for structures in the center of the valley.

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

Shear wave velocities down to 30 to 50m below ground were estimated from geophysical, as well as field and laboratory geotechnical tests. For below 50m, the shear wave velocities were extrapolated considering the effect of overburden pressure as suggested by Seed and Idriss (1970). Figure 4a shows, for the range of shear wave velocities used, the 5% damped acceleration response spectra of the calculated ground surface motions and the input rock motion in the N-S direction. Figure 4b plots the corresponding spectral ratios between ground surface and rock outcrop. From Figure 4b it is noted that the peak soil amplification ratio occurs at a period of about 2 seconds, or slightly greater. This value corresponds to the natural period of the soil deposit and is consistent with the 2-2.5 seconds fundamental period obtained from microtremor and aftershock records in Leninakan by Borchardt et al. (1989). Note that although the fundamental period of Leninakan soil profile is about 2

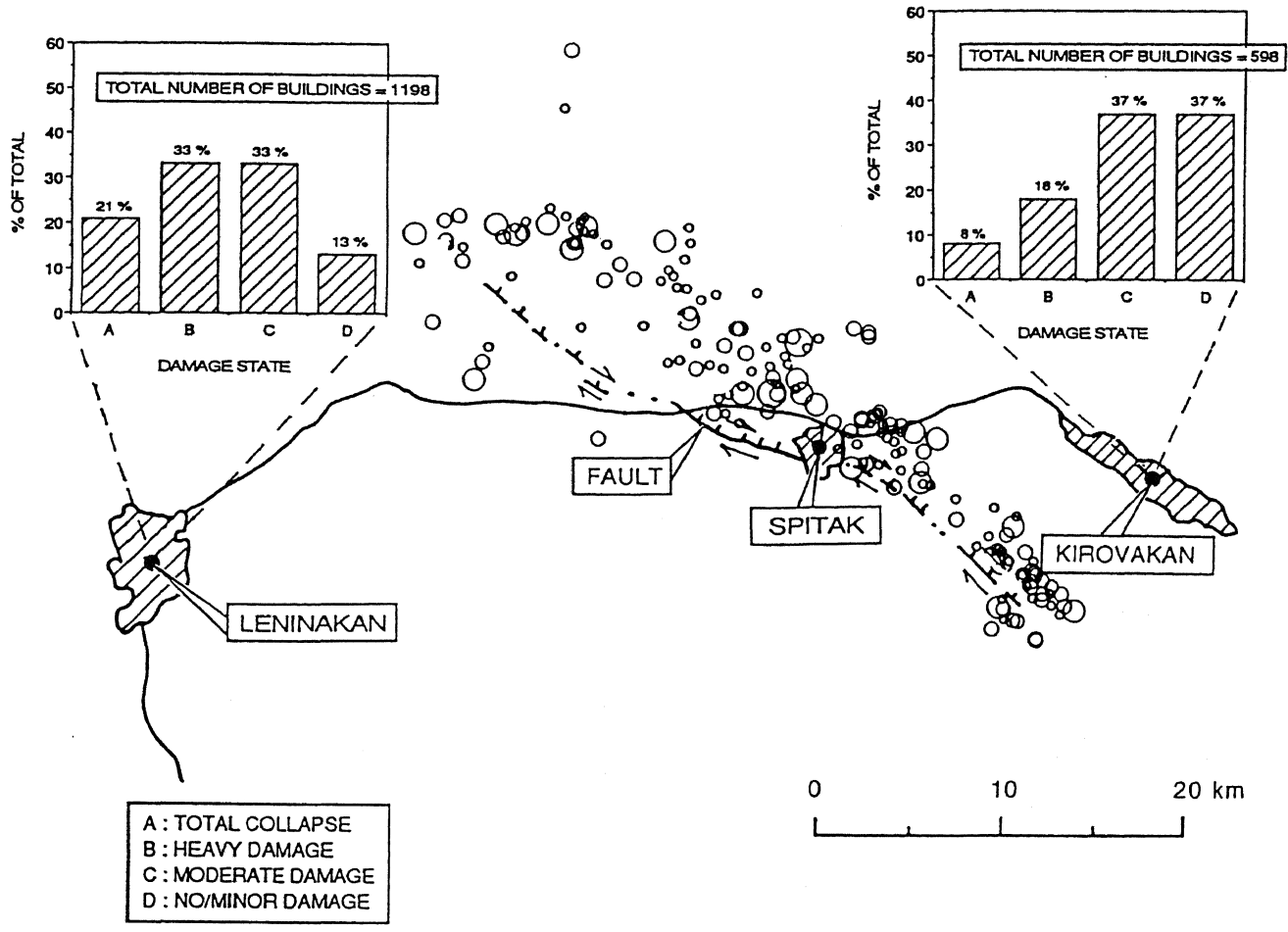


Fig. 2. Overall Building Damage Statistics in Leninakan and Kirovakan; the Location of the Two Cities with Respect to the Ruptured Fault; and the Epicenters of the Aftershocks

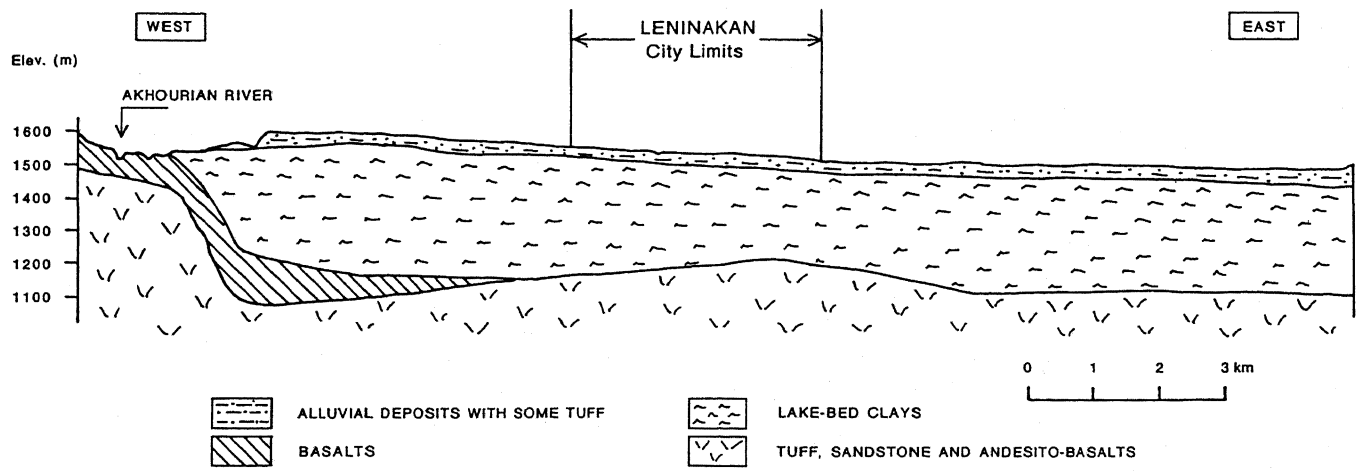
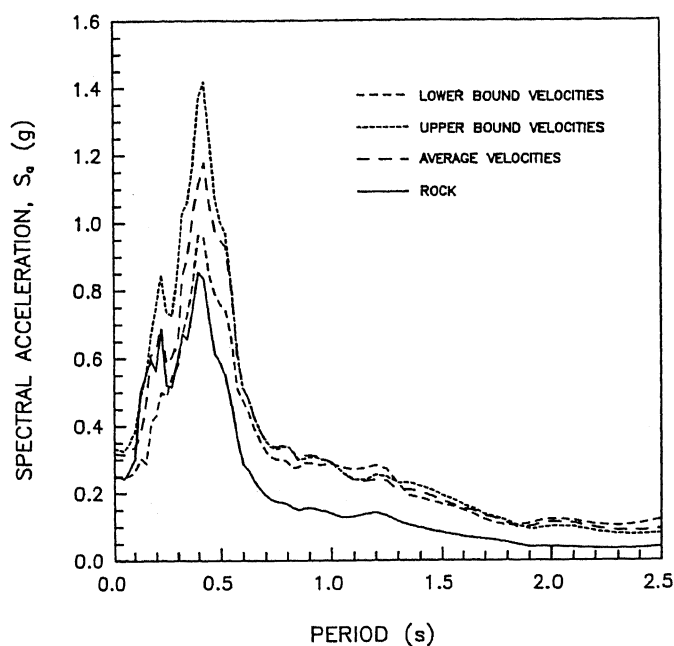
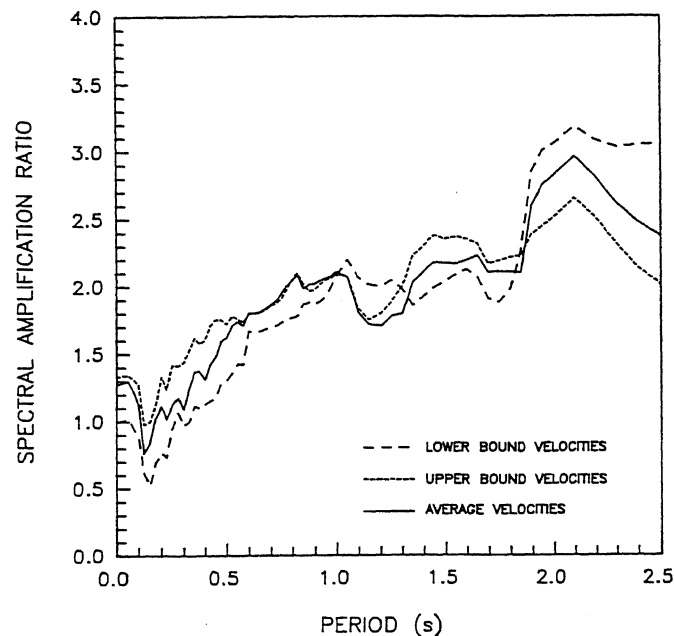


Fig. 3. Geologic Cross Section Through Shirak Valley (from Avetisian 1990)



(a)



(b)

Fig. 4. (a) Acceleration Response Spectra (5% Damping) for Leninakan; (b) Ratio of Spectral Acceleration (Soil/Rock) for Leninakan Using a Range of Shear Wave Velocities

seconds, all the buildings in the city had estimated natural periods falling between 0.25 and 0.90 seconds. Therefore, in Leninakan, although ground motions were somewhat amplified, there was no "resonance" between buildings and soil profiles.

In the period range of 0.25-0.40 seconds, typical of 4 to 5 story buildings, soil amplification effects were marginal (ratio less than 1.5). In the period range of 0.4-0.9 seconds, corresponding to buildings with 6 stories and higher, soils are predicted to have had a measurable effect on ground motions, with amplification ratios of 1.5 to 2. Thus, one could not persuasively attribute the enormous earthquake damage in Leninakan (where 641 buildings, about 54% of the total, either collapsed or were heavily damaged) to soil effects alone. Even if Leninakan were founded on rock, most probably damage would have still been very significant, although undoubtedly reduced.

Yegian et al. (1993a) have also demonstrated that 1-D soil amplification analyses of the Leninakan profile, where the sedimentary basin width-to-maximum-soil-thickness ratio is 55, yielded realistic results. In fact, many of the patterns in building damage distribution and various key field observations could be adequately confirmed with such analyses.

City of Kirovakan

As was stated earlier and summarized in Figure 2, the overall damage statistics for the two major cities of Leninakan and Kirovakan were quite different. Also, while the distribution of damage was quite uniform in Leninakan, this was not the case in Kirovakan. In particular, one region of Kirovakan experienced extremely high degree of damage, even higher than Leninakan --- despite the smaller rock accelerations experienced in Kirovakan (Yegian et al. 1993b).

Figure 5 shows a geotechnical profile through the city of Kirovakan. 98% of the buildings that collapsed in the city were located in the region identified as Zone 2. In this location, the soil profile appears to be in the shape of a conical bowl, filled with clays having a maximum depth of about 150 meters. Outside this zone, where most of the buildings in Kirovakan were located, the soil profiles consist of less than 30 meters of dense alluvium (Zone 3) or up to 20m stiff clays (Zone 4). By and large, all the buildings on these sites suffered little or no damage as shown in Figures 5 and 6.

To determine whether the observed building damage distribution in Kirovakan could have been predicted, 1-D soil amplification analyses were performed using soil properties from laboratory and field measurements. The results of these analyses follow.

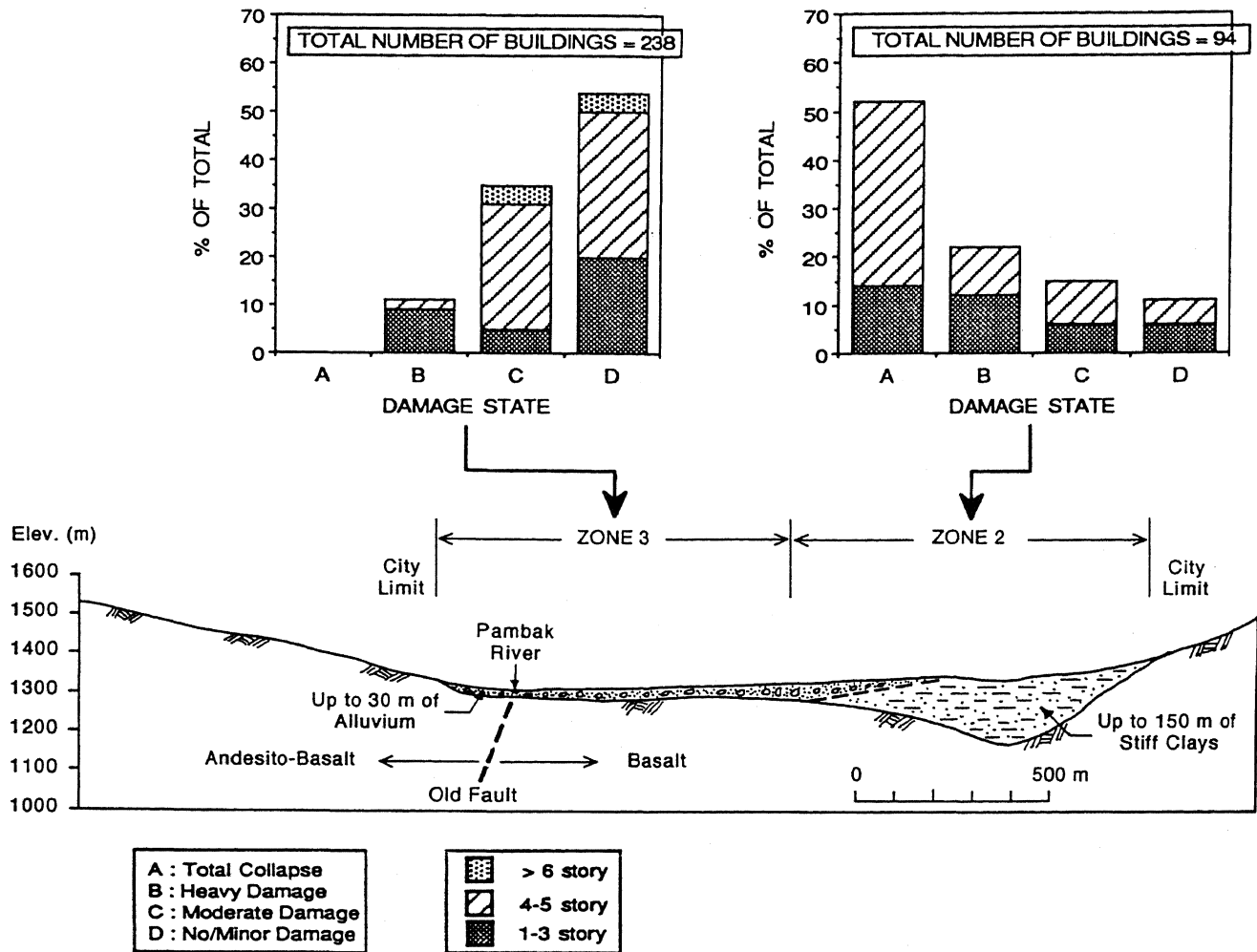


Fig. 5. Geotechnical Profile Through Zones 2 and 3 in Kirovakan, and the Corresponding Damage Statistics

Figure 6 compares the computed spectral accelerations for the 150 meter soil column of Zone 2 with that for a typical shallower soil column characterizing most part of Kirovakan where damage was very little (Zones 3 and 4). In Figure 6, although the spectral accelerations are slightly higher for Zone 2 (150m profile) than the shallower profile of Zone 4, their difference is not large enough to explain the very significant disparity of damage statistics in these two regions. For example, in Zone 2, where only one to five story structures with periods 0.25-0.4 seconds were built, 74% of the buildings either collapsed or were heavily damaged beyond repair; whereas, for the same type buildings in the rest of the city none collapsed and only 14% suffered heavy damage. This strongly suggests that the 1-D vertical wave propagation approximation substantially underestimates the amplification of motions in Zone 2, where the sedimentary basin width-to-maximum-soil-thickness ratio is only about 5.

A further comparison of spectra computed by 1-D soil amplification analysis for Leninakan and for Kirovakan's Zone 2 are made in Figure 7. The building damage statistics presented in Figure 5 indicate that of the four to five story structures with periods 0.25-0.40 seconds (the predominant type in Zone 2 in Kirovakan), about 62% collapsed or were damaged beyond repair; but only 21% of the similar structures collapsed in Leninakan. Yet, the computed response spectra shown in Fig. 7 predict almost the opposite trend. This leaves little doubt that for Zone 2 in Kirovakan 1-D soil amplification analysis substantially underpredicts the ground surface motions --- consistent with the earlier conclusion stemming from the comparison of the calculated spectra shown in Figure 6.

Empirical and theoretical evidence, compiled in recent years, show that earthquake ground motions on the surface of valleys similar to that of Kirovakan's Zone 2 are **stronger and longer** than the motions predicted with 1-D wave-propagation theories or recorded/experienced

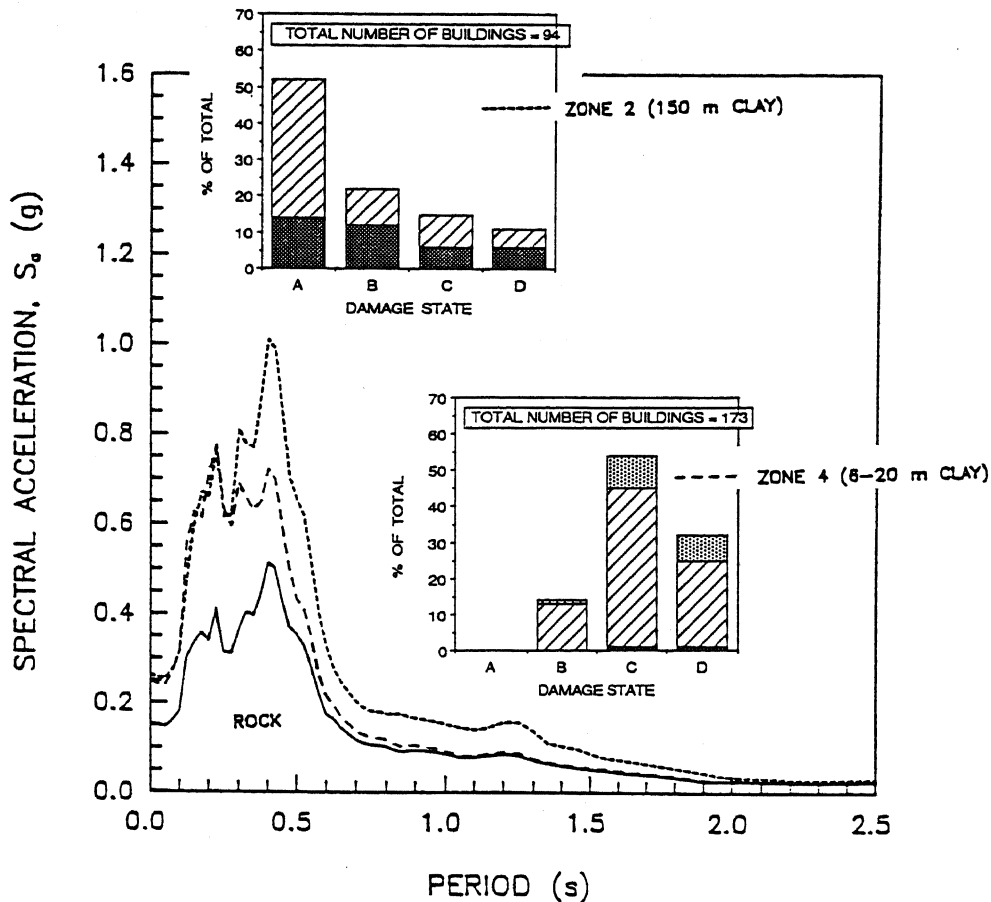


Fig. 6. Acceleration Response Spectra (5% Damping) Computed by 1-D Soil Response Analysis for Zones 2 and 4 in Kirovakan and the Corresponding Building Damage Statistics

on top of very wide plains (such as the Shirak Valley of Leninakan). Several wave-propagation phenomena, akin to the 3-D geometry, have been recognized as producing these deleterious effects: wave **focusing** tends to amplify the motion primarily near the center of the valley; **surface waves**, generated at the (steep) edges, propagate back and forth across the valley; "**trapping**" of obliquely-incident body waves amplifies the motion experienced near the edges of the valley.

The authors have presented theoretical results that lead to the conclusion that 3-D valley effects on the shaking of the ground surface in Zone 2 must have played an important role (Yegian et al. 1993b).

SUMMARY

The extent and pattern of damage from the 1988 Armenia earthquake posed a number of questions of interest to geotechnical and structural earthquake engineers.

Throughout the course of the authors' investigations, it became evident that a close link exists among seismological, geological, geotechnical and structural aspects of the earthquake, and hence no single factor alone convincingly explains the extent and, especially, the geographic peculiarities of the disaster.

Soil amplification was one of the significant factors but not always the dominant one. Other factors, including the high level of seismic shaking associated with the $M_s=6.8$ earthquake, and the high seismic vulnerability of the vast majority of buildings must have been important contributors to the overall destruction during the 1988 Armenia earthquake.

One-dimensional soil amplification analysis for Leninakan, where the ratio of width-of-valley to soil thickness is about 55, yielded reasonable results. Many of the patterns in building damage distribution and various field observations could be adequately confirmed with the results of such 1-D analyses (Yegian et al. 1993a).

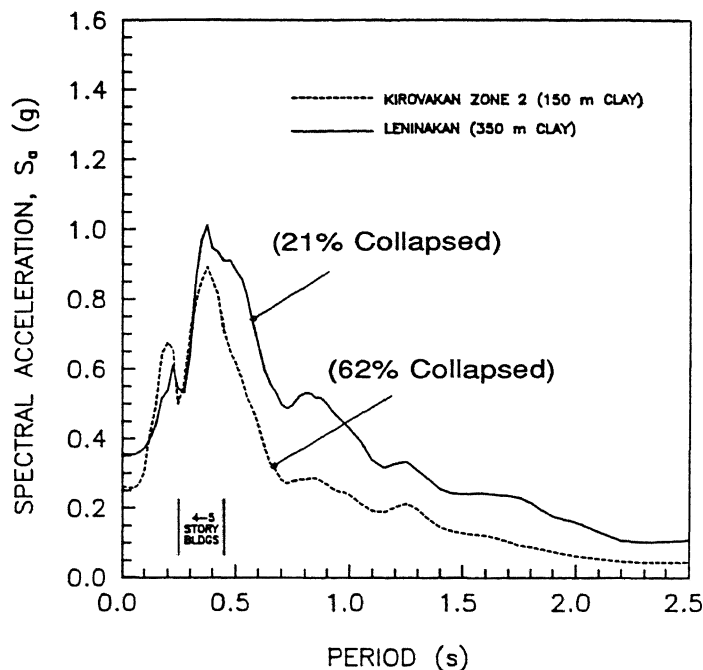


Fig. 7. Comparison of One-Dimensional Amplification Results for Soil Profiles of Leninakan and Kirovakan (Zone 2)

In a particular region of Kirovakan, where the ratio of the width of the sedimentary basin to soil thickness is about 5, building damage was very high. For this region, 1-D soil amplification analysis substantially underpredicts the ground surface motions. 3-D valley effects on the ground shaking must have played an important role in this region of Kirovakan.

ACKNOWLEDGEMENT

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