Title: The December 7, 1988 Armenia earthquake effects on selected power, industrial and commercial facilities

Contributor: R.D. Campbell

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THE DECEMBER 7, 1988 ARMENIA EARTHQUAKE EFFECTS ON SELECTED POWER, INDUSTRIAL, AND COMMERCIAL FACILITIES

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Section 1
INTRODUCTION

On December 7, 1988, at 11:41 A.M. local time, a powerful earthquake of body-wave surface magnitude 6.83 struck northwest Armenia, a Soviet republic with 3.5 million people. Armenia occupies approximately 30,000 square kilometers in the southern Caucasus Mountains, generally considered the boundary between Europe and Asia. The event caused catastrophic damage that resulted in tens of thousands of deaths in a 400-square-kilometer epicentral region occupied by approximately 700,000 people. Damage and several deaths also occurred in the Kars region of Turkey, 80 kilometers southwest of the earthquake's epicenter.

The Soviet estimate of the deaths in the Armenia Earthquake exceeds 25,000, but unofficial estimates put this figure at 2 to 3 times this number, making it one of the worst natural disasters of this century. The great majority of deaths were caused by buildings collapsing on occupants. Approximately 20,000 people were injured; more than 30,000 were left homeless with probably as many jobless. Fifty-two percent of Leninakan, Armenia's second largest city with 290,000 people, was destroyed or heavily damaged. Moderate damage also occurred in Kirovakan, the republic's third largest city with 150,000 inhabitants. Almost all structures in the town of Spitak, located near the causative fault, were essentially destroyed, and the majority of its 30,000 residents were killed. Over 350 smaller communities were affected, 58 of these completely destroyed. Over 8 million square meters of living space (residential) was destroyed, which is equivalent to 17% of the total residential space in the Armenia Republic (14).

In terms of human and economic loss the full impact of the Armenia Earthquake will never be known. On February 20, 1989, the Soviet press reported that property losses amounted to over $16 billion. Financial losses from business interruption and closing of the Armenian nuclear plant at Oktembryyan may double this figure. Perhaps the most striking aspect of this earthquake is that the worst damage and the majority of deaths resulted from the collapse of relatively modern buildings. Rarely has the importance of systematic risk identification
and proper seismic-structural design and construction in earthquake-prone areas been more apparent.

The following report on the Armenia Earthquake is based primarily on the observations from two separate reconnaissance efforts. The first effort was composed of a 19-member team of earthquake investigators sent by the United States to Armenia shortly after the event. The team, which was organized through an agreement between the United States Academy of Sciences and the Soviet Academy of Sciences, consisted of geologists, seismologists, structural engineers, search and recovery experts, and sociologists. Mr. Peter Yanev of EQE was the primary investigator for EPRI's study of electric power and industrial facility performance. The full U.S. team is identified in the appendix.

This first investigation had several problems. The major problem had to do with the severity and destructiveness of the earthquake, which placed a tremendous burden on the community. The request for additional resources to support the team increased this burden. This factored heavily in requests for transportation, and locating knowledgeable facility engineers and the time for interviewing them. A second major problem was obtaining information on types of facilities and locations. Information, such as location of power plants, substations, dams, etc., is not general knowledge among Soviet researchers or professionals. Valuable time was spent in determining sources for this type of information. However, once the facilities of interest were located, the facility personnel were most receptive to the investigative teams' information requests. Because of the above problems, essentially 24 hours out of eight days were spent actually collecting data. Thus, a second reconnaissance was necessary.

The second investigative effort occurred in conjunction with an international symposium on the Spitak Earthquake held May 23-26, 1989, in Yerevan, the Soviet Republic of Armenia, which was sponsored by the United Nations Educational, Scientific and Cultural Organization (UNESCO). Dr. Charles Scawthorn and Mr. Michael Griffin of EQE participated in the symposium and spent an additional three days investigating the earthquake. The three days were spent in the high-intensity areas of Leninakan, Spitak, and Kirovakan. While the same problems existed as during the first effort, albeit to a lesser degree, new data were collected in Kirovakan and Leninakan, as well as corroboration of the information collected during the first effort. This report reflects data collected from both of these reconnaissance efforts.
The earthquake of December 7, 1988, occurred north of the interface of the Eurasian and Arabian tectonic plates, a band of moderate to high seismicity that extends from northeastern Turkey southeastward into the Indian Ocean. The location of the earthquake was in the highlands on the southern side of the Caucasus Mountains. The Caucasus range itself is evidence of the compressional effects of the tectonic interface, where the southern Arabian plate is subducting beneath the Eurasian plate.

2.1 HISTORICAL SEISMICITY

Northern Armenia is a region of moderate seismicity compared to neighboring zones to the south, such as the northeastern Mediterranean coast, Turkey, or Iran. For example, within this century major earthquakes to the south have included events in eastern Turkey in 1971 (M = 6.8), 1966 (M = 6.8), 1930 (M = 7.3), and 1924 (M = 6.9) (1, 2).

The historical seismicity of Armenia has been generally confined to moderate events. The long-term history of the Armenian region indicates damaging earthquakes in 863 A.D., in 1045, in 1283, in 1320, and in 1679 are greater than magnitude 5. Within this century several events with estimated magnitudes between 5.5 and 6.0 have caused damage. These include earthquakes in 1899, 1926, 1935, and 1940. The most serious was the 1926 event, estimated at magnitude 5.7. It was reported to have killed several hundred people and damaged thousands of structures (1, 2).

Northern Armenia includes a complex pattern of thrust faults that generally trend in a northwest-southeast direction, following the compressional interface of the two tectonic plates to the south. Because of its historically moderate seismicity, the region has received only minor attention in seismological studies until the recent event. Therefore not all of the active faults within the area
have been mapped. The recent earthquake, for example, appears to have occurred along an extension of a fault that has not shown significant activity within historical time. It is likely that this earthquake represents the "1,000 year event" (7).

2.2 GEOLOGIC SETTING

The northwestern section of Armenia affected by the earthquake is a high plateau of mountains interspersed with river valleys containing the populated areas. The earthquake-affected region lies at elevations ranging from 1,500 to 2,000 meters above sea level (Figures 2-1 and 2-2).

Volcanic formations dominate the local geology. The highest peak in the country is the inactive volcano Mount Aragats (4,090 meters), lying directly southeast of the city of Leninakan. The mountainous areas and the bedrock underlying the river valleys consist primarily of igneous rock--basalts, andesites, rhyolites, pumice, and volcanic tuffs (3, 4).

The major populated areas damaged by the earthquake are located on deep alluvium in river valleys. The city of Leninakan is located in the Shirak Valley along the Akhurian River, which drains south into the Aras River on the Turkish border. The towns of Nalband, Spitak, and Kirovakan are located northwestward across a mountain pass in the valley of the Pambak River, which drains to the northeast.

The soils of the river valleys are the product of periodic glaciation and natural weathering of the volcanic rock. Soil deposits were laid down by a combination of alluvial fans from ancient rivers, glacial till, and sedimentation from lakes that have covered the area in the past. Typical soil profiles in the valleys include interbedded layers of sand, clay, loam, and gravel. Occasional pockets of lava indicate volcanic action within the last million years. Shear-wave velocities for various soils near the surface range from 200 meters/second for clay, 300 meters/second for gravel, and 500 to 600 meters/second for the volcanic tuff deposits (4).

Soil deposits in the Shirak Valley near Leninakan reach a depth of about 300 meters. The water table in the area is close to the surface, typically at a depth of 3 to 6 meters. Soil depth in the Pambak Valley near Spitak is more shallow, ranging from about 20 to 40 meters (3). The town of Kirovakan, southeast of Spitak, is founded partially on shallow soil and partially on recent
volcanic deposits. Local soil conditions appeared to have some influence on damage intensity. Leninakan, with its foundation of deep damp soil, was more heavily damaged than Kirovakan, although the two cities are roughly the same distance from the location of surface faulting.

2.3 FAULTING

The fault mechanism was a reverse thrust with a right-lateral strike-slip component, as illustrated in Figure 2-3 (adapted from 5). The mechanism was actually more complicated, with substantial curvature to the rupture surface (15). The rupture initiated at the intersection of a reverse fault with two right-lateral faults. The northern section of crust pushed upward over the southern section and shifted slightly along the rupture to the east-southeast. The fault plane dips toward the north-northeast at 55° from the horizontal. The orientation of the rupture, or strike, was reported as 292°, or west-northwest (5). Hypocentral depth was estimated as shallow, about 10 kilometers.

Faulting broke the surface at sporadic points over a length of about 8 kilometers, roughly from the town of Spitak to the village of Nalband (Figure 2-2). The vertical displacement of the surface scarp was measured as a maximum of 1.6 meters, but averaged about 1 meter of offset over most of the length. Surface breaks ranged from a single concentrated scarp to a series of breaks over widths of about 10 meters (5).

The following preliminary parameters of the main shock were computed by the National Earthquake Information Center (NEIC) and the U.S. Geological survey (USGS):

- Body wave magnitude $m_b = 6.3$
- Surface wave magnitude $M_s = 6.8$

Based on preliminary calculations, Lamont-Doherty Geological Observatory computed the following parameters:

- Moment = $1.0 \times 10^{26}$ dyne-cm
- Moment magnitude $M_w = 6.6$

For comparison, the California Institute of Technology Seismological Laboratory computed:
Moment = $1.7 \times 10^{26}$ dyne-cm

Moment magnitude $M_w = 6.8$

All parameters listed above were reported in Reference 2.

2.4 EARTHQUAKE SEQUENCE

The sequence of seismic events is listed in Table 2-1 (2). The main shock of December 7 was preceded the previous day by a minor foreshock. The foreshock created little notice since it is typical of the moderate seismicity of the region. The main shock at 7:41 A.M. UTC on December 7 was followed 4 minutes later by a strong aftershock, which added to the damage. A dozen strong aftershocks occurred within the next month, several of them of significant size, such as the event of January 4.

Portable strong-motion seismographs were set up in the weeks following the earthquake. The epicentral locations of aftershocks were reported to follow two general zones, a linear pattern extending from the surface scarp toward the southeast, and a scattered pattern to the west of the surface scarp (2).

The spread of the aftershock activity, rather than clustering close to and in alignment with the surface scarp, may indicate complexities in the source of the main shock. Based on studies by Lamont-Doherty Geological Observatory of the long-distance body waves (15), it is possible that the earthquake was caused by two or more distinct fault ruptures, occurring some distance from each other and in slightly different alignments (2). This would mean that the reverse thrust defined by the surface scarp (described in the previous section) would represent only part of the causative faulting of the main shock.

2.5 STRONG-MOTION RECORDS

A strong-motion instrument recorded the main shock in the town of Gukasian, 27 kilometers north of Leninakan, and some 15 to 20 kilometers west of the fault trace. This instrument was operated by the Institute of Geophysics and Earthquake Engineering in Leninakan. It produced the only accelerographs within the strong-motion area of the main shock (6).

The Gukasian instrument was reported to be a Soviet-made accelerograph, recording three components of motion on optical film (6). The instrument apparently was founded on firm soil. The recorded accelerograms for the two horizontal
components of motion in the main shock were digitized at the University of California Seismographic Station. The resulting accelerograms are reproduced in Figure 2-4 (6). The corresponding pseudo-acceleration response spectra are shown in Figure 2-5, plotted as a function of period (6).

The accelerograms indicate about 7 seconds of strong motion (accelerations exceeding 0.1g). The peak accelerations of the two horizontal components are comparable, about 0.21g for one component and about 0.19g for the other. (The specific orientation of the two horizontal components has not been reported.)

Both components of motion are seen by the response spectra to be rich (broadband) in frequency content. As shown by the spectra plotted in Figure 2-5, component 1 has a lower frequency content with three distinct peaks at about 1, 3, and 6 Hz. The spectral peak for component 1 is about 0.5g (5% damping). Component 2 has a more-uniform broadband frequency content, ranging from about 2 to 8 Hz, with a spectral peak of about 0.7g.

Within the city of Leninakan were located several seismographs and strong-motion instruments operated by the Institute of Geophysics and Earthquake Engineering. Unfortunately, four of the instruments were destroyed by the collapses of the buildings in which they were housed. Seismographic recording stations that survived the earthquake included single- and multi-pendulum seismoscopes and displacement seismographs.

Although the seismoscopes do not measure acceleration, estimates can be made from their measured amplitude of displacement. Based on established correlations between seismoscope displacement and peak ground acceleration, it is estimated that Leninakan may have experienced a peak ground acceleration as high as 0.4g (6). The soft, deep alluvium underlying most of the city likely produced substantial amplification due to resonance with the motion at the deeply buried bedrock interface. Studies of the seismoscope recordings indicate that perceptible motion lasted over 1 minute in the Leninakan area due largely to trapped surface waves. The motion was apparently of low-frequency content, about 1 to 2 Hz, characteristic of the soft soil and distance from the fault.

Extensive studies of aftershock recordings have been conducted by Borcherdt et. al. in an effort to correlate observed ground motion and damage with local geologic conditions (15). Recordings of large aftershocks were obtained at four
sites in Leninakan and at sites in a region underlain by rocks. Findings indicate that ground response (both in amplitude and duration of horizontal ground motion) at periods of 0.6 to 3 seconds was significantly greater in Leninakan than at other sites at similar distances founded on rock. Peak spectral amplification ratios of horizontal motion 20 to 30 times larger than at equidistant rock sites were obtained. The spectral ratios suggest that the site conditions beneath Leninakan significantly amplified the ground motion causing the extensive damage observed.

2.6 CONCLUSIONS

The Armenia Earthquake of December 7, 1988, is an event of moderate magnitude for the region lying north of the Eurasian-Arabian tectonic interface. Based on examination of the surface faulting, the event appears to have been caused by reverse thrusting of the northern crust over the southern, coupled with a secondary right-lateral strike-slip component. However, the aftershock pattern indicates that faulting was more complex, involving two or more ruptures starting at different locations on different fault planes.

Local site conditions influenced the intensity of ground motion and subsequent damage to populated areas. The city of Leninakan suffered far more damage than the city of Kirovakan, due to amplification and increased duration of longer-period motions experienced in Leninakan. Although the cities are at similar distances from the fault and epicenter, Leninakan is founded on deep alluvial deposits while Kirovakan is founded on shallow soil or rock.

The only accelerogram from the main shock was recorded by a strong-motion instrument in the town of Gukasian, north of Leninakan and about 15 to 20 kilometers west of the surface scarp. Peak horizontal ground accelerations of about 0.21g and 0.19g were recorded by the instrument, which is reported to be founded on rock or firm soil. The record shows a broadband frequency content, but a relatively short duration of strong motion. About 80 kilometers to the south, an instrument in Yerevan recorded about 0.06g, also on a rock foundation. Based on measured displacements of seismoscopes in Leninakan, peak ground acceleration in that city has been estimated at perhaps 0.4g. Comparing the levels of damage in Leninakan and in Nalband and Spitak adjacent to the fault, it is apparent that peak ground acceleration in the near field likely exceeded 0.50g and may have approached 1.0g.
Table 2-1
THE SEQUENCE OF SEISMIC EVENTS SURROUNDING
THE MAIN SHOCK OF 7:41 A.M., DECEMBER 7, 1988 (2)

<table>
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<td>Min</td>
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<td>15</td>
<td>55.7</td>
<td>4.8</td>
</tr>
<tr>
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<td>01</td>
<td>49</td>
<td>41.4</td>
<td>4.1</td>
</tr>
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<td>09</td>
<td>37.2</td>
<td>4.7</td>
</tr>
<tr>
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<td>46</td>
<td>00.0</td>
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<td>06.2</td>
<td>4.7</td>
</tr>
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</tr>
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Figure 2-1. Geographical location of the Armenia Earthquake of December 7, 1988.
Figure 2-2. Armenia Earthquake of December 7, 1988, epicentral area (Courtesy T. D. O'Rourke).
Figure 2-3. Faulting can be described as a reverse thrust with a right-lateral strike-slip component as illustrated by the sketch above (adapted from Reference 5). The ground surface was broken over a distance of about 8 kilometers between the towns of Nalband and Spitak.
Figure 2-4. Accelerograms for two horizontal components of motion from the instrument at Gukasian (reproduced from Reference 6).
damping ratio = 0.05

Figure 2-5. Response spectra for the two horizontal components of motion recorded by the instrument at Gukasian (reproduced from Reference 6).
The Armenia Earthquake of December 7, 1988, had a devastating impact on building structures located within the epicentral area. As learned from previous earthquakes, certain types of building construction are more vulnerable to earthquake ground motion than others. This was substantiated during the Armenia Earthquake; however, numerous engineered structures suffered severe damage, complete collapse in many instances, as a result of the earthquake. This chapter discusses the Soviet design code, design practices, and the performance of these designs in the earthquake. A brief look at reconstruction efforts is also presented in light of the devastating structural damage that occurred.

3.1 SOVIET DESIGN CODE

Building construction in seismically active regions of the Soviet Union follows the guidelines given in Part II, Chapter 7, of Standards and Regulations for Construction, USSR Gosstroy (8). Chapter 7 is the basic building code used throughout the Soviet Union for the seismic design of structures and uses an approach similar to that found in the U.S. Uniform Building Code (UBC).

The Soviet building code divides the country into seismic zones defined by the maximum ground shaking intensity expected in each region. Each zone is assigned a number on an intensity scale, which ranges from I to XII. This intensity scale, known as MSK-64 (Appendix B), is very similar to the Modified Mercalli Intensity scale used in the United States, but also assigns an expected ground acceleration to each intensity level. The provisions of Chapter 7 apply only to seismic zones rated intensity VII, VIII, or IX. The Soviet design philosophy assumes that earthquakes corresponding to intensity VI and below do not result in serious damage, and therefore buildings in these zones need not be designed for seismic loading. The Soviets also believe that it is not practical to design for the seismic forces generated by earthquakes of intensity X and greater. As a result, construction is not supposed to be permitted in zones X, XI, and XII.
The building code adjusts the assigned intensity of a given seismic zone based on the local soil properties. To this end, three soil categories are described in the code. Basically, the code allows a one-point reduction in intensity for stiff soils, no modification for medium soils, and a one-point increase in intensity for poor soils.

The Soviet seismic design formula defines a nominal seismic load, applied to point \( k \) and corresponding to the \( i \)-th building frequency, by the following equation:

\[
S_{ik} = K_1 K_2 S_{0ik}
\]

For structures with a fundamental period equal to or less than 0.4 second (25 Hz), only one building period (frequency) is included in the analysis. For all other structures, at least three frequencies must be considered. \( K_1 \) is a multiplier that allows for a reduction in the design acceleration based on a structure's importance. \( K_1 \) is set equal to 1.00 for structures in which residual deformation and local damage are unacceptable, such as nuclear power plants. For structures in which residual deformation, cracking, etc., are acceptable, \( K_1 \) is set equal to 0.25. It is accepted that damage caused by the design basis earthquake will interfere with the normal use of these buildings. For structures "not containing valuable equipment" and where "human safety is assured," \( K_1 \) is set equal to 0.12.

\( K_2 \) is a multiplier that accounts for the structural system used and reflects the ability of the system to adequately resist the dynamic loading. Values of \( K_2 \) range from 0.9 for large panel buildings less than six stories tall, to 1.5 for high-rise structures.

\( S_{0ik} \) is the value of the seismic load at the \( i \)-th period (frequency) of the structure at node \( k \), as determined by the formula:

\[
S_{0ik} = Q_k A \beta_i K_4 N_{ik}
\]

where \( Q_k \) is the weight of the building at node \( k \). "A" refers to the applied ground acceleration and equals 0.1g, 0.2g, or 0.4g for Intensities VII, VIII, and IX, respectively. The variable \( \beta_i \) is a dynamic amplification factor obtained from a set of acceleration response spectra provided in the code. As shown in Figure 3-1, a spectral curve is provided for each of the three soil categories.
described in the code. A design acceleration multiplier is read from the appropriate curve for each frequency considered.

$K_4$ is an amplification factor that varies from 1.5 for flexible structures to 1.0 for stiffer structures. Flexibility is determined by a building's structural type and height-to-width ratio.

$N_{ik}$ represents an equation that computes the forces throughout the structure, based on the modal displacement of the structure at the frequency under consideration at node $K$. For analyses requiring more than one frequency, results are combined by the Square Root of the Sum of the Squares (SRSS) method.

Analyses in the two orthogonal horizontal directions are treated as separate, independent cases, and torsion must be considered when buildings are longer or wider than 30 meters. Vertical seismic loads are normally considered for the following cases only:

- Cantilevers (horizontal and sloping)
- Bridge spans
- Trusses, arches, and girders
- Toppling or sliding
- Stone structures

Design forces are calculated by combining load cases in a manner similar to that found in the UBC; different load combinations are specified in the code, along with appropriate combination multipliers. For strength and stability analysis, modifying factors are also given, based on the structural material used.

In summary, the Soviet seismic design code appears to be very similar in philosophy and approach to the U.S. Uniform Building Code.

3.2 BUILDING DESIGN AND PERFORMANCE

The Soviet design code has specific requirements for three categories of usage: public and industrial buildings (including houses), transportation facilities, and hydroelectric facilities. In general, the design and analysis of transportation and hydroelectric facilities are more conservative and detailed than for other structures.
There are essentially four basic modern structural types in Armenia that were affected by the earthquake:

- Masonry bearing wall
- Precast concrete frame
- Precast concrete large panel
- Concrete lift-slab with concrete frame

All design and construction in the Soviet Union are performed by government design institutes and the State Committee for Construction Affairs (Gosstroy). A limited number of buildings are developed by these agencies, with no special provisions for seismic loads. Instead, a local agency is responsible for modifying the generic design to account for seismic loads, following strict cost and material limitations. In Armenia, wood and structural steel are scarce, and hence minimized as construction materials.

Industrial facilities are predominantly concrete-frame structures, though a few steel frames have been constructed. Affected buildings in Armenia were generally designed to code criteria for Intensities VII and VIII. Actual intensities were probably from VII to VIII in Leninakan and IX to X or more in Spitak.

The three largest cities that sustained heavy damage during the earthquake are Spitak, Kirovakan, and Leninakan. Of the total number of multistory residential buildings in the city, 87% of these structures in Spitak collapsed or sustained heavy damage. In Kirovakan and Leninakan, this number is 24% and 52%, respectively (2). Table 3-1 provides a summary of the damage to multistory residential structures in the three cities. In addition, the Soviet press reported that the earthquake shut down 130 industrial facilities in the epicentral area.

Following is a discussion of the building types found in the affected region and a brief summary of their structural performance.

- Masonry Bearing Wall. Most of these buildings were constructed prior to 1970, and usually do not exceed five stories in height. Typically, the bearing walls are constructed with two wythes of stone blocks joined by mortar, with some steel reinforcement. In newer structures erected since about 1950, the floors and roof use precast, hollow-core planks that bear on the walls. Most often,
planks are not tied together, nor is a topping slab used. This results in a poor diaphragm for transferring lateral loads.

Performance. Bearing wall buildings were the predominant structural type in Spitak, and almost all were totally destroyed. Many of these buildings were also constructed in Leninakan, where they suffered substantial damage. In many structures, walls tilted away from the concrete floor planks, resulting in the collapse of floors. In some structures, the walls toppled completely. In other buildings, end walls survived, but the middle of buildings collapsed, indicating that the connections of precast planks to walls were inadequate to transfer the lateral loads into the end walls. Figures 3-2 and 3-3 show partially collapsed bearing wall buildings at the Spitak Sugar Refinery and an electrical substation near the town of Nalband.

Precast Concrete Frame. The majority of frame buildings in Leninakan were nine-story residential apartments, built to one of three floor plans of the Soviet Building Type III Series. Construction of precast concrete-frame buildings began in the 1970s, and has become the predominant design for both residential and industrial/commercial structures in the Soviet Union and much of Eastern Europe. The design typically uses a rectangular configuration, with floors and roof constructed of hollow-core, precast planks. The precast planks are not interconnected, nor is a topping slab provided. The precast planks also lack positive attachment to the building frame. Interior and perimeter walls are typically unreinforced masonry infill or precast concrete panels. The precast concrete frames provide stability (as moment frames) in the longitudinal and transverse building directions, while infill or precast panels are intended to stabilize the transverse direction. However, the precast panels are few in number and often contain openings for doors.

Performance. The precast-frame buildings sustained a variety of damage. In general, they performed very poorly. Infill masonry walls often fell out of the frames, resulting in a loss of stability. Poor connections between the infill walls and precast panels to concrete frames failed to adequately transfer loads into the walls. Infill walls that did resist significant amounts of shear worked their connections, spalled, and cracked. Where openings in the shear walls occurred, spandrel beams were often shattered. Numerous cases of severe damage at column splices were also observed. Figure 3-4 shows typical damage to a precast-frame building at an industrial site.

As was found with the bearing wall buildings, the lack of continuity in the intended floor diaphragm systems resulted in an inability to transfer out-of-plane loads to the resisting structural elements. Several buildings were observed where the ends of the structure were still standing, but the middle section had collapsed (Figure 3-5).

Precast Large Concrete Panel. This building type is essentially a bearing wall structure that uses large, precast concrete panels for the vertical- and lateral-load-resisting elements. Typically, cast-in-place concrete is used to connect the panels at horizontal
and vertical joints using pour pockets. Reinforcing steel in the panels is apparently extended into the cast-in-place pocket sections. In addition, almost all precast interior walls are used for vertical and shear load resistance, resulting in a very stiff, redundant system. Precast concrete planks are used for the roof and floors. Positive connections between the various structural elements were observed. The quality of the precast concrete members appeared to be good, but field work often appeared careless.

Performance. Approximately 16 precast panel buildings were completed or under construction in Leninakan at the time of the earthquake, and ranged in height to 9 stories. Performance of these buildings was very good, with little obvious damage. There was also one 5-story, precast, large panel building located in Spitak that appeared to have suffered only minor damage. It was the only building in the city without major structural damage.

- Concrete Lift-slab. Many lift-slab structures have been constructed in Armenia, but only two were located in the affected area.

Lift-slab buildings are constructed around cast-in-place concrete shear cores. Floor slabs are cast on the ground, lifted to the appropriate story height, and connected to supporting columns. The shear core provides lateral stability for the structure, and attachment of the slabs to the core is critical for building performance. The two lift-slab buildings affected by the earthquake were located in Leninakan and were 10 and 16 stories high. The 10-story structure used dual shear cores, while the 16-story building relied on a single core.

Performance. The 10-story dual-core building collapsed completely and could not be investigated. The 16-story building shown in Figure 3-6 did not collapse, but was damaged beyond repair. Observations of the building indicated that the building experienced a significant rocking response to the ground motion.

- Steel Frame. Several steel-frame buildings were investigated at large industrial complexes in the affected area. These structures tend to have long, rectangular, low- to mid-rise configurations. The structural system typically relies on steel bracing and/or moment-resisting frames for lateral resistance.

Performance. Extensive damage to infill masonry walls was observed in steel-frame buildings. Damage to the steel frames, however, appeared to be minor and repairable. Figure 3-7 shows the intact steel-frame building at the Spitak Sugar Refinery, with collapsed masonry curtain wall.

3.3 RECONSTRUCTION

Due to the extreme devastation of the earthquake, major reconstruction efforts are being undertaken. During the May reconnaissance effort, extensive construction was observed in Leninakan, Figure 3-8, where Soviet authorities
reported that approximately 80% of the engineered structures were destroyed. Spitak is intended to be reconstructed approximately 10 kilometers south of the essentially destroyed city.

Soviet officials have been quick to develop a reconstruction program for Armenia. The existing seismic resistance criteria have been enhanced for new construction, based on new microzonation levels established for the epicentral areas. As established by Gosstroy, the Soviet Union State Committee for Construction Affairs, the maximum story height mandated for new construction is five stories. Additionally, the problem addressing quality of construction is being reviewed, as it was a major contributor to building damage. Current thinking as reported by Michael Melkumian, Chief of Laboratory, Armenian Scientific Research Institute of Civil Engineering and Architecture, is for design and construction practices to focus on more precast building element construction, as it is believed that a higher level of quality can be obtained in the precast concrete factories. However, additional study must be placed on connectivity of the precast building elements. Numerous poor connection details contributed to collapse of precast-frame buildings, as they were insufficient to resist the seismic loads.

In summary, massive reconstruction efforts are occurring in Soviet Armenia. The intent of studying building performance when subjected to earthquakes is to understand current design behavior such that adequate changes can be incorporated into design codes and construction practices to mitigate similar destruction from occurring in future earthquakes.

3.4 CONCLUSIONS

Several factors appear to have significantly affected the performance of engineered structures in Armenia. These observations are summarized as follows:

- Ground shaking in the hardest-hit areas was higher in intensity than the design basis earthquake. This deficiency was possibly compounded further by soil amplification of the ground motion in Leninakan.

- The use of nonductile building materials, structural configurations, and structural details, such as masonry bearing walls and underreinforced precast concrete frames, severely limited the capacity of buildings to absorb inelastic deformations.

- Connections and other structural details were poorly designed and/or constructed with little ductility, and often formed the weak link in overall seismic performance.
The lack of competent floor and roof diaphragms greatly compromised the buildings' integrity. The poor performance of many structures could be directly attributed to the inability of the diaphragms to distribute inertial loads to the resisting structural elements due to poor connection details.

Poor construction quality was evident in many damaged buildings and obviously affected seismic performance.
Table 3-1

DAMAGE STATISTICS FOR MULTISTORY RESIDENTIAL STRUCTURES*

<table>
<thead>
<tr>
<th>City</th>
<th>Precast Panel (5,9 Stories)</th>
<th>Precast Frame (5,9,12 Stories)</th>
<th>Composite Frame Stone (4,5 Stories)</th>
<th>Stone Masonry (≤4 Stories)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% No.</td>
<td>% No.</td>
<td>% No.</td>
<td>% No.</td>
</tr>
<tr>
<td>Spitak</td>
<td>0 1</td>
<td>0 0</td>
<td>88 9</td>
<td>88 25</td>
</tr>
<tr>
<td>Kirovakan</td>
<td>0 4</td>
<td>0 108</td>
<td>23 571</td>
<td>41 244</td>
</tr>
<tr>
<td>Leninakan</td>
<td>0 16</td>
<td>95 133</td>
<td>62 229</td>
<td>38 498</td>
</tr>
</tbody>
</table>

Percentages are of structures collapsed or needing to be demolished (9), Page 25.

*
Figure 3-1. Design acceleration response spectra for the three Soviet soil categories. Soil category I is stiffest, followed by II and III, respectively.
Figure 3-2. Partially collapsed bearing wall building at the Spitak sugar mill.

Figure 3-3. Damaged masonry bearing wall building at an electrical substation near Nalband.
Figure 3-4. Damaged industrial precast-frame high-bay structure in Spitak. Typically, these structures collapsed completely in Spitak.

Figure 3-5. Collapsed precast-frame building. Building is the Spitak Telephone central office.
Figure 3-6. This 16-story lift-slab building in Leninakan was damaged beyond repair.
Figure 3-7. Steel-frame structure at the Spitak Sugar Refinery. Note collapsed in-fill masonry wall.
Figure 3-8. The New Leninakan being built to the northwest of the Devastated City. Maximum story-height has been limited to five stories, mandated by Gosstroy, the Soviet Union State Committee for Construction Affairs.
4.1 INTRODUCTION

The region affected by the December 7, 1988, Armenia Earthquake included the cities of Leninakan, Nalband, Spitak, Stepanavan, Kirovakan, and Razdan. More than 700,000 people were affected. The region is highly industrialized and contains numerous light and heavy industrial facilities and various power facilities. For example, Kirovakan has large chemical food processing, machine tooling, and other light industries; several large electrical substations; and a thermal power plant. Spitak also has large food processing (sugar and flour mills), machine tooling, and other industries. Leninakan is well known for its textile, machine tool, shoe, woodwork, glass, precast concrete, electronic, and numerous other industries. Most of this industry has developed during the last 40 years.

The industry of the area was devastated by the earthquake. At first, the Soviet authorities reported that the earthquake caused work stoppages in at least 300 factories in the strongly shaken region. The Spitak industries observed were all severely damaged and experienced long-term business interruption. Many if not most industrial structures collapsed completely or were severely damaged. The Soviet authorities reported that about 52% of the engineered structures in Leninakan, a city with a population of about 290,000 people, were destroyed.

The effects on power facilities in the region were much less severe; however, extensive damage occurred in localized areas. Figure 4-1 presents a schematic diagram of the power system in and around the area. The affected facilities include the 220-kV Leninakan-2 electrical substation and the smaller 110-kV Leninakan-1 electrical distribution station, the 110-kV electrical substation at Nalband, the thermoelectric power station and two 220-kV electrical substations in Kirovakan, and a large thermoelectric power station in Razdan. Damage varied throughout these facilities. For example, the two major electrical substations in Leninakan were lightly damaged. In contrast, the major electrical substation...
in Nalband suffered major damage. Both thermal power plants were affected: the one in Kirovakan suffered light to moderate damage (primarily to building structures), and the unit in Razdan experienced light damage.

The earthquake was also felt at the two-unit Armenia nuclear power plant located approximately 75 kilometers south of the epicenter. Only minor shaking occurred and no damage was reported. However, the earthquake figured importantly in a decision by the Soviet government to close the plant permanently.

In terms of economic loss the impact of the Armenia Earthquake will not be fully known. The only official estimate has come from the Soviet press on February 20, 1989, which reported that property losses amounted to more than $16 billion. This figure has been supported from statistics that appeared in an Armenian newspaper dated March 17, 1989. The financial losses from business interruption and the closing of the Armenian nuclear power plant may result in the doubling of this figure.

Due to the large number of affected facilities, only a small percentage could be reviewed during the course of the two investigative efforts. The major power generation and distribution facilities were concentrated on as well as the larger industrial facilities that remained standing. In addition, it was not possible to interview knowledgeable facility managers or engineers for the majority of the facilities surveyed. Data collected were therefore from direct observations during the investigations. Some data on individual equipment and system operability were collected during the subsequent follow-up investigation conducted in May and are reflected in the following section, which summarizes the performance of several industrial and power facilities from each of the affected cities.

4.2 LENINAKAN

Leninakan is the second largest city of the Armenian Soviet Socialist Republic, the center of the Shirak economic region. The city covers an area of 36 square kilometers and had a population of 290,000 people prior to the earthquake. Its industry includes textile, machine-tool, food, shoes, clothes, precast concrete, woodwork, glass, and nearly 40 other industries occupying approximately 300 facilities.
The city of Leninakan suffered extensive damage. During the May reconnaissance it was reported (Hevhanisjan Sewada, Academy of Sciences, Leninakan) that approximately 25,000 people remained in Leninakan, with the remaining inhabitants displaced to other cities, such as Yerevan, during the reconstructive efforts.

The city is essentially being rebuilt to the northwest of the damaged city, due to the extensive devastation. Figure 4-2 shows a map of Leninakan and the area marked where the city is being rebuilt. The new construction for Leninakan includes predominantly reinforced concrete shear-wall structures. Figure 4-3 shows several photographs of the new structures under construction. The maximum story height for new Leninakan structures has been mandated at four by Gosstroy, the Soviet Union State Committee for Construction Affairs. The new buildings correspond to a revised microzonation level for the area of MSK intensity IX. This is an increase from the previous design intensity of VII and VIII.

A major result of studying the causes of building damage was the recognition by the Soviet technical communities that Soviet quality control on construction is poor. Discussions with scientists from the Armenian Scientific Research Institute of Civil Engineering and Architecture indicated that Soviet building design practices are under review in an effort to assess and correct the poor construction quality. The scientists believe building design should concentrate on preventing column failures by using cast-in-place construction for the columns and precast construction for the other building elements. They also believe that a greater level of quality can be achieved through the use of precast building elements (Source: M. Melkumian, Chief of Laboratory, Armenian Scientific Research Institute of Civil Engineering and Architecture).

The performance of industrial facilities in Leninakan during the earthquake was poor. Although investigative efforts concentrated on several facilities, it was reported (Hevhanisjan Sewada, Academy of Sciences, Leninakan) that none of the estimated 300 industrial facilities in Leninakan were operational following the earthquake. In fact, the majority of these facilities were completely destroyed with only three or four reported intact following the earthquake. None of the remaining facilities were believed to be operational during the May reconnaissance, five-and-one-half months following the earthquake. Figure 4-4 illustrates a concrete pipe and culvert manufacturing plant on the eastern edge of Leninakan where steel silos containing cement were undamaged. However, other plant structures sustained extensive damage.
The performance of power facility equipment in Leninakan, specifically the two substations Leninakan-1 and -2, was significantly better than that of industrial facilities. The performance of these two facilities is presented in the following sections.

Leninakan-1 Substation

The Leninakan-1 electric substation is located in the center of Leninakan near Lenin Square (See Figure 4-2). The substation contains a control house, two adjacent circuit breaker/switchgear buildings, and 110- and 35-kV switchyards. The control house and an adjacent circuit breaker/switchgear building were constructed in 1927. In 1960 the distribution capacity of the substation was expanded by extending the existing circuit breaker/switchgear building to the west. Minor structural damage occurred to the circuit breaker/switchgear buildings and substation equipment, with one fire occurring to an air circuit breaker/switchgear cubicle (top photo Figure 4-7). The cause of the fire is unknown. The substation was reported to have been down after the earthquake for three days, due to the extensive switchyard damage, before power could be restored. Peak ground accelerations at the facility are estimated at 0.40g.

The control house is a three-story, concrete-frame structure with unreinforced stone infill walls. The control room occupies the third floor, with the dc battery room located on the second floor. The remainder of the building contains various offices and maintenance shops. No damage occurred to the control house structure. Small interior plaster cracks were noted on the walls in the control room, however. The upper photograph in Figure 4-5 shows the Leninakan-1 control house.

The circuit breaker/switchgear buildings are two-story, concrete-frame structures with exterior unreinforced stone infill walls with precast concrete floor and roof members. Structural damage was isolated to the interface between the 1927 breaker building and 1960 building. Damage also occurred to the west end of the new building. In both areas, damage was limited to minor frame damage and damage to the stone infill wall sections. It appeared as if out-of-phase response (pounding) between the old and new buildings caused the damage. Surprisingly, none of the busbar sections that span across the building interface were damaged, in spite of damage that occurred to the busbar supports (Figure 4-6). Figure 4-7 shows a typical interior view of the breaker/switchgear building with a photograph of typical cable routing through the building.
The performance of equipment at the substation was marginal. In the 110-kV switchyard three 110/35-kV oil-filled transformers supported on wheels jumped off of their rails, but did not overturn. One transformer displaced sufficiently to pull the attached overhead bus wiring loose from the yard towers. This cascading effect resulted in extensive insulator damage. It was estimated by facility personnel that approximately 70% of the 110-kV yard insulators were damaged. This estimate appears high, based on direct observations. Three sets of 110-kV oil-filled circuit breakers performed well, with no damage occurring to the breakers or attached insulator columns. The breakers were anchored with six 1/2-inch-thick friction clips and 5/8-inch-diameter anchor bolts. Figure 4-8 shows the 110-kV switchyard, oil-filled circuit breakers, and a typical 110/35-kV transformer. No damage was reported in the 35-kV switchyard.

The control room equipment sustained no damage. The benchboards are standard front panel frame and open-back construction. The benchboards were unanchored, but have their bases recessed approximately 1-1/2 inches below the flooring, effectively wedging them in place. The relay panels were wall mounted and were welded at the top and bottom to embedded steel, typically at four places. The control room did not have a suspended ceiling. Figure 4-9 shows several photographs of the control room benchboards and relay panels. The unanchored dc batteries in the control house building were undamaged.

No damage occurred to equipment located in the two circuit breaker/switchgear buildings. The breaker or switch sections are housed in independent concrete cubicles along the length of the building. The fire that broke out was confined to one cubicle and quickly extinguished. The cause of the fire is unknown.

Leninakan-2 Substation

The Leninakan-2 electric substation is located in the southwest part of Leninakan and is the largest of the two substations in Leninakan. The substation contains a control building, air compressor building, and 220-, 110-, and 35-kV switchyards. Leninakan-2 is believed to have been constructed during the late 1920s. Leninakan-2 sustained relatively minor damage, particularly when compared to the damage experienced in the city of Leninakan and at the Leninakan-1 substation. Power to the 110-kV bus was restored approximately 13 hours following the earthquake, while power to the 220-kV bus was restored in approximately three days. Peak ground accelerations for the Leninakan area are estimated at 0.40g, but are believed to be high for the Leninakan-2 substation.
Equipment construction and support do not justify the relatively minor damage observed. For example, no unanchored station battery cells toppled over.

The control building is a single-story, precast concrete-frame structure with unreinforced stone infill masonry shear walls. One interior masonry wall was reported to have collapsed during the earthquake, but did not damage any equipment. Extensive cracking occurred in the north exterior shear wall. Also, nearly complete separation occurred from the west wall along the upper half of the wall height. Figure 4-10 shows two photographs of the north end of the control building and the damage discussed above.

The compressor building is a one-story concrete-frame structure with unreinforced stone masonry infill walls. No damage was observed to this structure or the five compressors, four control panels, and air piping housed inside.

Equipment damage at the substation was light. The main status board in the control room overturned forward and came to rest after impacting an adjacent control panel 3 feet away. The status board was unanchored and has a high aspect ratio (12 feet tall by 20 inches deep, front to back). The status board base was recessed approximately 1-1/2 inches below the flooring, effectively wedging the base; however, due to the high aspect ratio (H/D = 6) this wedging action was insufficient to resist the overturning inertial loads. After the earthquake the status board was uprighted and tied with ropes near the top. The relay panels and control panels in the control room have similar base restraints, but much lower aspect ratios. No damage was reported to any of these panels, including the control panel that was impacted by the status board. Typical electrical panel construction observed was vertical panel fronts with open sides and rear framing. Figure 4-11 shows the status board and typical base restraint for the electrical panels.

Damage to the switchyard equipment was minor considering the uniqueness of the switchyard component designs. The transformers are unanchored and supported on rails. The circuit breakers are of the air-blast design, with one breaker arranged in the double-stack configuration. Damage was confined to the 220-kV yard. One 220/110-kV oil-filled transformer supported by wheels on rails was reported to have displaced off its rails, but was undamaged. No damage occurred to the bushings on top of the transformer. Two phases of three 220-kV air-blast circuit breakers failed at their ceramic support columns. The 220-kV yard
contains 15 identical phases of these breakers. One phase of three current transformers connected to the damaged breakers failed at its connection to the concrete support column. These components are supported on precast reinforced concrete columns with embedded steel caps at the tops to facilitate welding the component base support to the column. The precast columns are tied into an embedded foundation. Figure 4-12 shows the replaced air-circuit breakers and current transformers as well as their connection to the support columns.

Additional damage in the switchyard occurred to capacitor banks and inductors. One inductor connected to a section of a capacitor bank failed at the connection to its insulator column. The insulator columns are supported from precast reinforced concrete columns similar to the current transformers discussed above. Several inductors fell to the ground, pulling a section of the capacitor bank with it. Current transformers from two of the capacitor banks were also reported damaged. The specific details are not known.

No damage was reported to equipment in the 110- and 35-kV yards.

4.3 NALBAND

Nalband is a small town of approximately 6,000 people, located 10 kilometers west of Spitak. The town sustained near-total damage to the principally low-rise unreinforced masonry commercial buildings and residential dwellings. Peak ground accelerations are estimated to be 0.50g to 0.75g based on observed damage. The town lies just north of the northwest end of the fault trace and is located in the highest-intensity area of the earthquake.

Nalband contains one 110-kV Railroad substation facility, which was heavily damaged. The precast concrete control building roof collapsed completely on top of the electrical equipment. This equipment remained nearly intact despite the building collapse. Figure 4-13 shows the damage to the Nalband substation control building, Figure 4-15 shows the substation five-and-one-half months later and some of the discarded damaged equipment following its replacement.

The switchyard at the Nalband substation was also damaged. One set (three phases) of 110-kV oil circuit breakers toppled due to a failure of the concrete support pedestals. The support structure for the breakers is constructed of concrete beams bearing on concrete columns. The breakers are anchored to the beams with friction clips. The cause of the support failure is believed to have
been the circuit breakers shifting off center (the friction clips were ineffective), resulting in an eccentric load on the support. Poor connection details between the support beams and columns were also believed to have contributed to failure. The connections are grouted in U-bolts. Figure 4-14 shows the toppled circuit breakers. Additional damage included all three transformers jumping off of their support rails, with one toppling over. This in turn pulled the attached bus cabling and connections, causing additional switchyard damage.

4.4 SPITAK

The Spitak area experienced the greatest damage from the earthquake. The town was essentially destroyed, with few buildings left standing. It is located in the highest-intensity area, with estimated peak ground accelerations of 0.5g to over 1.0g. It was reported during the May reconnaissance that the town is being rebuilt 5 to 10 kilometers to the south of the old town.

Spitak is a highly industrialized area with numerous manufacturing facilities such as textile, machine tooling, and food processing. The majority of these facilities were completely destroyed during the earthquake. Two of these facilities, the Spitak Sugar Refinery and Flour Mill, were investigated after the earthquake and are discussed below. During the May reconnaissance effort only the flour mill had been returned to partial operation.

Spitak Sugar Refinery

The Spitak Sugar Refinery is a large facility near the epicenter. The facility is located on alluvium at the extreme western part of the town and closest to the surface trace of the fault. The facility has many steel-frame and masonry load-bearing-wall buildings; two steel towers; stacks; tanks; and numerous equipment, piping, and other systems.

At the time of the first visit, about two weeks after the earthquake, extensive demolition work was in progress. None of the surviving equipment and systems were restarted, so only structural effects data could be collected.

Several completely or partially collapsed masonry-bearing-wall and precast concrete structures were observed at the site. One example is shown in Figure 4-16. In contrast, the steel structures appeared to be lightly damaged (Figure 4-
17). Typically, they had lost most of their cladding, which appeared to be unreinforced masonry and precast concrete elements. The failure of the cladding is due to either inadequate lateral-load-carrying capability of the connections or lack of reinforcing for the masonry, or both.

Figure 4-18 shows a view of two steel structures that have lost their cladding. Much of the debris has been removed. The typical construction is built-up, welded, ladder construction with built-up welded steel braces. The floor slabs include cast-in-place concrete, steel grating, and precast concrete slabs. These structures are typical of industrial building construction prevalent in the United States during the first half of this century. Erected in long, rectangular, low- to medium-rise configurations, the lateral stability of these structures depends on steel bracing and moment-resisting frames. The diagonal bracing is often highly eccentric. Its purpose was probably not for seismic loads but rather to stiffen the structures against vibrations from the heavy rotating equipment that they house.

The observed damage to the steel-frame structures consisted of collapsed cladding and broken welds, which are easily repairable, at eccentric diagonal-brace connections to columns.

The complex contains much equipment, piping, and other systems. Unanchored and poorly anchored equipment slid and toppled, and much equipment was heavily damaged by falling debris. Piping and well-anchored equipment that had not been struck appeared to have escaped structural damage, although at the time of both investigations, equipment had not yet been restarted. Figures 4-19 through 4-21 illustrate the effects of the earthquake on these equipment.

Spitak Flour Mill

The large flour mill complex is located on the eastern edge of Spitak and is composed of several cast-in-place and precast concrete structures. This complex was the source of one of the largest losses from the earthquake. Except for its cast-in-place concrete silos, the complex appeared to be a total loss.

Figure 4-22 shows an overview of the mill. There are two types of silos, cast-in-place and precast concrete, used at the facility. Figure 4-23 shows the cast-in-place concrete silos. A massive precast concrete-frame silo, comparable in size to the one shown in Figure 4-22, collapsed completely. This structure is
located on the west end of the existing concrete silos and can be seen in the foreground of Figure 4-22. In contrast, the cast-in-place silos performed well, with only some damage at construction joints located at the base of the silos. At the ground level both types of silos are supported on columns that are framed into a massive shear-wall supporting structure.

Several concrete shear-wall structures typical of the region collapsed or were severely damaged. One of these buildings had continuous openings in its shear walls near the base, and failed in shear. It was similar to the failed Olive View Hospital in Sylmar in the 1971 San Fernando, California Earthquake.

4.5 KIROVAKAN

Kirovakan, located on the eastern end of the Pambak River Valley, is a highly industrialized city with a population of 150,000. Typical industry includes several large chemical producing plants, machine tools, various manufacturing facilities, and other light industry.

The city suffered moderate damage, but not as severe as either Leninakan or Spitak. Section 3 of this report discusses building damage in the area. Little information, other than for the sites discussed below, is known about the performance of industrial and power facilities in Kirovakan. A large chemical plant, a machine tool plant, and a two-unit geothermal power plant were toured very briefly by the reconnaissance teams. The performance of the chemical plant and the power plant is discussed further in the following sections.

There were no ground motion recording instruments in Kirovakan or the surrounding areas. However, based on observed damage at the power plant and area structure performance, it is estimated that Kirovakan experienced peak ground accelerations in the range of 0.2 to 0.4g, with potentially higher levels in isolated softer soil areas. This range is equated to typical equipment damage and unreinforced masonry structure performance observed in past earthquakes [Bay of Plenty, New Zealand Earthquake, (11); Whittier-Narrows Earthquake, (12)].

Chemical Plant

The chemical plant in Kirovakan is a large industrial facility located in the southern portion of the city. Specifics on the facility and damage estimates could not be obtained; however, there were reports of several toxic chemical
spills. An interview with the local fire chief suggests a minor hazard occurred, as their fire unit responded to the fire alarm at the facility but were told upon arrival that the chemical plant’s fire department had the situation under control. The local fire unit subsequently left to fight several small fires that occurred in the city.

Kirovakan Geothermal Power Plant

The Kirovakan power plant is a two-unit geothermal power plant of 100 MW each providing electricity for the local community and industry. The plant was constructed in 1962 with equipment of Russian design and manufacture. The plant sustained moderate damage. The estimate of damage was placed at approximately $1.6 million U.S. dollars. The majority of the damage cost is associated with the reconstruction of the central administration building, which sustained heavy structural damage. Equipment damage was light and confined to localized failures of yard and plant components. Figure 4-24 shows a general overview of the power plant.

The plant turbine-generators tripped off-line automatically during the earthquake for unknown reasons. The plant was then manually shutdown after the event. Power was restored within three days. However, only one turbine was on-line during the May reconnaissance effort, due to a reduced electrical load demand from the community and local industry. This provides insight into the level of damage that occurred to the local industry and the extent of the recovery efforts.

The plant has two main structures, the administration building and turbine bay. The administration building is precast or cast-in-place frame with unreinforced masonry infill walls. This building suffered heavy damage to the masonry infill walls. A major portion of the building's north wall (running east-west) collapsed. However, no structural damage occurred to the control room or battery room visited that was sufficient to cause equipment damage. The turbine bay consists of precast columns with unreinforced masonry infill walls and a steel truss high-bay roof frame. Damage to the turbine bay was limited to minor concrete column cracking at the turbine deck level on the north side of the building. The turbine bay structure's north side sits adjacent to the administration building. The turbine bay is a relatively light structure when compared to the administration building, with essentially the same type of structural system, such that the greater inertial loading, and thus response, was...
the primary contributor to the administration building and turbine bay’s north side damage.

The performance of mechanical equipment and systems at the plant was excellent, with a few minor effects attributable to the earthquake. One turbine bearing was damaged and the cause was believed to be lack of lubricating oil. The lubricating pumps and turning gear motor could not operate after the earthquake due to loss of power; thus, as the turbine was spinning down, the bearing was damaged. This turbine, due to the damaged bearing, was not used to restore power. Figure 4-25 shows Turbine 2 and turning gear, which were operational during the May reconnaissance effort.

Damage to the piping at the plant was light. Piping systems included welded and threaded piping and were typically rod hung with spring hangers. Reference 9, Chapter 9, reported a small leak to a 60-millimeter welded branch line connection to a flexible 200-millimeter main header. Figure 4-26 shows several photographs of the Kirovakan power plant piping.

No other instances of damage to mechanical equipment were reported. Figures 4-27 and 4-28 are photographs taken within the turbine bay, showing several motor-operated valves, the turbine bay, and overhead bridge crane, which were all undamaged.

The plant contains four 35,000-metric-ton oil storage tanks, which sustained no damage during the earthquake. The tanks are of welded steel construction, unanchored, and supported on concrete ring wall foundations. The tanks were reportedly full during the earthquake. Figure 4-29 shows two of the tanks and a typical foundation.

Damage to electrical equipment in the plant was light, but is more extensive than that of the mechanical equipment. The dc power system station batteries located on the ground floor of the central administration building were damaged completely, which disabled this system. The station batteries were freestanding on a pair of 5-1/4-inch-deep channels, which were bearing on unanchored, short base insulator columns. The unrestrained batteries and racks overturned, damaging the battery cells. Identical new station batteries were installed after the earthquake, using the same support configuration. Figure 4-30 shows the
post-earthquake station battery installation, which is identical to the pre-earthquake configuration.

The plant control room located on the third floor of the central administration building sustained light damage, primarily to the suspended ceiling and building walls. Numerous ceiling tiles dislodged and fell; however, no damage to components below was reported in spite of the large distance that exists between the ceiling and control room floor level. Figure 4-31 shows the control room suspended ceiling. The ceiling system is supported by vertical wire supports only; no lateral ties or diagonal wire bracing was observed. Figures 4-32 and 4-33 show some of the control room benchboards and panels. These components were unanchored and sustained no damage. The panels are recessed approximately 2 inches below a wood base flooring, effectively wedging the panel bases in place.

Limited damage to the control room walls was reported as part of the overall structural damage that occurred to the central administration building. Both the north and east walls in the control room were reported to be damaged; however, the building damage did not affect the control room components.

An estimated 50% of the 110-kV switchyard porcelain insulators were damaged. One oil-filled circuit breaker was reported to have leaked oil and caught fire. The fire did not spread and was quickly extinguished. Figure 4-34 shows the three oil-filled circuit breakers, of which the left breaker caught fire. Figure 4-35 shows photographs of the 110-kV switchyard.

Three out of four of the oil-filled transformers displaced off of their support rails, causing damage to the bushings and lightning arresters on top of the transformers. The transformers were supported on wheels to railroad rails with no restraint against rolling or uplift. Rockfill was placed up to the top of the rails on both sides, which is believed to have prevented overturning. Figure 4-36 shows the transformers and bushings on top of the transformer. The three transformers were replaced on their rails and reconnected, and functioned properly. The upper photograph of Figure 4-37 shows the east transformer, which also sustained damage to its high-voltage electrical bus duct. The extent of damage could not be determined; however, it is believed to have been caused by the displacement of the transformer from its support rails. The figure shows replaced bushings on this transformer as well.
4.6 RAZDAN

The Razdan Thermal Generating Station is an eight-unit facility generating a total of 1,120 MW, located approximately 65 kilometers south-southeast of the epicenter (Figure 4-1). Construction began in the mid-1950s, with the first unit going on-line in 1959. Subsequent plant expansions have occurred over the years. Damage, particularly to the 220-kV switchyard, was reported as moderate. The dc station batteries were reported as damaged. The cells were unanchored and supported similarly to the station batteries at the Kirovakan power plant. There was also a report of an oil-filled transformer that leaked oil and caught fire by switch sparking. The fire reportedly spread and led to an explosion of a hydrogen insulated generator. The latter fire and damage are unconfirmed as of this writing. Power was restored in stages: 60% of operating capacity in 16 days, 80% of capacity in 2 days, and full operating capacity was restored in 25 days. The peak ground accelerations at the site are estimated at 0.2g.

4.7 ARMENIA NUCLEAR POWER PLANT

Armenia Units 1 and 2 (Figure 4-38) constitute the nuclear facility at Oktembryan, about 75 kilometers south of the epicenter, as shown in Figure 4-1. The units are in the Soviet VVER-440 class; Unit 1 began operation in 1977, Unit 2 in 1980. Two planned 1,000-MW reactors for the same site were cancelled recently. Officials reported that the December 7 earthquake caused neither scram nor damage at the plant, which continued to operate. The December reconnaissance team visited the plant collecting data. The May team did not pursue additional data, as the Soviet government had decided to close the plant permanently shortly after the earthquake (see below).

The plant is equipped with three motion detectors—in the office building, chimney stack, and electric substation—that are designed to activate at a peak ground acceleration of 0.05g, which plant engineers have correlated to shaking intensity MSK VI. The reactors are programmed to shut down if two of the three detectors are triggered. Intensity at the site was estimated in the mid-V range and no triggering occurred. However, vibration-reduction dampers connected to turbines activated after this equipment was displaced 2.4 millimeters during the earthquake. The horizontal peak ground acceleration at the facility was reported to be 0.03g, with amplified building response slightly exceeding 0.05g. Following the earthquake, the plant was shut down for 48 hours for a safety inspection. No significant damage was found, and upon restart all systems functioned normally.
Unit 1 was founded on flat, layered volcanic and alluvial deposits, a site the Soviets believed did not present a realistic seismic hazard. The original design was based on MSK-64 Intensity VII, which during design was upgraded to VIII as required for important facilities in the Soviet Union. Following the 1977 magnitude 7.2 Vrancea, Romania, Earthquake that damaged the Kozloduy nuclear plant on the Danube River in Bulgaria, the Soviets began implementation of more-rigorous seismic design criteria for nuclear facilities in high earthquake risk areas, which include the Armenian site. Criteria are based on two design basis earthquakes, a 100-year event and a 10,000-year event.

The criteria specify that equipment and structures be segregated into three categories: I for inventory essential to safe shutdown; II for inventory generating power not directly critical to the integrity of category I equipment; and III for inventory comprising all equipment not contained in the first two categories. A retrofitting program for critical equipment was implemented at the Armenian site shortly after imposition of the enhanced criteria, which specified that reactors, pumps, steam generators, and valves be designed to resist shaking intensity MSK IX.

The following additional seismic strengthening features were observed during the December reconnaissance:

- All electrical cabinets were bolted down and extensively braced to each other in the control room of Unit 2.
- The suspended ceiling of the Unit 2 control room was seismically braced.
- The plant manager was planning to strengthen the steel-frame roof trusses of the turbine building of Units 1 and 2.
- The steel-frame turbine building is a massive, well-designed building that appears to have a large seismic capacity.

Despite the upgrading program the Armenian units still lack either a complete emergency core cooling system or a containment, both of which are mandatory in the United States. U.S. investigators also noted that the control room for Unit 2 had windows, a feature that has been eliminated from critical structures at U.S. nuclear plants to reduce the risk from tornado missiles. Soviet officials acknowledge that to remain operationally safe the plant would have to be retrofitted to resist a revised microzonation of intensity MSK X, a program they say would be prohibitively costly. Because of the plant’s proximity to the Araks...
Valley, the major agricultural area in Armenia, and to quell the population’s fears that a nuclear accident similar to the Chernobyl disaster may occur, the Soviet Council of Ministers announced that Unit 1 would be shut down as early as February 25, 1989. Shutdown of Unit 2 would follow on March 18, 1989. In a related announcement made shortly after the Armenia Earthquake, officials stated that construction of six nuclear plants, three of these in the Caucasus Mountains region, would be halted or suspended for seismic and other safety-related reasons.

During the first half of 1989 Soviet officials will study the feasibility of converting the Armenian plant to a natural-gas facility. Even if such a conversion is successful, the process will be lengthy and will only partly compensate for power lost by the elimination of the nuclear units. Additional power will eventually be provided by two other nuclear facilities: in the Republic of Russia the Rostov plant, which has not yet been commissioned to operate, and in the Republic of Kazakh the Razdan plant, which is currently undergoing physical upgrade. In the meantime strict power rationing and sharing will be implemented in the Armenia/Georgia/Azerbaijan region.

Twenty-five percent of the power that had been generated by the Armenian nuclear plant was transmitted to Georgia, which sold a portion of this to Turkey. Operation of the plant had caused growth of a working and residential community of approximately 10,000 people around the site.

4.8 CONCLUSIONS

Several conclusions can be drawn with respect to the performance of industrial and power facilities subjected to the Armenia Earthquake. These conclusions are summarized in the paragraphs below.

Industrial Facilities

Extensive damage was sustained by industrial facilities within the epicentral area, particularly Leninakan and Spitak. While the majority of damage can be attributed to poor design and construction resulting in complete collapse (52% of the engineered structures in Leninakan collapsed), several conclusions can be made based on the small number of facilities reviewed.

- Properly engineered and constructed structures are essential in preventing the extensive loss of life, capital, and jobs, and financial loss due to business interruption that occurred in this.
earthquake. The dominant contributors to building damage were structural element connections--floor-to-wall connections and beam-to-column connections—all of which were poorly constructed. In Leninakan, of the nearly 300 industrial facilities only three or four facilities remain, with none of these facilities reported as operational five-and-one-half months following the earthquake.

- Properly anchored equipment, providing structural collapse did not occur, were undamaged in areas of the highest-intensity shaking. Performance was similar to that observed for U.S. equipment subjected to earthquakes (12). Mechanical equipment performed well, with the majority of the damage sustained by electrical equipment. Standard engineered anchorage sufficient to resist mechanical equipment operational loads proved equally capable of resisting seismic inertial loads, as proved in past earthquakes. Unanchored electrical equipment performed poorly and is a lesson repeated in nearly all major earthquakes affecting industrial facilities.

Power Facilities

The effects on power facilities in the epicentral area were much less severe than those for industrial facilities. General conclusions related to power facility performance are:

- As shown in past earthquakes, high-voltage switchyard equipment shows the greatest susceptibility to damage. Particularly vulnerable are large high-voltage transformers on wheels supported by rails with no restraints. Numerous instances of transformer damage occurred during the New Zealand Earthquake (11) and were repeated in the Armenia Earthquake for this type of installation. This type of transformer support is seldom used for U.S. installations.

- Switchyard insulator damage was generally minor. Approximately 10% to 30% of the 220-kV switchyard insulators were damaged. This agrees with typical damage to U.S. installations for 220-kV switchyards, such as Devers substation subjected to the North Palm Springs Earthquake (10), and substations affected by the recent Loma Prieta Earthquake (13). Moderate to heavy damage typically occurs in higher voltage (>220 kV) switchyards. Nearly all of Armenia's power transmission is 220-kV (see Figure 4-1).

- Unanchored or marginally anchored electrical control and instrumentation cabinet equipment is susceptible to damage as shown in other earthquakes. The majority of the power facility control boards and relay panels were unanchored, but had their bases effectively wedged into recesses in the flooring. This apparently proved as sufficient restraint for most of the panels, as only the high aspect ratio (H/D > 3) cabinets overturned (see Leninakan-2, this section).

- Unrestrained station batteries are extremely susceptible to damage as shown in past earthquakes, and the Armenia Earthquake was no exception. Properly restrained batteries and racks are necessary...
to ensure continued dc power for control and instrumentation function both during and following an earthquake.

- In general, response time to restore power to the transmission and distribution facilities was excellent and parallels that of the U.S. Power was typically restored within 2 to 3 days following the earthquake. Power to individual dwellings is ongoing and will take many months due to the extensive building collapse.
Figure 4-1. Power Generation. Three electrical substations were investigated in the epicentral region: The 220-kV Leninakan-2 facility in Leninakan and two 110-kV facilities, one in Leninakan and one near Nalband. The Leninakan substations experienced light damage, while the substation at Nalband suffered extensive damage. Electrical service to Leninakan was restored within 48 hours.
Figure 4-2. Map of Leninakan, Armenia, showing the area where the city is being reconstructed. Reconstruction is being performed in the cross-hatched area northwest of Lenin and City squares. (from T. O'Rourke).
Figure 4-3. Northwest section of Leninakan where the city is being reconstructed. A mandatory maximum story height of four was established by Gosstroy, the Soviet Union State Committee for Construction affairs, due to the extensive damage experienced by the nine-story, precast-frame structures in Leninakan.
Figure 4-4. Concrete piping and culvert manufacturing factory located on the eastern edge of Leninakan where the steel silos containing cement were undamaged. However, other plant structures at the site sustained extensive damage.
Figure 4-5. Leninakan-1 substation sustained minor structural and equipment damage. The control house is shown in the upper photograph and the circuit breaker buildings in the lower photograph.
Figure 4-6. Leninakan-1 substation where structural damage occurred at the interface between the old and new circuit breaker/switchgear buildings. No damage occurred to the busbar shown.
Figure 4-7. Typical interior view of the Leninakan-1 circuit breaker buildings, second floor, and typical cable routing through the building.
Figure 4-8. Leninakan-1 110-kV switchyard and 110/35-kV oil-filled transformer. The transformer is one of three that displaced off of the support rails but did not overturn.
Figure 4-9. Leninakan-1 control room benchboards and relay panels that sustained no damage.
Figure 4-10. Leninakan-2 control building showing the damage that occurred to the north wall running in the east-west direction.
Figure 4-11. Leninakan-2 status board, which overturned impacting the control panel on the right. The lower photograph shows a typical panel base where the base is recessed below the flooring effectively wedging it in place. This proved effective for low aspect ratio panels.
Figure 4-12. Leninakan-2 220-kV air-blast circuit breakers (foreground) and current transformers (background), which failed during the earthquake. These are the replaced units. The lower photograph shows the typical component connection to the support column.
Figure 4-13. Nalband electric substation where equipment apparently remained intact or had limited damage within the collapsed control building. The top photo shows the electrical control cabinets supporting the roof fragment, and the bottom photo shows medium-voltage metal-clad switchgear.
Figure 4-14. Nalband electric substation where the elevated concrete footings of these oil-filled circuit breakers failed, toppling the units.
Figure 4-15. Electrical substation at Nalband five-and-one-half months after the earthquake showing the damaged equipment graveyard.
Figure 4-16. Severely damaged masonry-bearing-wall industrial structure with a light truss-supported roof in Spitak.
Figure 4-17. Spitak Sugar Refinery: a collapsed masonry and concrete-frame building surrounded by two lightly damaged steel-frame buildings that have lost their cladding.
Figure 4-18. Spitak Sugar Refinery: precast concrete and masonry cladding were shaken out of the steel frames of most structures. Frame, tanks, and piping are apparently undamaged.
Figure 4-19. Spitak Sugar Refinery where these horizontal pumps were undamaged.
Figure 4-20. Spitak Sugar Refinery contained piping that appeared undamaged even though an adjacent masonry wall collapsed around it.
Figure 4-21. Spitak Sugar Refinery where the top photo shows toppled electrical cabinets where poorly installed plug-welds failed to stabilize the units. Another cabinet (bottom) remained welded to its steel baseplate and appeared undamaged.
Figure 4-22. Spitak Flour Mill where one of several soft-story concrete shear wall structures collapsed. The lower photo shows the removed structure taken at the time of the May reconnaissance effort.
Figure 4-23. Spitak Flour Mill. The remaining cast-in-place concrete silos had damage (cracking) near the base to three of the individual silos.
Figure 4-24. Kirovakan geothermal power plant.
Figure 4-25. Turbine 2 and turning gear at the Kirovakan power plant, which sustained no damage.
Figure 4-26. Typical piping systems at the Kirovakan geothermal power plant. The only damage was the report of a small leak to a 60-millimeter welded branch line connection to a flexible 200-millimeter main header.
Figure 4-27. Typical motor-operated valves and remote operators at the Kirovakan power plant.
Figure 4-28. Turbine bay, overhead bridge crane, and motor-operated valves at the Kirovakan power plant.
Figure 4-29. 35,000-metric-ton unanchored oil storage tanks, which sustained no damage.
Figure 4-30. Kirovakan geothermal power plant replaced station batteries and rack. The pre-earthquake installation was identical and severely damaged as the racks and cells overturned disabling the dc power system. The lower photograph shows the battery rack base insulator columns.
Figure 4-31. Kirovakan geothermal power plant control room suspended ceiling. The ceiling system had numerous tiles dislodge and fall. No damage occurred to control room components due to tile impact. The suspended ceiling system was observed to have no lateral restraints or diagonal wire ties.
Figure 4-32. Kirovakan geothermal power plant main control room benchboards and control panels.
Figure 4-33. Kirovakan geothermal power plant relay panels. Note in the lower photograph that the anchorage is absent; however, the panels were recessed approximately 2 inches below a wood subfloor effectively wedging the panel bases.
Figure 4-34. Kirovakan geothermal power plant 110-kV switchyard. The left oil circuit breaker was reported to have leaked oil and caught fire, which was quickly extinguished.
Figure 4-35. Kirovakan geothermal power plant 110-kV switchyard where an estimated 50% of the porcelain insulators in the yard were reported damaged.
Figure 4-36. Kirovakan geothermal power plant transformer yard where three of the four oil-filled transformers displaced from their support rails, damaging the insulators and lightning arresters on top of the units.
Figure 4-37. Transformers at the Kirovakan geothermal power plant, which sustained damage. The transformer in the upper photograph also experienced damage to the electrical air bus duct system.
Armenia Nuclear Plant: Cross section of Main Building, Unit 2. Numbers identify seismic upgrades made following the 1976 Vrancea earthquake. 1 = steel ties; 2 = reinforced-concrete wall; 3 = concrete plate; 4 = sand fill; 5 = longitudinal concrete rib; 6 = reinforced-concrete rib. (Drawing courtesy of U.S. Department of Energy.)

Figure 4-38. Armenia nuclear plant: Unit 2 control room. The panel indicates that the unit was operating at 392 MW, approximately 90% of capacity, during U.S. investigation two weeks after the earthquake.
Section 5
CONCLUSIONS

The Armenia Earthquake prompts observations and lessons that are applicable in both the Soviet Union and the United States.

- Steel-frame buildings performed well even though they apparently were not designed for higher seismic loads than were the nearby precast structures. Their performance in Armenia is consistent with observations from numerous other earthquakes. The Soviet Union, as well as building owners in the United States, can learn from that experience, particularly for important industrial structures.

- Standardization in design and construction in order to mass-produce precast concrete industrial buildings at low cost can be a serious problem. The Armenia earthquake vividly demonstrates that constant repetition of accepted practice without proper seismic design quality assurance and engineering review can lead to damage of disastrous proportions. This was true of the precast-frame industrial buildings in Armenia and is applicable to many commercial and industrial concrete tilt-up buildings in the United States.

- Properly anchored industrial equipment was undamaged in areas of the highest-intensity shaking. Much of the equipment that appeared undamaged, however, had not been tested at the time of this inspection. Substantial reduction of equipment losses through proper anchorage is a lesson that has been demonstrated without fail in all major earthquakes affecting industrial facilities.

- Welded piping without seismic design performed well. This demonstrates that major changes to the American Society of Mechanical Engineers (ASME) code for the seismic design of piping should be made so that inertial loads are considered secondary loads, and loads caused by relative-support displacement are upgraded to primary loads.

- Switchyard equipment (unanchored transformers, circuit breakers, insulators) continue to be vulnerable to seismic-induced ground motion. Damage occurs even at relatively low ground acceleration levels. Typical damage observed is sliding, rolling, or toppling of components.
Power plant equipment without rigorous seismic design performed well. Mechanical equipment, pumps, valves, compressors, and piping all performed well with minimal damage. Electrical control equipment, relay panels, benchboards, and distribution panels, if properly anchored performed well nearly without exception.

Financial loss from long-term business interruption will probably equal the direct-damage cost of the earthquake. It is apparent that events such as the Armenia Earthquake affect all sectors of a society, and businesses that are not properly protected face complete ruin or major disruption.
Section 6
REFERENCES


APPENDIX A
APPENDIX A
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APPENDIX B
APPENDIX B

MSK-64 INTENSITY SCALE

I. **Not noticeable**  
   (a) The intensity of the vibration is below the limit of sensibility; the tremor is detected and recorded by seismographs only.

II. **Scarcely noticeable (very slight)**  
    (a) Vibration is felt only by people at rest in houses, especially on upper floors of buildings.

III. **Weak, partially observed only**  
     (a) The earthquake is felt indoors by a few people, outdoors only in favorable circumstances. The vibration is like that due to the passing of a light truck. Attentive observers notice a slight swinging of hanging objects, somewhat more heavily on upper floors.

IV. **Widely observed**  
    (a) The earthquake is felt indoors by many people, outdoors by a few. Here and there people awake, but no one is frightened. The vibration is like that due to the passing of a heavily loaded truck. Windows, doors, and dishes rattle. Floors and walls creak. Furniture begins to shake. Hanging objects swing slightly. Liquids in open vessels are slightly disturbed. In standing motor cars the shock is noticeable.

V. **Awakening**  
   (a) The earthquake is felt indoors by all, outdoors by many. Many sleeping people awake. A few run outdoors. Animals become uneasy. Buildings tremble throughout. Hanging objects swing considerably. Pictures knock against walls or swing out of place. Occasionally pendulum clocks stop. A few unstable objects may be overturned or shifted. Open doors and windows are thrust open and slam back again. Liquids spill in small amounts from well filled open containers. The sensation of vibration is like that due to a heavy object falling inside the building.  
   (b) Slight damage of Grade 1 in buildings of Type A is possible.  
   (c) Sometimes changes in flow of springs.

VI. **Frightening**  
    (a) Felt by most people indoors and outdoors. Many people frightened and run outdoors. A few persons lose their balance. Domestic animals run out of their stalls. In a few instances, dishes and glassware may break, books may fall down. Heavy furniture may possibly move and small steel bells may ring.  
    (b) Damage of Grade 1 is sustained in single buildings of Type B and in many of Type A. Damage in a few buildings of type A is of Grade 2.  
    (c) In a few cases cracks up to widths of 1 cm possible in wet ground; in mountains occasional landslides; change in flow of springs and in the level of well-water is observed.

VII. **Damage to buildings**  
    (a) Most people are frightened and run outdoors. Many find it difficult to stand. The vibration is noticed by persons driving motor cars. Large bells ring.  
    (b) In many buildings of Type C damage of Grade 1 is caused; in many buildings of Type B damage is of Grade 2. Many buildings of Type A suffer damage of Grade 3, a few of Grade 4. In single instances landslides of roadway on steep slope, cracks in roads, seams of pipelines damaged, cracks in stone walls.  
    (c) Waves are formed on
water, and water is made turbid by mud stirred up. Water levels in wells change, and the flow of springs change. In a few cases dry springs have their flow restored and existing springs stop flowing. In isolated instances parts of sand or gravel banks slip off.

VIII. Destruction of buildings (a) Fright and panic; also persons driving motor cars are disturbed. Here and there branches of trees break off. Even heavy furniture moves and partly overturns. Hinging lamps are in part damaged. (b) Many buildings of Type C suffer damage of Grade 2, a few of Grade 3. Many buildings of Type B suffer damage of Grade 3, and many buildings of Type A suffer damage of Grade 4. Occasional breakage of pipe seams. Memorials and monuments move and twist. Tombstones overturn. Stone walls collapse. (c) Small landslides in hollows and on banked roads on steep slopes; cracks in ground up to widths of several centimeters. Water in lakes becomes turbid. New reservoirs come into existence. Dry wells refill and existing wells become dry. In many cases changes in flow and level of water occur.

IX. General damage to buildings (a) General panic; considerable damage to furniture. Animals run to and fro in confusion and cry. (b) Many buildings of Type C suffer damage of Grade 3, a few of Grade 4. Many buildings of Type B show damage of Grade 4, a few of Grade 5. Many buildings of Type A suffer damage of Grade 5. Monuments and columns fall. Considerable damage to reservoirs; underground pipes partly broken. In individual cases railway lines are bent and roadways damaged. (c) On flat land overflow of water, sand, and mud is often observed. Ground cracks to widths of up to 10 cm on slopes and riverbanks more than 10 cm; furthermore a large number of slight cracks in ground; falls of rock, many landslides, and earth flows; large waves on water. Dry wells renew their flow and existing wells dry up.

X. General destruction of buildings (b) Many buildings of Type C suffer damage of Grade 4, a few of Grade 5; critical damage to dams and dikes, and severe damage to bridges. Railway lines are bent slightly. Underground pipes are broken or bent. Road paving and asphalt show waves. (c) In ground, cracks up to widths of several tens of centimeters, sometimes up to a meter. Broad fissures occur parallel to water courses. Loose ground slides from steep slopes. From riverbanks and steep coasts considerable landslides are possible. In coastal areas displacement of sand and mud; change of water level in wells; water from canals, lakes, rivers, etc., thrown on land. New lakes form.

XI. Catastrophe (b) Severe damage even to well-built buildings, bridges, water dams, and railway lines; highways become useless; underground pipes destroyed. (c) Ground considerably distorted by broad cracks and fissures, as well as by movement in horizontal and vertical directions; numerous landslips and rockfalls. The intensity of the earthquake requires that it be investigated specially.

XII. Landscape changes (b) Practically all structures above- and belowground are greatly damaged or destroyed. (c) The surface of the ground is radically changed, considerable ground cracks with extensive vertical and horizontal movements are observed. Fall of rock and slumping of riverbanks over wide areas; lakes are dammed; waterfalls appear, and rivers are deflected. The intensity of the earthquake requires that it be investigated specially.
Types of Structures

Structure A Building in field-stone, rural structure, adobe houses, clay houses.

Structure B Ordinary brick buildings, buildings of the large block and prefabricated type, half-timbered structures, buildings in natural hewn stone.

Structure C Reinforced buildings, well-built wooden structures.

Definition of Quantity

Single or few: about 5%; many: about 50%; most: about 75%

Classification of Damage to Buildings

Grade 1 Slight damage: Fine cracks in plaster; small pieces of falling plaster.

Grade 2 Moderate damage: Small cracks in walls; fairly large pieces of falling plaster; pantiles slip off; cracks in chimneys; parts of chimneys fall.

Grade 3 Heavy damage: Large and deep cracks in walls; chimneys fall.

Grade 4 Destruction: Gaps in walls; parts of buildings may collapse; separate parts of buildings lose their cohesion; inner walls and fill-in walls of the frame collapse.

Grade 5 Total damage: Total collapse of buildings.

Arrangement of the Scale

Introductory letters are used for paragraphs throughout the scale as follows: (a) persons and surroundings, (b) structures of all kinds, and (c) nature.