EQE

The December 7, 1988 Armenia, USSR Earthquake

An EQE Summary Report

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ACKNOWLEDGEMENTS

The U.S. investigation of the 1988 Armenia earthquake was jointly sponsored by the U.S. Academy of Sciences and the Soviet Academy of Sciences. The effort was a cooperative one in which information was collectively gathered and freely exchanged. Since returning from the investigation, members of the U.S. team have continued this spirit by sharing their findings at presentations to public and private organizations throughout the Unites States. A large part of the information in this report is based on those presentations. Special thanks are extended to the following team members: Dr. John Filson, Dr. Armen Der Kiureghian, Dr. Fred Krimgold, Dr. Thomas O'Rourke, and Dr. Robert Sharp. Additional thanks are extended to Dr. N. N. Ambraseys of Imperial College of Science and Technology in London, Mr. Waverly Person of the U.S. Geological Survey, and Dr. Lloyd S. Cluff of Pacific Gas & Electric. Finally, EQE's direct participation in the investigation and hence this report would not have been possible without the timely aid of Dr. Robert Kassawara of the Electric Power Research Institute in Palo Alto, California.

Cover: telephone exchange building in Spitak

1. INTRODUCTION

The areas damaged most heavily by the earthquake are in valleys surrounded by ranges of the Caucasus Mountains. View of under-reinforced concrete and masonry buildings in Spitak.

On December 7, 1988 at 11:41 A.M. local time, a powerful earthquake 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.

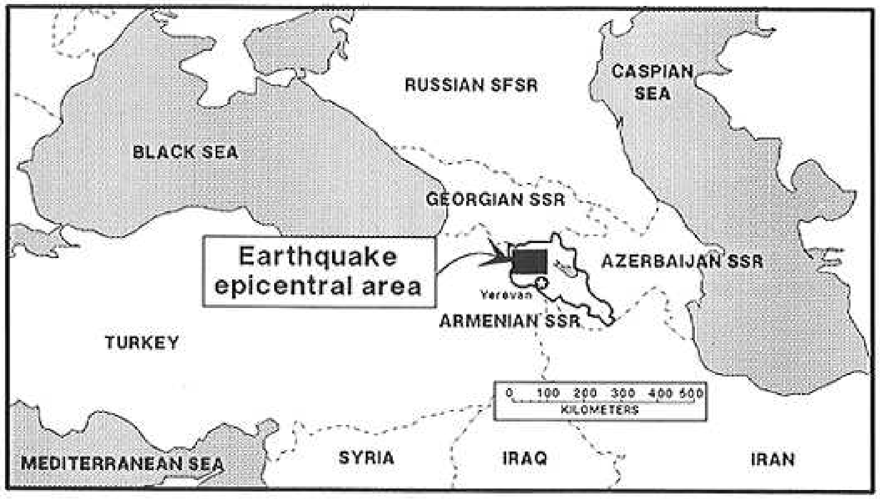
As of this writing the Soviet estimate of the deaths in the Armenia earthquake exceeds 25,000, but unofficial estimates more than double this number, making it one of the worst natural disasters of this century. The great majority of deaths were caused by buildings collapsing on occupants. Approximately 19,000 people were injured; more than 500,000 were left homeless with probably as many jobless. Eighty percent of Leninakan, Armenia's second largest city with 290,000 people, was destroyed or heavily damaged. Major 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 25,000 residents were killed. Over 350 smaller communities were affected, 58 of these completely destroyed. Eleven percent of Armenia's housing was destroyed or rendered uninhabitable.

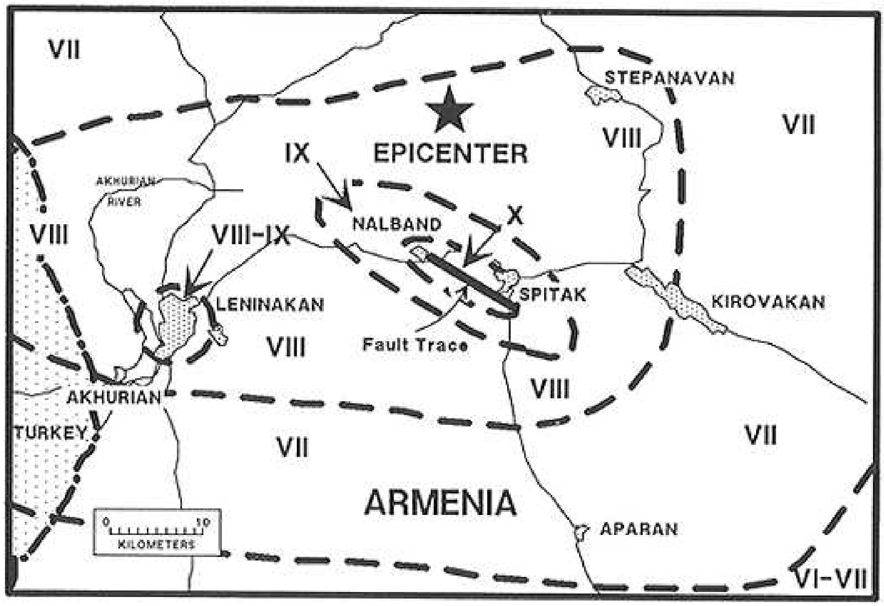
In terms of human and economic loss the full impact of the Armenia earthquake will not be known for many months although on February 20, 1989 the Soviet press reported that property losses amounted to over $16 billion. Financial losses from business interruption and closing of the Armenian nuclear plant at Oktembryan 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 summary of the earthquake is based primarily on the observations 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. Peter Yanev, Chairman of EQE Engineering in San Francisco, was a member of the team. Mr. Yanev was sponsored by the Electric Power Research Institute of Palo Alto, California and was the primary investigator of electric-power and industrial-facility performance. The full U.S. team is identified in the Appendix.

2. Geology and Seismology

Armenia is in the northern part of the Alpide-Himalayan seismic belt, which extends eastward from the countries of the southern Mediterranean through north Africa, Turkey, Iran, Afghanistan, Pakistan, India, and Burma. Most earthquakes in the Middle East and Balkan regions of this belt result from movement of the Eurasian and Arabian tectonic plates, which are converging on a northeast-southwest course at approximately 2 centimeters a year. Over many millions of years the crustal compression has caused intense geologic folding and thrusting of igneous Tertiary strata and Quaternary volcanic deposits to the north, giving rise to the Caucasus Mountains. During the past 25 years the most powerful earthquakes in the general area have occurred south of Armenia in Turkey and Iran, where the two plates actually meet and the surface crust is brittle and susceptible to sudden movement. Although recognized as an earthquake risk area, the Caucasus has not been subjected to the level of ongoing in-depth seismic studies being conducted in many of the high earthquake risk areas of other industrialized nations. Hence the mazes of many small, active faults in Armenia have not been accurately mapped. The December 7 event occurred along an extension of a mapped fault that had been inactive during the past 1,000 to 10,000 years.





Preliminary Soviet estimates of shaking intensities in the epicentral area.

Surface faulting approximately two miles southwest of Spitak. The figure is standing on the south plane of the fault, facing the north plane, which lifted upward. The raised ground directly in front of the figure shows the vertical component of the slippage, which was at its maximum near this point. The ground profile in the center of the photo had been smooth prior to the earthquake. (Photo courtesy of R. Sharpe.)

In 1951 Soviet seismologists installed a network of seismic recording instruments throughout Armenia. Prior to this date, instrumentation was limited and little accurate information on seismic activity apart from large events was documented. It is known that powerful earthquakes struck to the south and north of the region in 1045, 1283, 1320, and 1679. A long period of relative dormancy was followed by strong shocks in 1926 and 1935. Centered 18 kilometers southwest of Leninakan, the 1926 earthquake had an approximate magnitude of 5.7 with shaking intensities in the VIII to IX range on the Soviet MSK scale (discussed in Chapter 3). This event killed about 400 people and destroyed or damaged 6,000 homes. The most recent earthquake of significance had been a magnitude 5.1 event that occurred near Spitak in 1967. From this incomplete historical perspective, it appears that the December 7 earthquake may have been a 1,000-year event for the epicentral area.

During the last 25 years earthquakes in the Soviet republics of Armenia and Georgia have been concentrated in a region north of the December 7 event. These earthquakes are fairly frequent and are generally in the low- to mid-magnitude range. Their foci are typically shallow (25 kilometers or less) and hence carry a high potential for strong surface movement.

Soviet seismologists have acknowledged that Armenia and Georgia fall within a broad seismic zone that has the capacity to produce major earthquakes with high intensity ground shaking. As far as current geologic and seismologic methodologies allow, these scientists had, in effect, predicted that an event such as the December 7 earthquake would occur in the affected area.

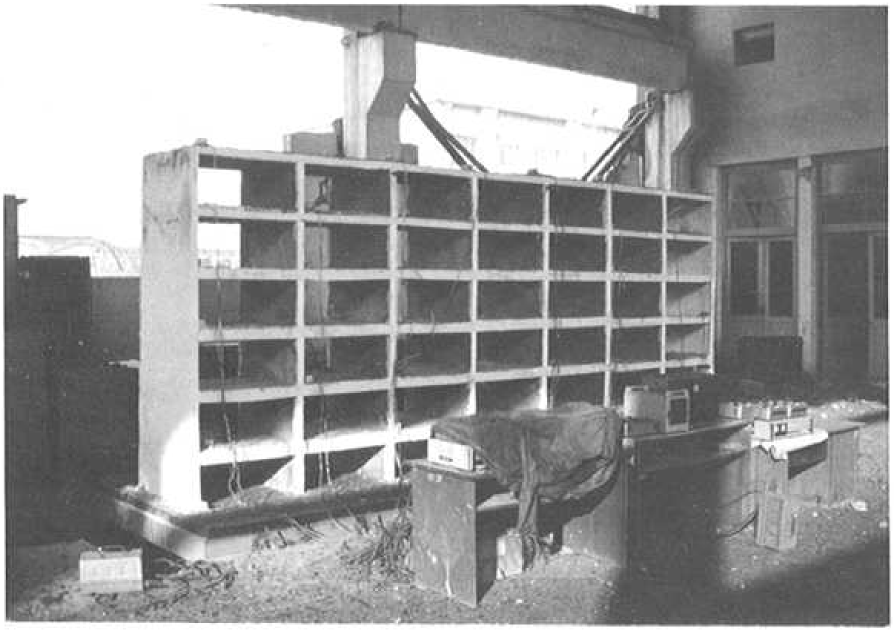
On December 6, 1988 a magnitude 3.0 earthquake began the seismic sequence that culminated the following day with the main earthquake. The epicenter of the main event was traced to 40.941° N and 44.275° E, approximately 75 kilometers northwest of the Armenian capital of Yerevan. The focus was estimated at 15 kilometers. Surface wave magnitude of the main shock was 6.9, moment magnitude 6.8, and body wave magnitude 6.2. Strong motion lasted about 30 seconds and was followed four minutes later by an aftershock with a body wave magnitude of 5.8. Motion was felt in Baku, capital of Azerbaijan, 480 kilometers east; in Tbilisi, capital of Georgia, 160 kilometers north; and throughout areas of Iran, several hundred kilometers south.

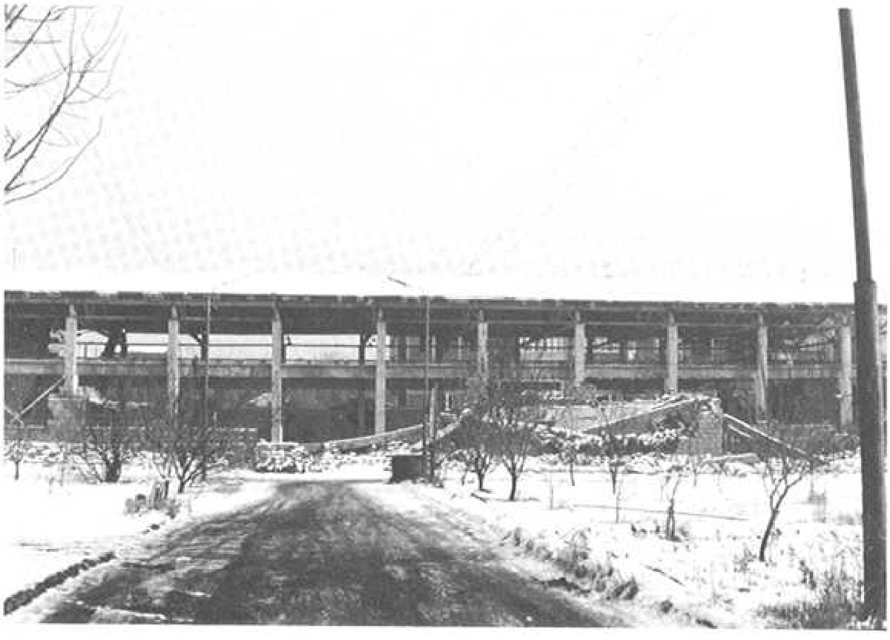
The earthquake was caused by a right-lateral reverse-thrust fault striking to the northwest and dipping to the northeast at about 55°. Movement was initiated by the fault plane to the southwest thrusting under and lifting the fault plane to the northeast, which also moved laterally to the south. A surface scarp 8 kilometers long extended from an area approximately 2 kilometers southwest of Spitak northwestly toward the village of Nalband. The maximum vertical offset of the rupture was approximately 1.5 meters, with the northeast side being lifted above the southwest side. The visible surface fault rupture length is considered short for an earthquake of this magnitude, and it is expected that further investigation in the spring will show that the rupture is in fact much longer.

On December 23, geologists on the U.S. investigation team installed portable seismic recording stations in a 10-by-40-kilometer region surrounding the epicenter. As of January 4 these stations had recorded hundreds of smaller aftershocks, the largest a magnitude 5.0 earthquake. These aftershocks fall in a multiple-source pattern along a 40-kilometer line of activity trending northwest-southeast. The 400 to 500 square-kilometer area defined by the recordings is consistent with the total fault planes of other earthquakes of this magnitude.

Strong-motion records of the earthquake are not yet available. Armenian engineers estimate that peak ground accelerations in Leninakan may have reached 0.4g. The much stronger ground motion generated in the Spitak area is possibly comparable to the 0.5g to 1.0g that was experienced in the Sylmar area during the 1971 San Fernando, California earthquake.

3. SOVIET BUILDING DESIGN AND PERFORMANCE





Structural model (top) on a shake table in laboratory of the Earthquake Engineering Research Institute in Leninakan. The model survived. The precast-concrete-frame building that housed it was less successful (bottom).

The 1988 Armenia earthquake is one of the most striking examples in recent history of the capacity of a strong earthquake to damage modern construction. This chapter summarizes key features of buildings affected by the earthquake and their performances. Brief discussions of site/soils response and microzonation are included at the end of the chapter.

Interviews with Soviet engineers and reviews of the governing building code indicate that Soviet seismic design is oriented in modern technical principals. The building code discretizes the country into seismic zones defined by the maximum ground shaking intensity expected in each zone. To this end, the Soviets utilize the MSK-64 scale, which gives 12 classifications of shaking intensity from I (hardly noticeable) to XII (total destruction). The classifications are similar to the 12 descriptions of shaking in the Modified Mercalli

Intensity scale used in the United States. Shake table testing is performed on critical equipment for nuclear installations, as in western practice. The buildings affected by the Armenia earthquake were generally designed to code criteria for shaking intensities VII to VIII. Actual intensities were at least VIII in Leninakan and IX to X in Spitak.

Soviet building construction is centrally planned at an agency in Moscow that develops a limited number of basic building designs to be implemented repeatedly throughout the USSR. Initially these designs have no provisions for seismic loading. When the designs are to be used in a seismically hazardous area such as Armenia, a local agency modifies the generic design to account for seismic loads. These changes are probably not extensive and must be

Contrasting earthquake effects on similar types of multi-story building clusters in Kirovakan at top and Spitak at bottom. (Photos courtesty of L. Cluff.)

Remains of an unreinforced masonry structure with precast elements in Spitak. Arrow indicates hollow-core floor plank in rubble.

made within strict cost and production limits. Building design in Armenia is also influenced by the general scarcity of wood and structural steel, which are minimized as construction materials. Most recent buildings are constructed in combinations of precast-concrete elements and stone masonry, which is locally available as a volcanic rock known as tuff.

The principal types of public and residential construction affected by the earthquake are unreinforced-masonry-bearing-wall, precast-concrete-frame, precast-concrete-panel, and concrete-lift-slab. Most industrial structures have precast-concrete frames; there is a smaller inventory of steel-frame structures. These general designs were used over and over again in the epicentral area. Thus the majority of damaged structures had similar seismic weaknesses that resulted in similar failures during the strong ground shaking.

Masonry-bearing-wall is the traditional construction technique for large buildings in Armenia, and most structures built prior to about 1970 are of this type. In the 1940s reinforced concrete floors and roofs replaced wood systems. Generally, these buildings do not exceed five stories in height.

Masonry walls typically consist of two wythes or stacks of carved stone blocks joined by mortar. These walls, which can be quite thick and are often without steel reinforcement, provide both lateral and vertical support for the concrete floors and roofs. In newer structures erected in the 1950s and 1960s, the floor and roof systems are constructed of precast hollow-core concrete planks that bear on the walls. Most adjacent planks have neither interconnections nor topping slab for diaphragm action. Typically there are no positive connections between floor planks and walls.

Masonry buildings of this design were the predominant construction type in Spitak, where destruction was almost total. Many of these buildings were also in Leninakan, where damage was also substantial, but in many cases not readily apparent from exterior observation. The difference in performance is primarily attributable to the much stronger ground motions experienced in Spitak, which is virtually on the fault rupture.

Remains of a five-story precast-concrete-frame residential building in Spitak.

Damage to masonry buildings occurred in stages. In some structures, the walls tilted away from the concrete plank floors, resulting in collapse of the planks. The onset of this damage was apparent at building corners where cracks were visible in nearly every surviving structure. Many structures deteriorated beyond this stage, with the now unsupported walls toppling. In some buildings the end walls remained upright, while the middle of the building collapsed. This resulted from the failure of the precast-concrete planks to act as effective floor diaphragms, causing the transfer of forces to the walls.

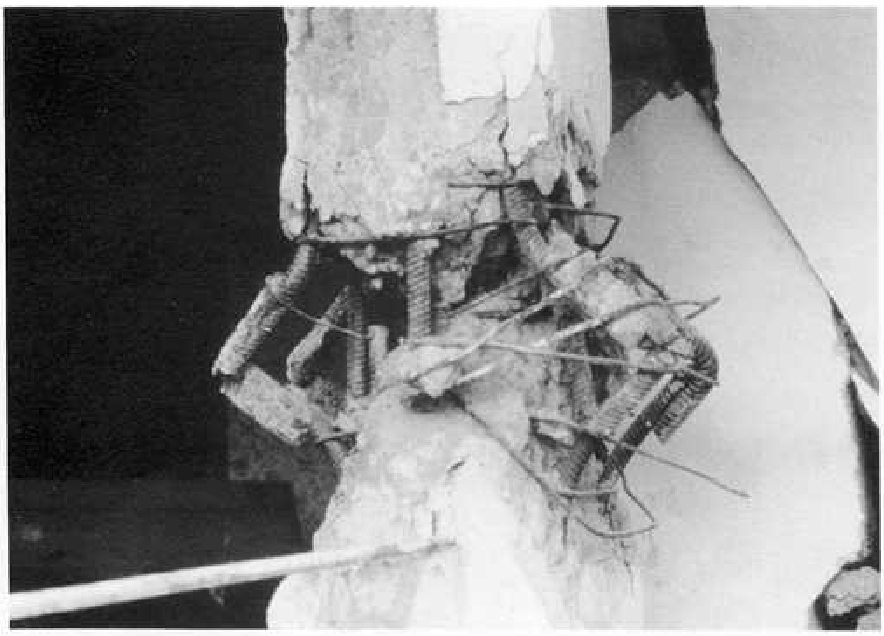
The use of **precast-concrete-frame** buildings began in the 1970s and continues to the present. This construction type is common throughout the Soviet Union and is the predominant design for residential and public structures. In the affected area the tallest of these buildings are nine stories with one-story penthouses. The collapse of many precast-concrete-frame structures in Leninakan was the major cause of the high number of fatalities.

Rubble of several collapsed precast-concrete-frame buildings in Leninakan in the foreground. A structure of the same design in the background.

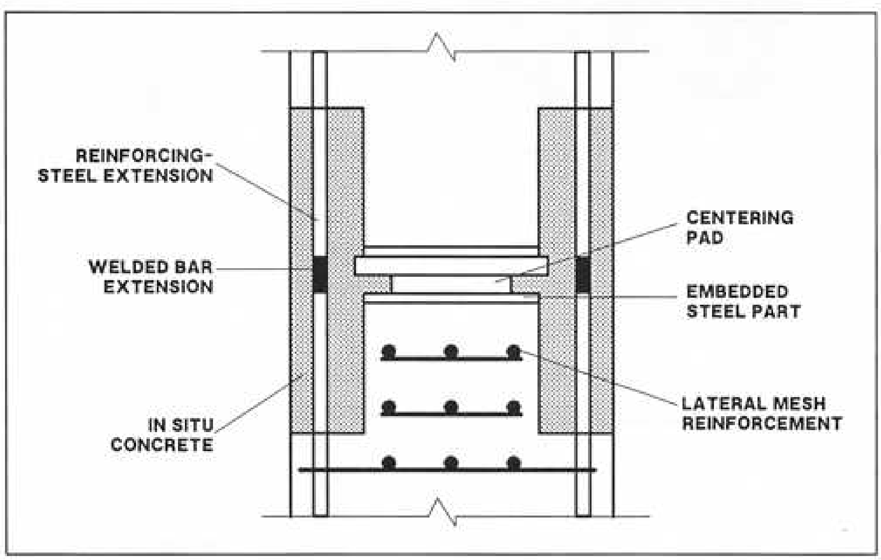
The lower half of this nine-story precast-concrete-frame building in Leninakan sustained the most damage. Separation at wall, floor, and corner connections was the common failure pattern for this type of construction.

Precast-concrete-frame buildings in Armenia are normally constructed in long rectangular configurations with columns and beams providing the primary vertical-load-carrying system. As with masonry construction, the floor and roof systems consist of hollow-core precast-concrete planks without topping slabs, interconnections, or consistent positive connections to the building frame. Perimeter walls and selected interior walls are unreinforced masonry infill, precast fascia panels, and precast-concrete shear panels. The frames are intended to provide the lateral-load-resisting path in the transverse direction. The infill and precast walls are intended for lateral stability in the longitudinal direction.

These buildings sustained damage in a variety of ways. Infill masonry typically fell out of the frames, resulting in loss of longitudinal stability. The frames also received insufficient support from precast shear panels, which had large, poorly reinforced openings and weak frame connections. Some of the most severe damage occurred at column splices, which consisted of lap welds of reinforcing bars extending from the upper and lower column sections. Examination of both the damaged structures and those currently under construction indicated that quality control of the field work was poor and that the splices were inherently eccentric with minimal hoop reinforcement for confinement. The strong ground shaking apparently initiated buckling of column reinforcing splices at these joints, resulting in progressive failures of the building frames.



Buckled connection between two precast-concrete columns joined end-to-end at mid-story height.



Schematic of end-to-end precast-concrete-column joint.

In Leninakan the tall large-panel structures under construction in background sustained little damage. Foreground has wreckage of several nine-story precast-concrete-frame structures. (Photo courtesy of T. O'Rourke.)

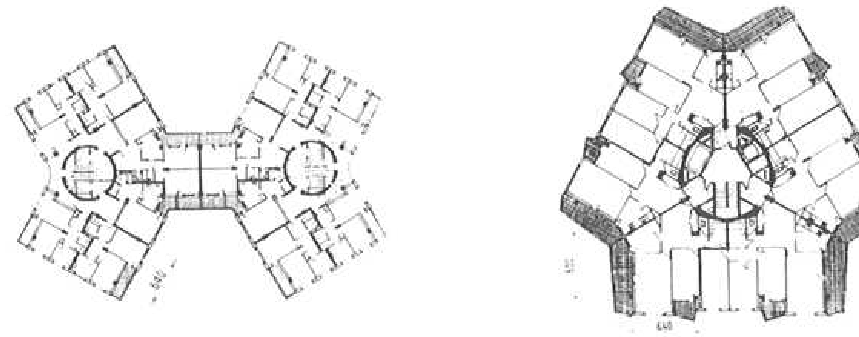
Large concrete-panel buildings are a contemporary building type, and 14 structures were completed or under construction in Leninakan at the time of the earthquake. Used for public and residential occupancy, these buildings range in height to nine stories. In general their performance was quite good with little obvious damage noted by U.S. investigators.

Soviet concrete-panel buildings are similar to concrete tilt-up buildings popular in the United States in low-rise commercial and industrial construction. An important difference is that Soviet design utilizes virtually every precast interior wall as a load-bearing element with shear capacity. The result is a much stiffer and much more redundant structure than the U.S. equivalent. As with the other structures discussed, floors and roofs are precast-concrete planks. Positive connections between the various elements were evident. Quality control of the precast elements appeared to be good. However, field work with these structures, as with all the structures investigated, often appeared careless. Nonetheless, the redundancy and good intra-structural ties inherent in the design were obviously effective in resisting damage.

Two **concrete-lift-slab** structures with heights of 10 and 16 stories had been erected in Leninakan. The 10-story structure completely collapsed while the 16-story structure was heavily damaged and was targetted for demolition. Lift-slab construction is common in the eastern United States.

Lift-slab construction involves either one central core or double cores of cast-in-place-concrete shear walls. Elevated floor and roof slabs are cast at grade, lifted into place, and supported by columns. The cores provide lateral stability for the structure, and building performance is critically dependent on attachment of the slabs to the cores.

The two cores in the 10-story structure were joined by slabs. It is probable that these cores were not adequately tied together, resulting in independent move-



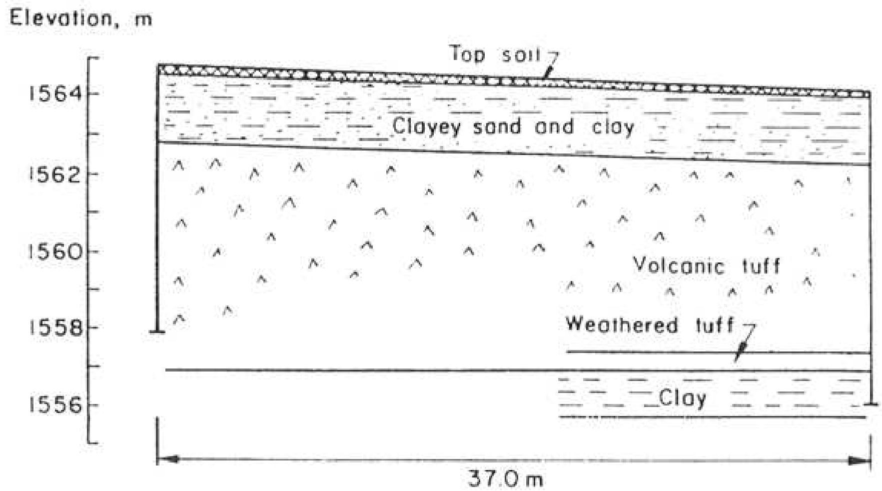
Floor plans of Leninakan's 10- and 16-story lift-slab buildings with double and single shear-cores respectively.

Collapsed 10-story lift-slab building. In foreground, entrance to a subterranean walkway that was undamaged.

Apparently intact, the 16-story lift-slab stucture was in fact damaged beyond rapair.

ment of the cores and collapse of the building. In the 16-story structure the shear core and attachments of the various precast elements were extensively damaged. Observers noted that reinforcing steel was protruding from the concrete elements, suggesting poor quality control during construction.

Several **steel-frame** buildings were investigated at large industrial complexes in the affected area. These structures are typical of mill building construction prevalent in the United States during the first half of this century. Erected in long rectangular low-rise to mid-rise configurations, the lateral stability of these structures depends on steel bracing and moment-resisting frames. Extensive damage to infill masonry walls was observed in Armenia. The structural steel frames themselves remained stable. Most damage noted was minor and easily repairable.

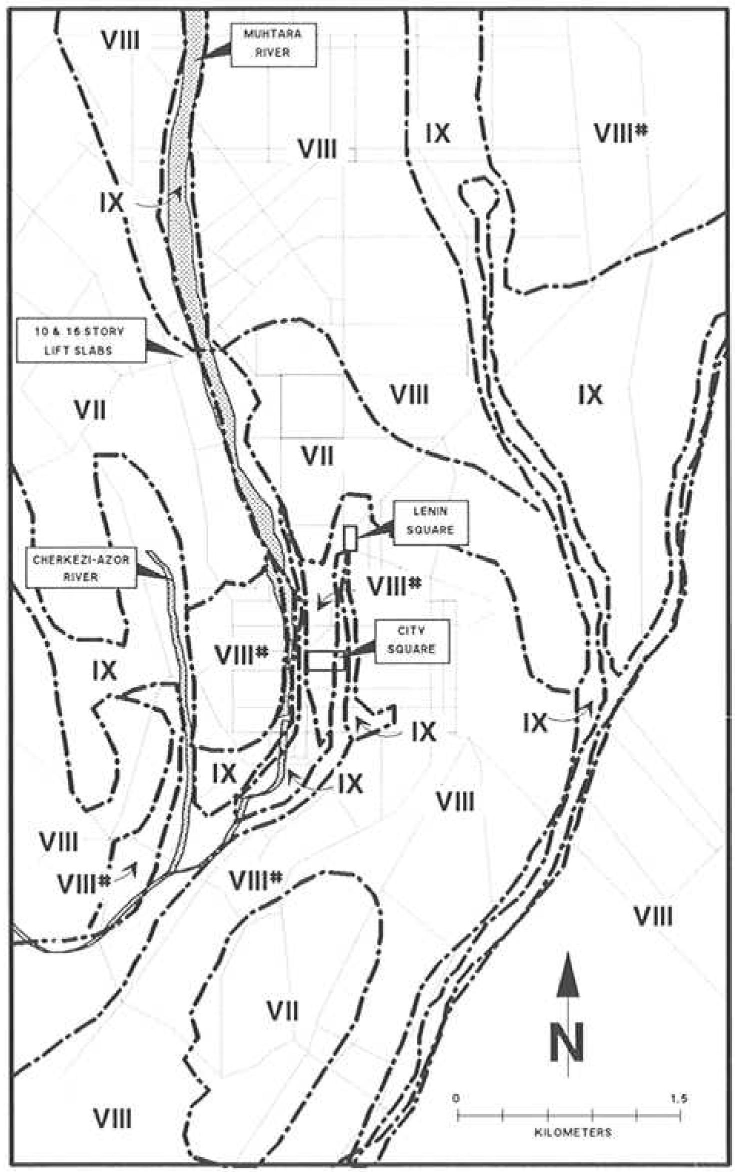


Profile of soil boring taken from site of lift-slab buildings in Leninakan. (Drawing courtesy of T. O'Rourke)

Site/Soils Response and Microzonation. Investigators acknowledged that correlating the sites of the most severe damage with the nature of soil response at those sites is a critical issue. For example, the majority of damage in the city of Kirovakan was concentrated in a three- to five-square-block area founded on a filled marsh. Soviet officials stated that only 40 buildings were heavily damaged in this city although 400 to 500 additional buildings also sustained damage.

At present it does appear that damage in Leninakan, which lies in an alluvial valley, correlates with local soil conditions. For example, damage was more extensive in filled areas along rivers running through the center of the old part of the city. The presence of 200 to 300 meters of sedimentary deposits underlying the city is also a probable factor in surface-soil response to the earthquake. Study will be needed to explain the relatively minor damage in Akhurian, which is approximately 5 kilometers south of Leninakan and founded on essentially the same soils. Spitak also lies in an alluvial valley, but its proximity to the fault itself was probably more contributory to the devastating damage than soil conditions. Also, towns scattered throughout these valleys showed a wide variation in damage.

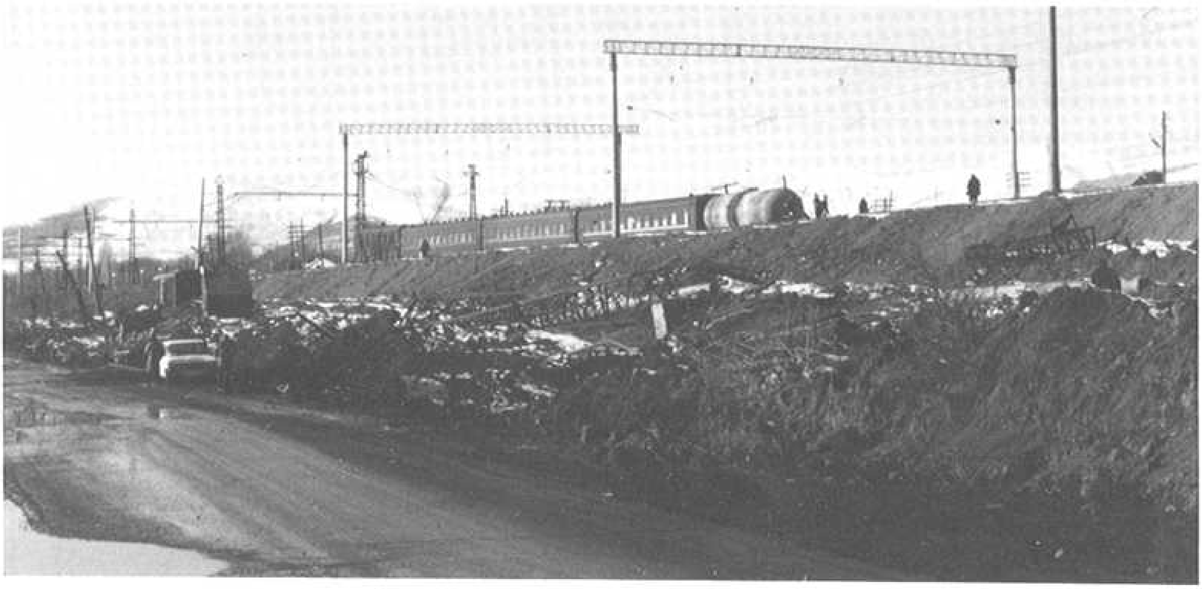
An additional subject of interest is the Soviet practice of microzonation. Basically this process utilizes site-specific soil conditions to discretize national seismic zones into much smaller zones. The most notable example of microzonation is in Leninakan, located in a national zone of shaking intensity VIII. In many parts of the city this shaking intensity had been either reduced or increased by one intensity level because foundation soils were judged either firm or soft. In effect this either halved or doubled the anticipated lateral-load forces for which structures were designed.



Soviet microzonation of Leninakan.

The heavily damaged concrete-lift-slab buildings described above were sited on a hard layer of tuff that was microzoned to shaking intensity VII. However, this layer is only about 4 meters thick and is underlain by a column of softer sediments over 200 meters thick. In addition this zone is immediately adjacent to an area with a riverbed that had been microzoned for shaking intensity IX. These distinctions are excessively fine for so small an area. General recommendations on microzonation are included in Chapter 7.

4. Lifelines



Main rail line at Nalband between Leninakan and Spitak. Ties, rails, and overhead components damaged by massive landslide had been replaced and service restored at time photograph was taken. Part of the landslide debris has been moved to roadside.

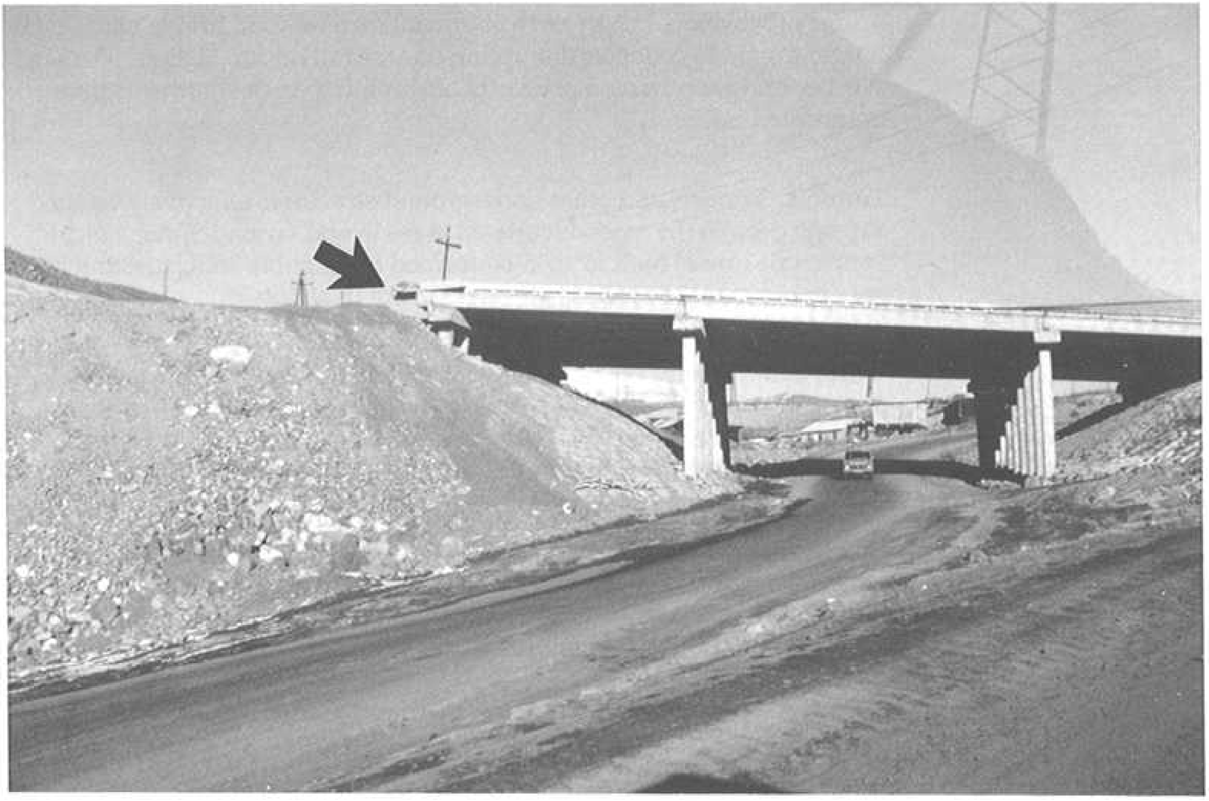
In contrast to the disastrous performance of structures in the epicentral area, lifelines* responded relatively well considering the magnitude of the earthquake and the nature of the terrain. Where lifelines did fail, essential-service backup was provided by the Soviet military and emergency personnel.

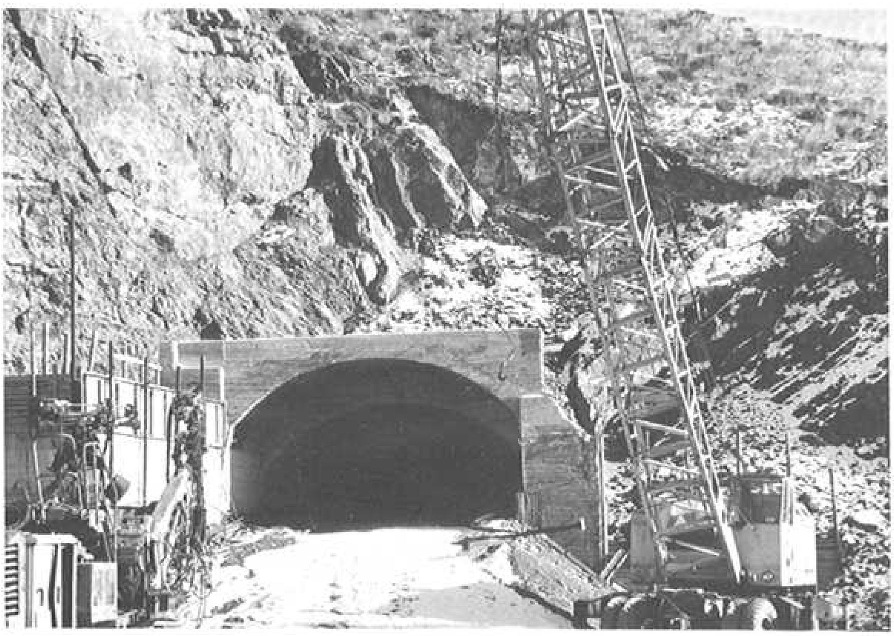
The epicentral area stands about 5,000 feet above sea level and is surrounded by mountain ranges with many peaks over 15,000 feet. The sharp changes in elevation create a high potential for landslides and rock falls, thousands of which may have occurred in a wide range of severity. These ground failures were the single factor most disruptive to lifeline service. The following is a summary of lifeline performance.

Roads. Widespread rock falls, embankment slumping, and failures to earth-retaining walls stalled transportation on rural highways and roads. Most road service was restored within 24 hours.

Railroads. A large landslide covered approximately 300 meters of the main line between Leninakan and Spitak with 6-meter-deep deposits of soil, interrupting rail transportation of much needed heavy equipment for about seven days.

* *Lifelines refers to utilities such as electric power, water, and highways that are essential to an urban region.*





Slumping earth abutments (arrow) damaged both ends of this concrete overpass in west Spitak.

This concrete-lined tunnel under construction near Spitak sustained superficial damage.

Bridges. Movement of an earth abutment on a railroad bridge near Spitak caused a span to collapse, disrupting transportation for 20 days. Damage at other bridges consisted primarily of slumping earth abutments that interrupted traffic.

Tunnels. Tunnels and other underground structures effectively resisted damage even in the most devastated areas in and around Spitak. Near Spitak, one tunnel built in 1898 performed remarkably well, sustaining only minor exterior spalling and cracking of its lining.

Water and Sewage. North of Leninakan, a massive rock fall heavily damaged two of three water mains to the city, depriving the fire department of water for two days. Also, heavy damage to the main sewage treatment plant eliminated service in Leninakan.

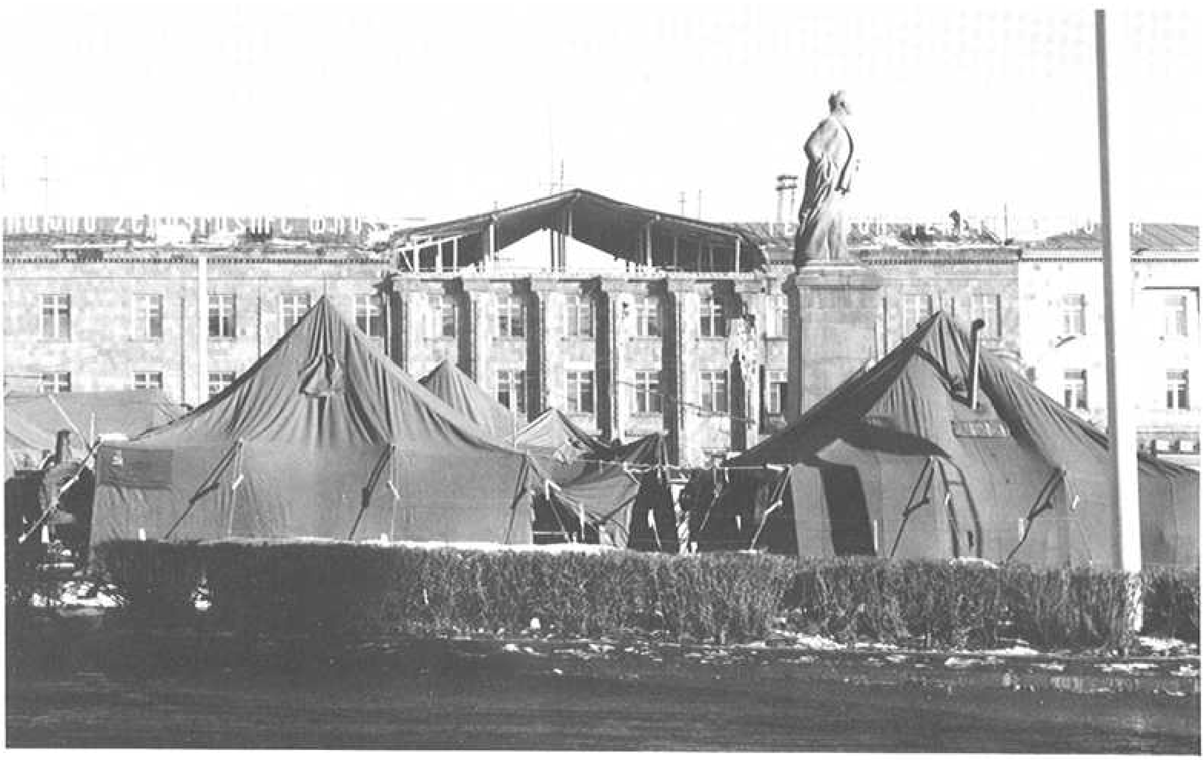
Gas. Damage to building connections caused loss of pressure in the main gas transmission lines in Leninakan. As a result, automatic shut-off valves terminated service, effectively eliminating the potential for explosions and fires. Most fires occurred in residences and were extinguished before spreading.

Communication. Residential and commercial communication was severely disrupted. However, by utilizing portable microwave stations, military communication was brought to almost full capacity within two days after the earthquake. Many wood telephone poles snapped at rotted bases and toppled. Also at least two steel communication towers on mountaintops collapsed.

Electrical Power. Power in the affected area was down for four to seven days. Chapter 6 addresses power generation and substation performance in more detail.

The telephone exchange building in Spitak, a precast-concrete-frame structure with shear end-walls. The failure of poorly connected precast floor planks to act as diaphragms contributed to the collapse. Communication equipment lies amid the rubble on the second floor.

5. Emergency Response



Temporary shelters in Lenin Square in central Leninakan.

The earthquake occurred just before lunchtime on a working day, and virtually all public buildings that collapsed were occupied. All hospitals in the epicentral area were heavily damaged, and approximately 70% of medical personnel were either killed or severely injured, crippling immediate efforts to treat casualties. Local residents implemented the initial rescue effort, which basically involved digging through the wreckage for survivors. As of December 21, Soviet officials estimated that over 23,000 survivors had been pulled from the rubble, almost all of these during the first several days after the earthquake.

Trained personnel, earth-moving vehicles, and emergency supplies needed for the rescue effort were not immediately available. Therefore, on December 9, the Soviet government formally requested foreign assistance, which began to arrive within 48 hours from over 70 nations in what was described as the largest flow of aid to the Soviet Union since the end of World War II. Specialized rescue teams from nearly 30 nations, including Algeria, Bulgaria, Cuba, Czechoslovakia, Finland, France, the German Democratic Republic, the German Federal Republic, Israel, Italy, Poland, Sweden, Switzerland, the United Kingdom, and the United States, were sent into the disaster areas to assist in victim recovery and treatment.

Although the Soviet government was initially slow in delivering emergency supplies, by December 11 and 12 enormous amounts of material were arriving by plane and truck in the affected areas. The influx of aid may in fact have been overwhelming, and western correspondents reported that distribution was not being effectively managed in the stricken region. Planes carrying supplies were forced to stay airborne for many hours before landing. The airport at Yerevan where most planes landed had to accommodate many times its traffic capacity and much emergency equipment and supplies had to be unloaded by hand. Two cargo planes bearing provisions and workers crashed, killing all 85 passengers and crew. The large landslide on the main rail line between Spitak and Leninakan impeded the transport of earth-moving equipment for about seven days. In general, traffic congestion both between and within the main population centers resulted in long delays.

In a typical major earthquake the ratio of injured to dead is 3 or 4 to 1; in the Armenia earthquake this was reversed if the higher, unofficial death estimate is used. This can be largely explained by the nature of the building collapses. The precast segmented construction types and very heavy construction materials common in the affected area collapsed in compact piles with few void spaces and little chance for occupant survival.

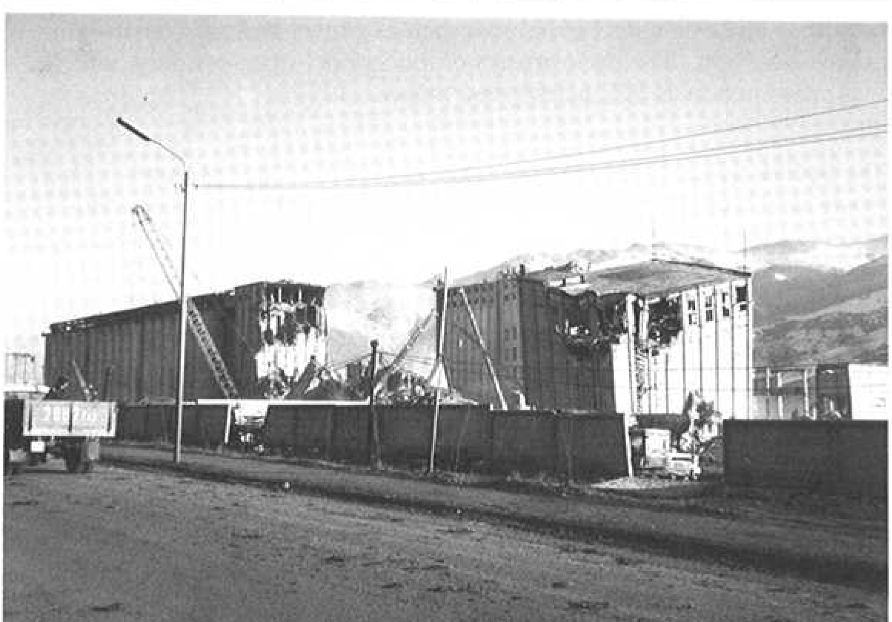
Many survivors suffered crush injuries, which are particularly severe and demand the kind of immediate attention that was mostly unavailable. The welfare of trapped and injured people was threatened further by exposure to freezing temperatures and the long waits that had to be endured during transport to functioning hospitals outside the epicentral area.

Most of the search and rescue effort was concluded by December 17.

6. INDUSTRIAL AND POWER FACILITIES

The area affected by the earthquake contains extensive light and heavy industry, including several large textile and grain facilities and a sugar refinery. The Soviet press reported that the earthquake caused work stoppages at 130 factories in the epicentral area. As in commercial and residential practice, industrial construction uses precast-concrete-frame design for the majority of large structures.

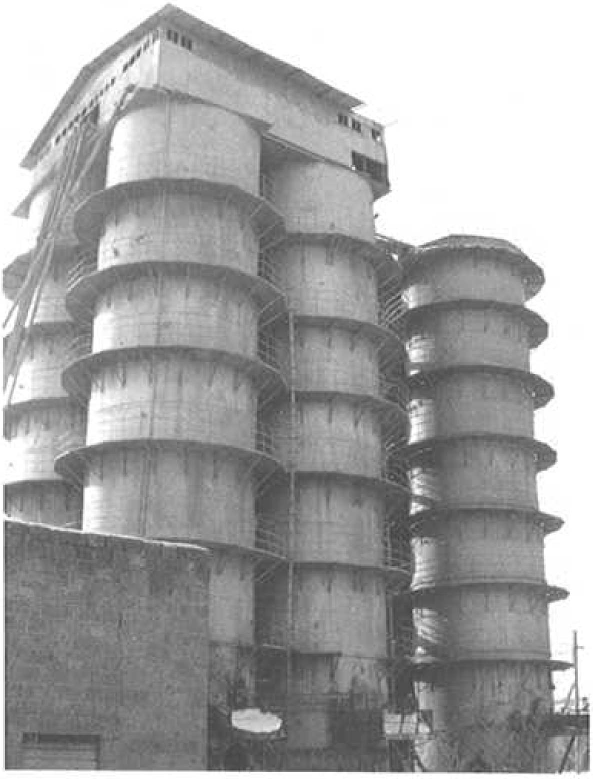
Textile factory in Leninakan prior to earthquake and smashed textile equipment at another site following event.



Standing remnant of precast-concrete furniture factory in Leninakan. It was reported that over 300 workers were killed in the collapsed sections of this structure.

Large granary and baking facility in Spitak.

At a concrete pipe factory in Leninakan these steel silos containing cement were undamaged. Building damage in the immediate area was extensive.

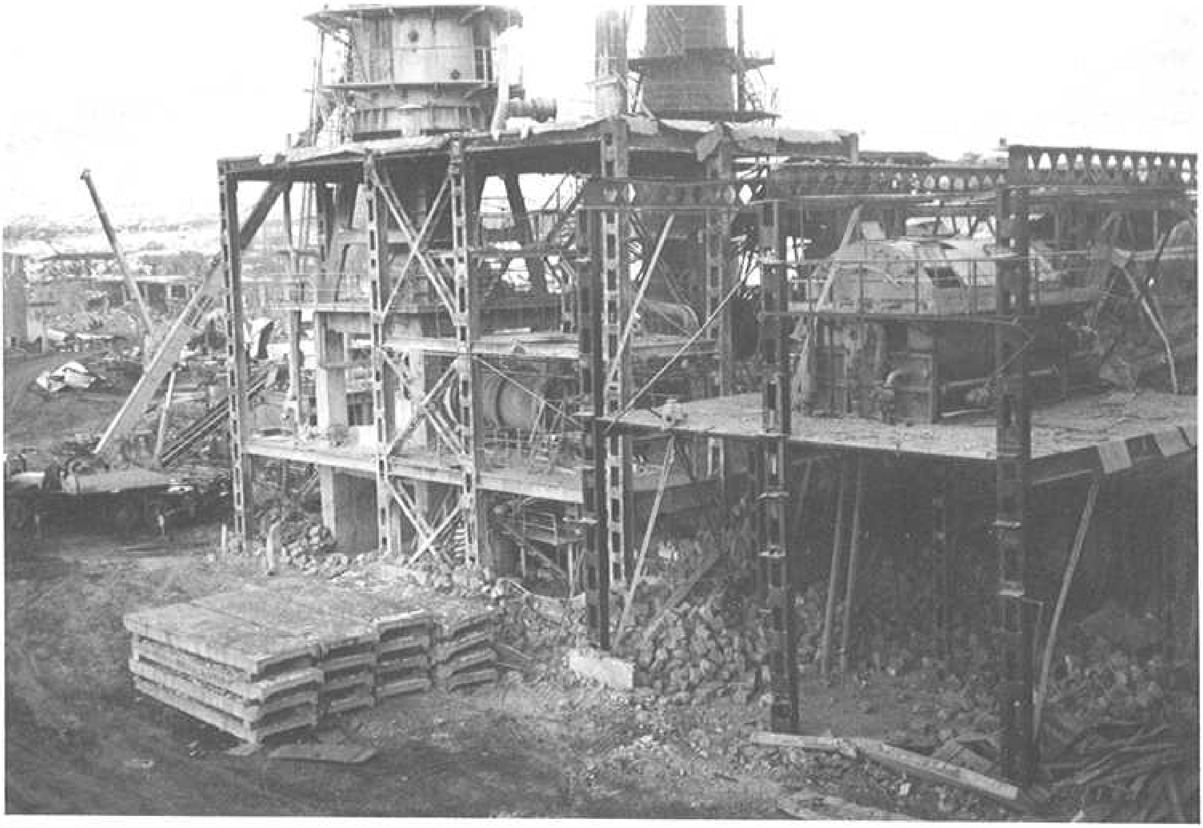


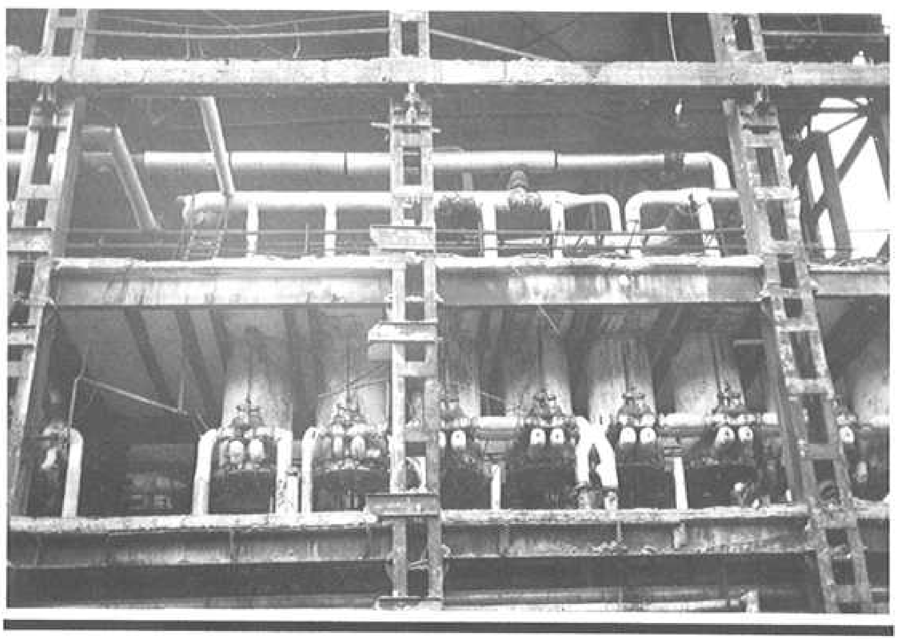
Generally, older structures with cut-stone walls and wood roofs performed better than newer structures with concrete components.

In Spitak the performance of industrial precast-concrete and masonry structures was possibly worse than that of residential and commercial buildings. The U.S. team found that most industrial structures in Leninakan erected with precast-concrete elements were also heavily damaged, many completely collapsed. Damage to the steel frames of buildings and other steel structures such as gantry and tall construction-cranes was light. The performance of the Spitak Sugar Refinery, which was examined in detail, is described below.

The **Spitak Sugar Refinery** is the only facility near the epicenter with many steel-frame buildings that was reviewed by the U.S. team. The refinery experienced high-intensity shaking. Virtually all precast-concrete cladding and cut-stone infill were shaken out of their frames. The steel frames themselves had adequate bracing and welded connections and maintained their structural integrity. Highly eccentric connections at brace locations probably contributed to weld breaks, which were repairable.

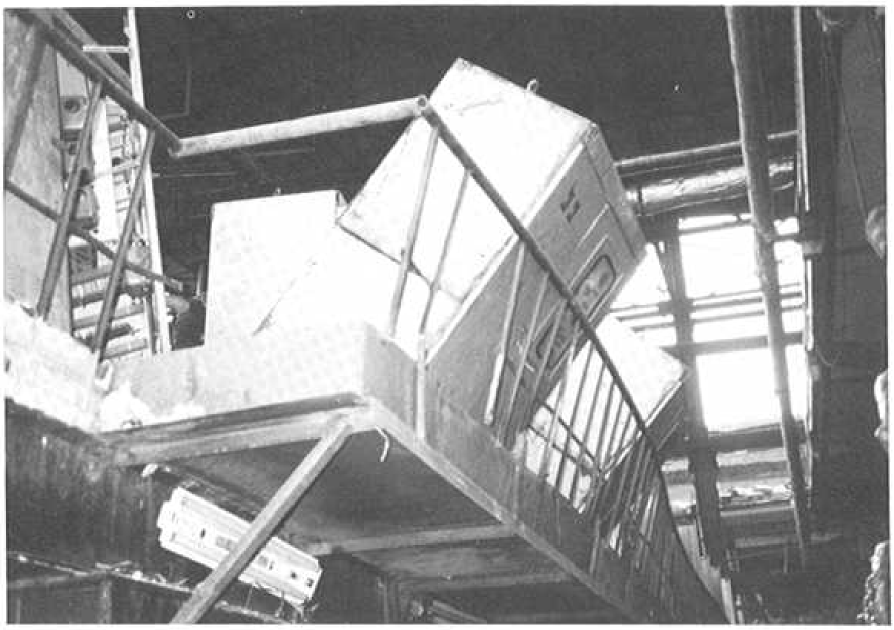
Unanchored and poorly anchored equipment slid and toppled, and much equipment was heavily damaged by falling debris. Piping and well anchored equipment that had not been struck appeared to have resisted structural damage although at the time of the investigation equipment had not yet been tested by restarting.

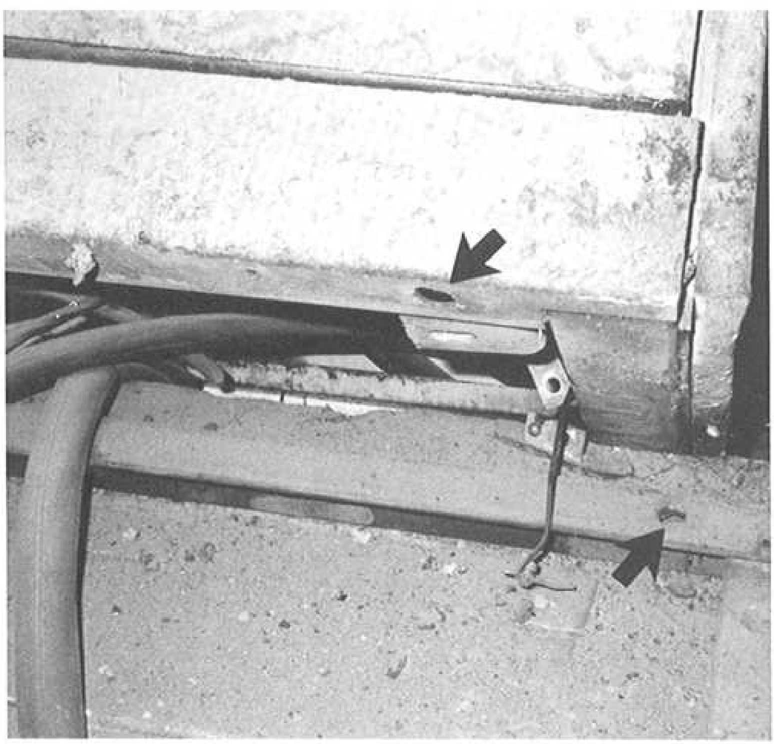


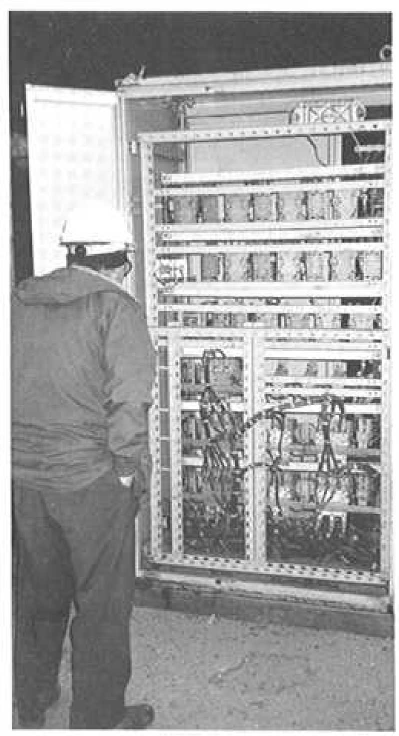


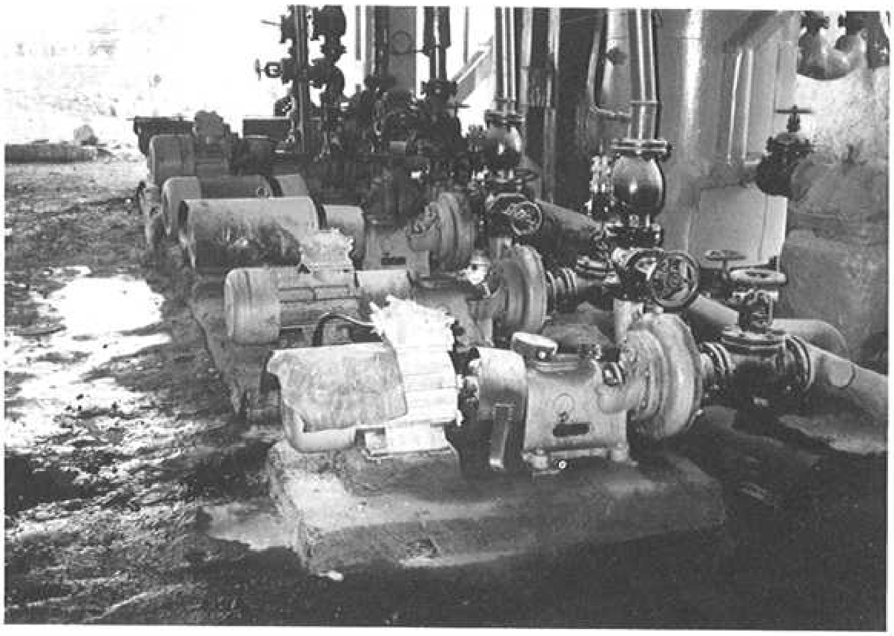
Spitak Sugar Refinery: Precast-concrete and masonry fascia were shaken out of steel frame of main structure. Frame, tanks, and piping are apparently undamaged.

Spitak Sugar Refinery: Toppled electical cabinets and detail of base where two poorly executed puddle welds (arrows) failed to stabilize unit. Another cabinet (bottom right) remained welded to its steel base-plate and was undamaged.

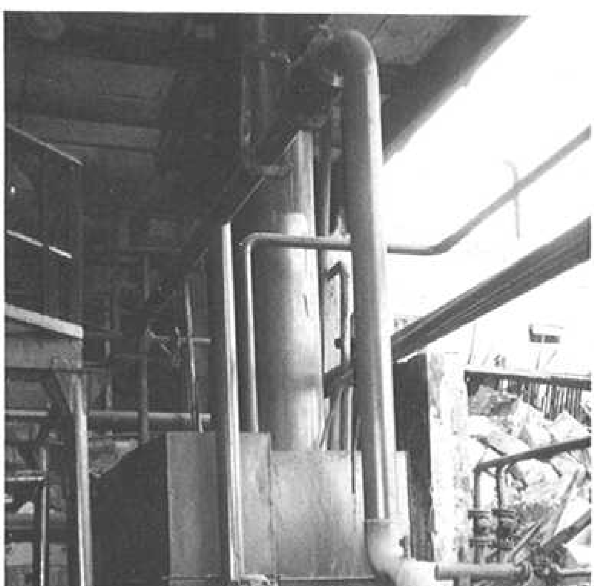






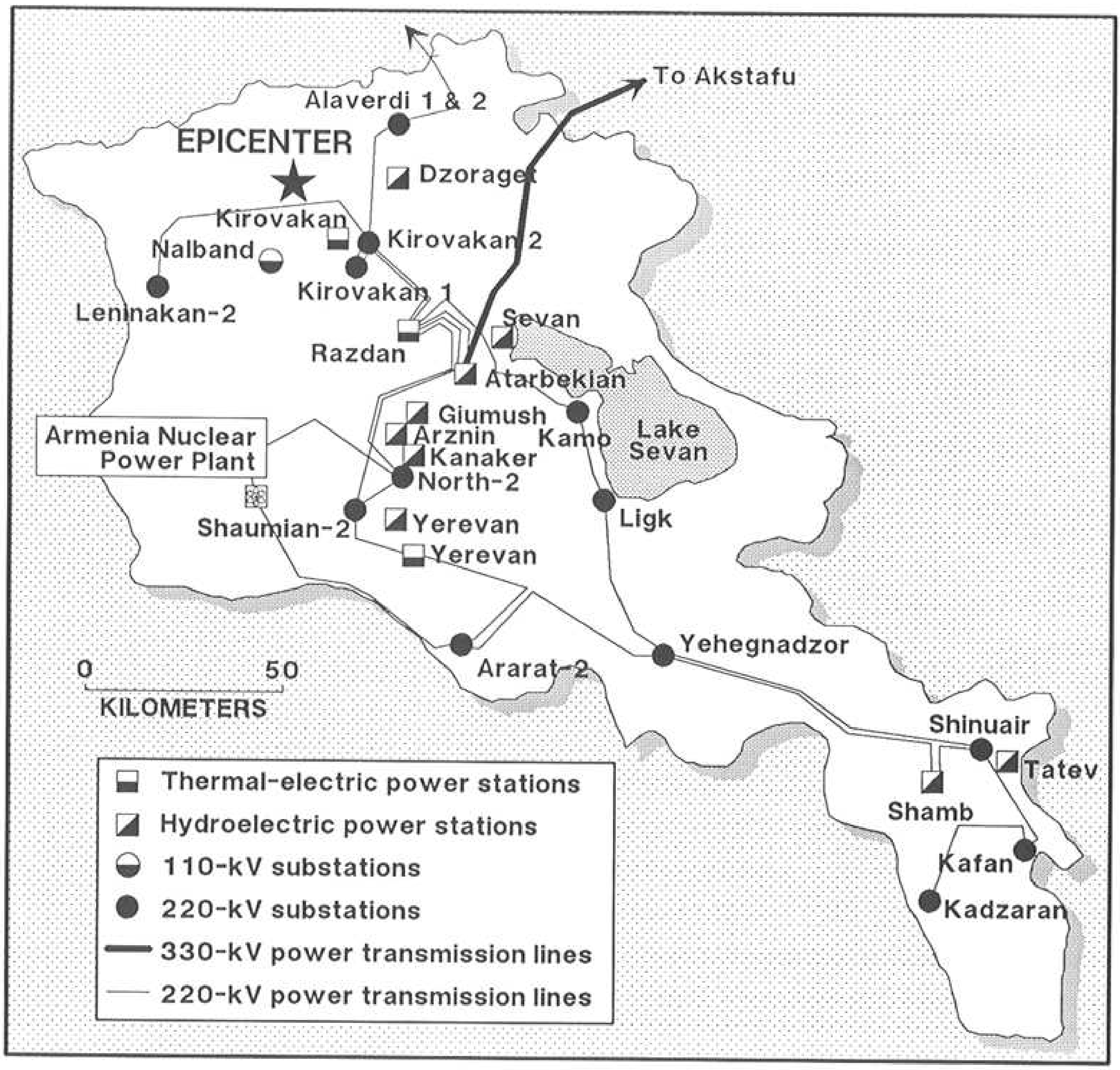


Spitak Sugar Refinery: Piping and horizontal pumps appeared undamaged near masonry and concrete rubble.



Spitak Sugar Refinery: Unanchored and corroded vertical tanks that had probably contained liquids collapsed or sustained severe damage and lost their contents.

At a tank farm in Spitak several horizontal tanks on elevated supports with narrow concrete footings toppled. The tank shells appeared to sustain minor damage from collapse, but no damage from inertial forces. However, piping ruptured and contents were lost.



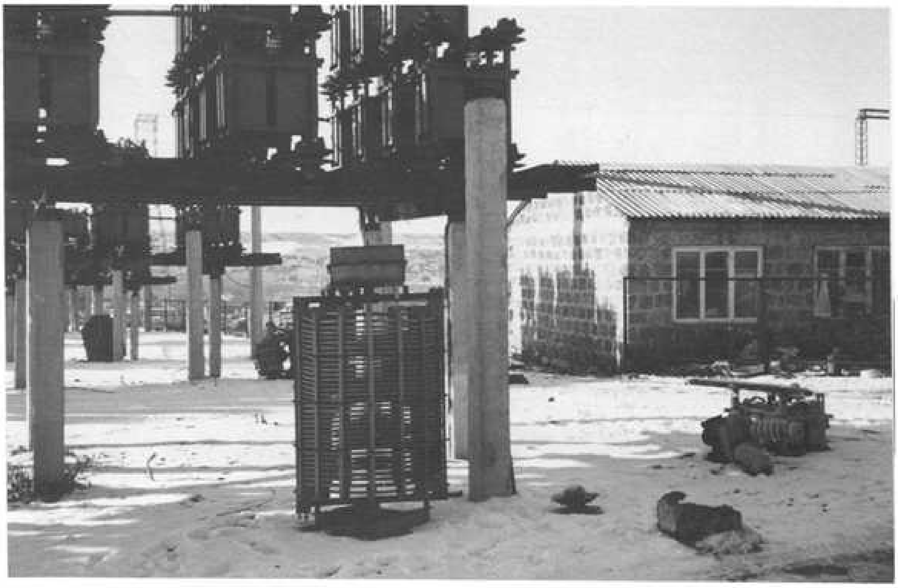
Electrical power grid of Armenia.

Power Generation. Two electrical substations were investigated in the epicentral region: the 220 kV Leninakan-2 facility in Leninakan and a 110 kV facility near Nalband. Damage to capacitor racks, ceramics, and circuit breakers at the Leninakan facility was similar to effects at the Devers Substation, which experienced an average peak ground acceleration of 0.81g during the magnitude 6.0 1986 North Palm Springs, California earthquake, an event with a much shorter duration than the Armenian event (see reference, Chapter 8). Housed control equipment at the Leninakan substation were anchored and undamaged. Electrical service to Leninakan was restored within 48 hours.

Leninakan-2 Electric Substation: Damaged ceramics in the 220 kV yard.

The 110 kV substation at Nalband was almost totally destroyed. The most striking damage occurred to the control house, a one- and two-story concrete-frame building with load-bearing walls. This building collapsed completely and struck nearby bus structures. The control house was a concrete frame structure with unreinforced masonry load-bearing walls. Transformers, circuit breakers, and capacitor banks also sustained damage of varying severity. Shortly after the earthquake, Soviet authorities successfully deployed a rail-mounted substation to restore electrical power in the Nalband area.

Steel transmission towers in the power grid throughout the strongly shaken area, including Spitak, performed very well with no reported damage.



Leninakan-2 Electric Substation: Fallen wave traps and ceramics on ground to right.

Leninakan Electric Substation: Undamaged relay-board cabinets are welded to steel base-plates. Note cracked rear wall of heavily damaged control house.

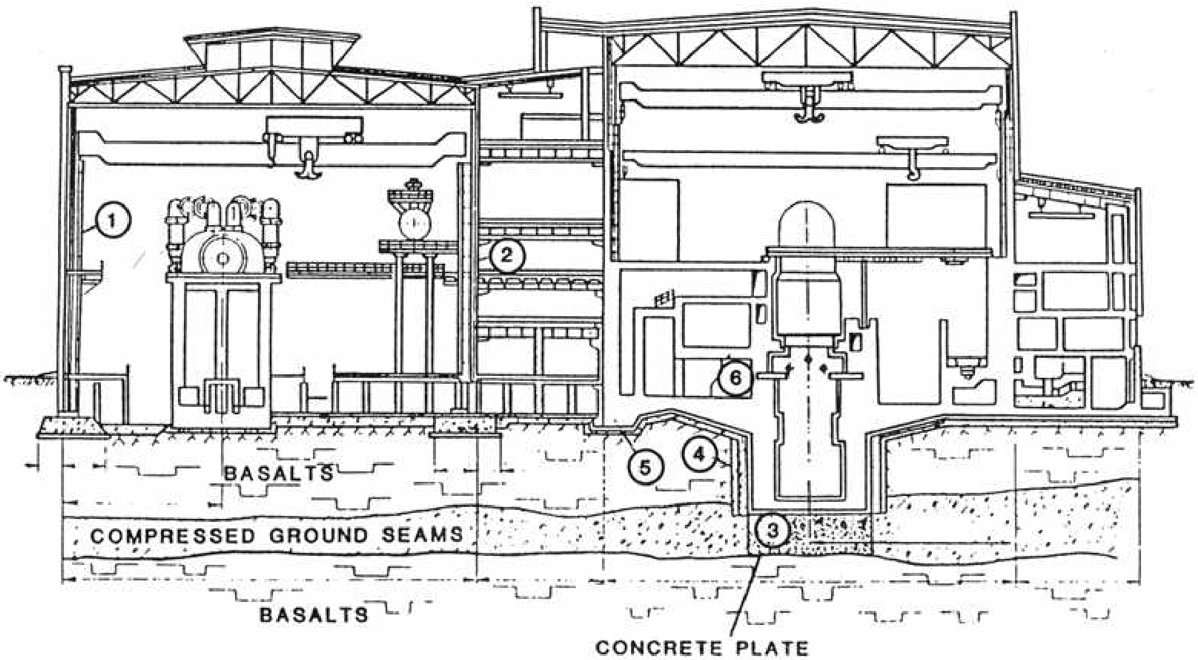
Nalband Electric Substation: Equipment that apparently remained intact or had limited damage within collapsed control building. Electrical control cabinets supporting roof fragment (top), medium-voltage metal-clad switchgear (bottom).

Nalband Electric Substation: The elevated concrete footings of these three oil-filled circuit breakers failed and the units toppled to the right.

Armenia Nuclear Plant: From left to right, office building (precast-concrete-frame), Unit 1 reactor building (concrete-shear wall), Unit 1 turbine building (steel-frame with precast-concrete fascia).

The Armenia Nuclear Power Plant. Armenia 1 and 2 comprise the nuclear facility at Oktembryan, about 75 kilometers south of the epicenter. The units are in the Soviet VVER-440 class, which is comparable to the western pressurized water reactor. Unit 1 began operation in 1977, Unit 2 in 1980. Officials reported that the December 7 earthquake caused neither emergency shutdown nor damage at the plant, which continued to operate.

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 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 PGA at



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.)

Armenia Nuclear Plant: Unit 2 control room. The panel indicates that unit was operating at 392 MW, approximately 90% of capacity, during U.S. investigation two weeks after earthquake.

Armenia Nuclear Plant: Overhead seismic bracing of electrical cabinetry and relay panels in control room area of Unit 2. Original start-up of Unit 2 was delayed three years while seismic modifications such as this were made.

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 of the plant was founded on flat layered volcanic and alluvial deposits, a site the Soviets believed did not present a realistic seismic hazard to the facility. 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 that 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; 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 IX.

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 intensity 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 at 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.

7. CONCLUSIONS

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

General

- The earthquake was a major disaster. While Soviet seismologists had expected such an event, Soviet society had not prepared for it. The primary cause of death, injury, and destruction was the total collapse of modern engineered structures that were not designed for the expected earthquake loads. Similar failures on this scale were observed in the Tangshan, China earthquake of 1976 and the Vrancea, Romania earthquake of 1977, but Soviet society apparently took no notice.

- In terms of damage and death directly caused by seismic shaking, the United States has not experienced anything comparable to the Armenian disaster. However, the combination of seismologic and engineering conditions that resulted in this disaster in the Trans-Caucasus exist in such areas as Puget Sound in Washington; the region centered on New Madrid between St. Louis, Missouri and Memphis, Tennessee; the region around Charleston, South Carolina; and the Salt Lake City region in Utah. Given the regional similarities in earthquake potential, building types, and the absence of earthquake preparedness programs, the possibility for an earthquake with consequences of comparable proportions is realistic. While such disasters are feared by the U.S. earthquake engineering community, U.S. society has not exhibited consistent concern about the risk.

Structures

- Of the building systems affected by the earthquake, seismically under-designed precast-concrete frames with precast shear walls performed most poorly. This system is used extensively in Armenia for commercial, residential, and industrial buildings. A similar design either with or without precast shear walls is also popular in the United States. While the system is probably adequate in zones with very low seismicity, the earthquake demonstrated that it should be eliminated or radically modified in higher risk zones in both countries.

- Many buildings that have been designed and constructed with little resistance to earthquake motion are still in use in Armenia and other seismic risk regions of the Soviet Union and United States. The Soviet government and governments at all levels in the United States must make important political and engineering decisions on reducing the risk from such structures in seismically active areas to prevent repetition of the Armenian disaster. Whether through retrofitting or new design and construction, resolution of the problem will be lengthy and enormously expensive.

- Seismic design in Armenia appears to have been practiced as an afterthought influenced more by mass production, economy, and functionality than by sound engineering decisions applicable to specific risk. This is also true in the U.S. areas mentioned above. Good seismic performance in a structure requires that seismic considerations be incorporated from the inception of the design process and include selection of materials, development of plan layout, and detailing of the basic elements.

- Although there are major differences between building design in Armenia and in the United States, several important factors bear on U.S. practice. For a building to perform satisfactorily in strong ground shaking, all structural elements must be positively tied together. The lateral-load-resisting system must be ductile or able to withstand real seismic forces far in excess of code-specified design forces. The detailing necessary to achieve this, including steel ties between precast elements, reinforcing in masonry, and confining reinforcement in concrete, was generally absent from the Armenian buildings. With the general exception of California, these same design omissions continue to be made throughout the United States, including in areas known to be seimsically vulnerable such as Charleston and the region between St. Louis and Memphis.

- The quality of field construction was often poor and probably contributed to the number of collapses. This problem is not unique to Armenia. To ensure that a structure is properly constructed and will perform as designed, it is necessary that the design engineer actively check the construction process.

- Most steel frames in industrial structures performed well. Large concrete-panel buildings with massive shear walls also resisted major damage, although these were in areas of lower intensity shaking than that experienced by the most heavily damaged structures.

- Deficiencies in Armenian seismic design and construction can be traced to a history of politically enforced isolation of Soviet engineers from the international earthquake-engineering community. By having opportunities to perform on-site investigation of major earthquakes throughout the world, Soviet engineers will be able to learn, as we have, from both the mistakes and good designs of the past. The international cooperation that followed the Armenian event is an encouraging sign that additional knowledge can be shared and repetition of such disasters can be avoided.

- Standardization in design and construction as practiced with precast-frame buildings in Armenia and concrete-tilt-up buildings in the United States should not be equated with high quality results. The Armenia earthquake vividly demonstrates that constant repetition of accepted practice can lead to damage of disastrous proportions.

- Microzonation is an effective method to upgrade design requirements for seismic shaking intensities related to poor soil conditions. As a means to downgrade intensities, the practice should be used cautiously or avoided completely. Seismic hazard characterization is dependent on many factors, including frequency of occurrence, source characteristics, regional attenuation relationships, and local site effects. All factors must be thoroughly studied before assigning an intensity to any location.

Emergency Response

- Soviet search and rescue was not organized for immediate response to an earthquake disaster of this scope and complexity. The most obvious explanation for this is simply that the need was not anticipated. Similar preparedness problems exist in the United States and in many industrialized and most non-industrialized countries where the potential for major natural disasters exists.

- Search and rescue demands highly specialized personnel and equipment, which the Soviet military simply did not have when the earthquake struck. Thus the expectation that the military can perform search and rescue at disaster sites is unjustified. Similar expectations exist in the United States, also without foundation.

Industry and Business

- Properly anchored industrial equipment were undamaged in areas of the highest intensity shaking. However, much equipment that appeared undamaged was not yet tested for function. Piping without intentional seismic design remained functional or appeared capable of function. In the United States, industrial equipment, particularly electrical control equipment, is typically unanchored. Substantial reduction of equipment losses through proper anchorage is a lesson that has been repeated without fail in all major earthquakes affecting industrial facilities.

- 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.

In preparing a reconstruction program for Armenia, Soviet officials stated that seismic resistance criteria would be substantially enhanced for new construction and that no new buildings would exceed four to five stories in height. It was also decided that the reconstruction of Leninakan would be divided into 15 sections comprising 100,000 apartments; reconstruction in each section is to be managed through a separate Soviet republic to introduce diversity and spread the cost.

The information in this summary has been presented from the viewpoint that performance under actual earthquake conditions is the best test of seismic reliability. It is in this spirit that EQE continues to actively investigate the behavior of engineered structures in earthquakes and to disseminate our findings in reports such as this.

The 19th century cathedral in central Leninakan before and after the earthquake.

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