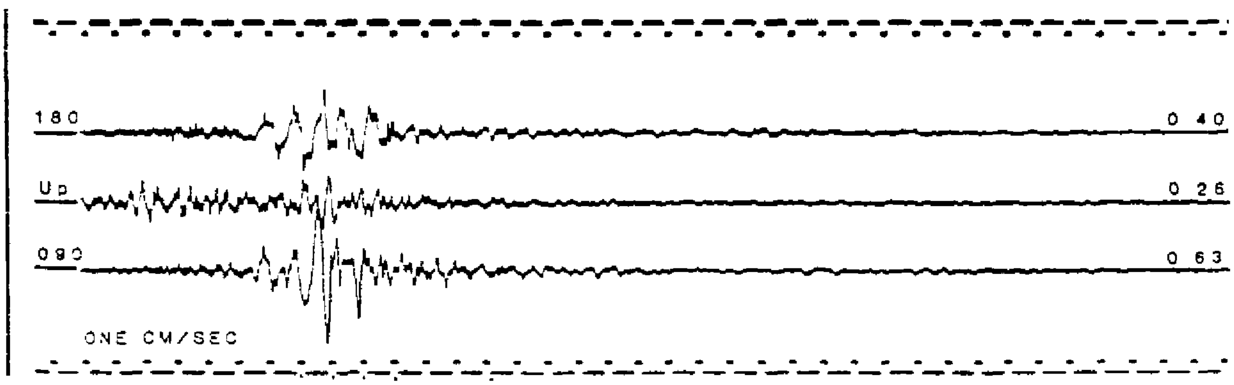
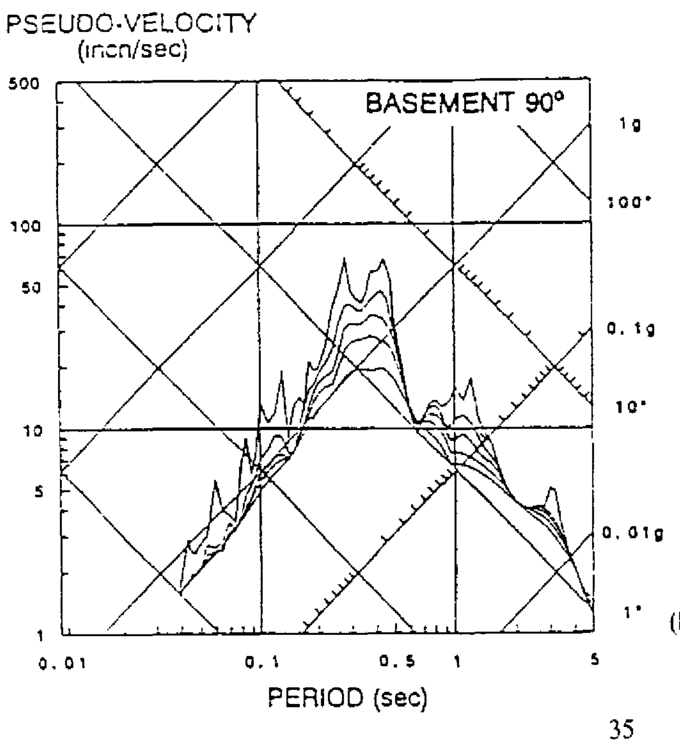
**Fig. 28 GENERAL VIEW OF THE 10-STORY RC BUILDING WHERE THE ACCELEROGRAMS SHOWN IN FIG. 29 WERE RECORDED**




(a). ACCELEROGRAMS




(b). LEDRS

**Fig. 29 ACCELEROGRAMS RECORDED IN THE BASEMENT OF THE BUILDING IN FIG. 28 [27] (a), AND THE LERS FOR THE 90% HORIZONTAL COMPONENT ($\xi$=0, 2, 5, 10 AND 20%) (b)**

Priestley concluded that the damage was very extensive, and emphasized the need for detailed studies of the performance of this bridge in order to assess the need for column retrofits to other complex bridges. The importance of the observed damage and Priestley's recommendations will be discussed later in the context of the discussion of lessons learned, in particular in discussion of the damage to highway structures during the 1989 Loma Prieta EQ.

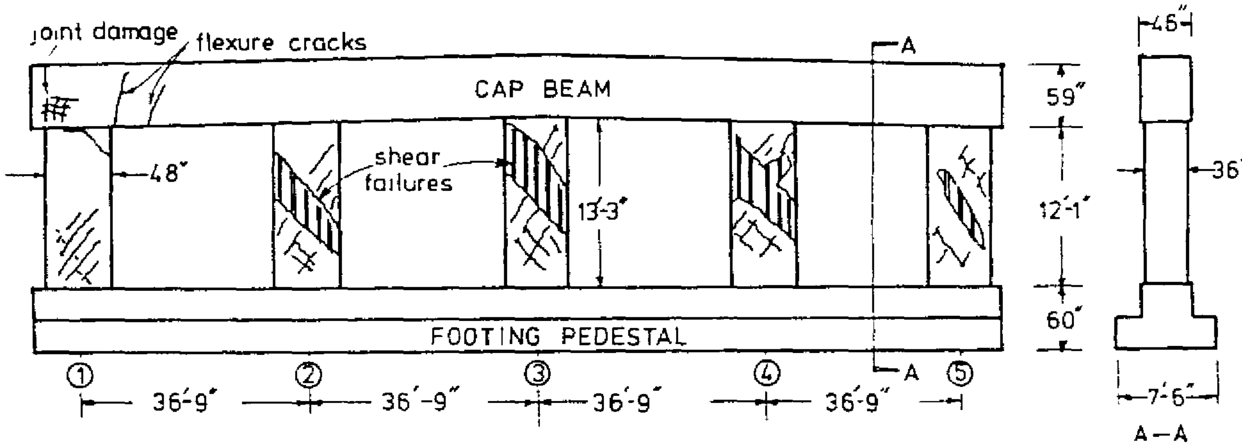



**Fig. 30 ILLUSTRATION OF THE DIMENSIONS OF AND DAMAGE TO BENT 6 OF A MAJOR FREEWAY OVERPASS (PRIESTLEY [27])**

**THE ARMENIAN EARTHQUAKE OF DECEMBER 7, 1988 [28, 29].** The main shock of this EQ, with a body wave magnitude $M_b$=6.3, corresponding to a surface wave magnitude $M_s$=6.8 and an estimated moment magnitude $M_w$=6.8, occurred at 11:41 am local time near the relatively new town of Spitak (population about 20,000), which is located midway between the cities of Leninakan (population about 290,000) and Kirovakan, 60 km east of Leninakan (population about 170,000). This main shock, with a focus (hypocenter) estimated at 15 km and with strong motion lasting nearly 30 seconds, caused catastrophic damage and was followed four minutes later by an aftershock with $M_b$=5.9, causing significant additional damage. Although the exact number of people killed is not known, official reports placed it at about 28,000 (ranging from 25,000 to 35,000) and unofficial reports gave a death toll ranging from 45,000 to 60,000. It has been estimated that about 130,000 people were injured, of which 18,000 required hospital care. The mortality among the injured was also high, particularly among those who remained buried alive for long periods of time. The number of people left homeless was estimated at between 500,000 and 700,000. There is no doubt that the Armenian EQ was one of the most lethal of the 1980-90 decade. But an even more important lesson learned from this $M_s$=6.8 EQ is that most of the life and economic losses resulted from the collapses of modern buildings. A summary of the main features of this EQ follows.

**Recorded EQGMs.** The only strong motion record available from the most affected area was from the three-component accelerograph located in the town of Ghoukasian, 27 km from the fault break. The records obtained during the main shock and the major shock four minutes later were digitalized at the University of California at Berkeley [28, Chapter 4] and at Imperial College [29]. While the records digitalized at Berkeley show a horizontal PGA of 0.21g in one direction and 0.19g in the other, the records digitalized and corrected using special filters at Imperial College show horizontal PGAs of 0.18g for both horizontal components. The peak ground velocities (PGV) for the two components were calculated at 14.7 and 23.7 cm/sec, and the peak ground displacements (PGD) as 3.2 and 6.7 cm. Figure 31 shows the filtered acceleration record for the transverse horizontal component with the computed velocity and displacement. The predominant frequency for this record is estimated at nearly 30 Hz (predominant ground period $T_g \doteq 0.33$ sec). The duration of strong motion was less than 12 seconds. The vertical PGA was 0.14g. The horizontal PGAs of the major aftershock four minutes later were 0.16g and 0.10g.

In the city of Leninkan there were 8 stations. Four of the stations were in buildings that collapsed, and the records could not be recovered. The remaining stations produced seismoscope and seismograph records. Although the quality of these records was poor, it was estimated [28] that the motion due to the main shock consisted of about

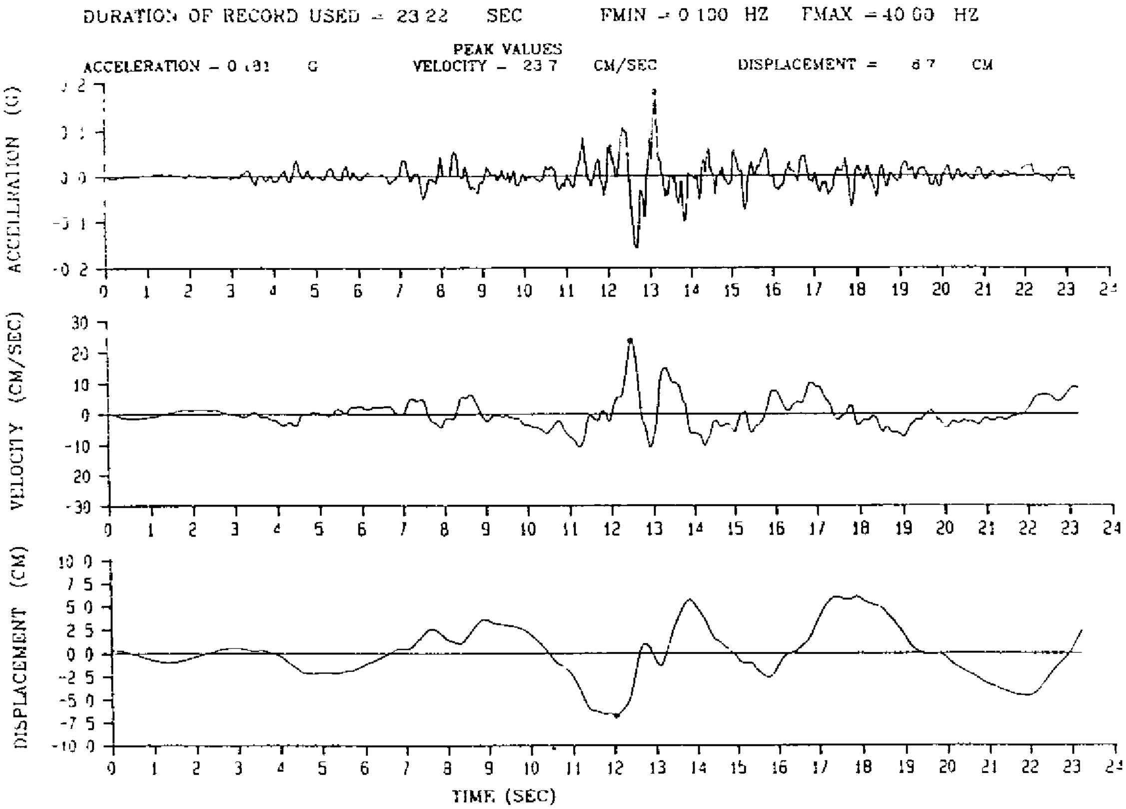



**Fig. 31 1989 ARMENIAN EQ, GHOUKASIAN: FILTERED ACCELERATION RECORD FOR TRANSVERSE HORIZONTAL COMPONENT WITH COMPUTED VELOCITY AND DISPLACEMENT.**

50 seconds of strong motion, followed by more than one minute of ground vibration owing to the response of the local soil structure. The motion of the aftershock consisted of 15-20 seconds of strong shaking, followed by more than 40 seconds of ground vibration due to soil response. The predominant frequency of the strong-motion phase was about 1 Hz ($T_g$=1 sec), and that of the locally produced vibration was around 0.5 Hz ($T_g$=2 sec). Comparison of the records obtained at Ghoukasian with estimates from the records obtained at Leninkan shows clearly that the motions at Leninkan lasted much longer, and that the low-frequency components of the motion at rock level may have been amplified significantly owing to soil response. These estimates are confirmed by recordings of the aftershock [28]. Armenian engineers estimated that the PGA in Leninkan might have reached 0.49g. This agrees with the estimates that have been made from the seismoscope records.

No records were obtained at Spitak, but judging from the damage observed, the soil conditions, and the fact that this town was the closest to the rupture zone (1-9 km), it is estimated that the PGA might have reached 0.80g.

**Geotechnical Effects.** From analysis of the recorded EQGMs, local geological conditions, and observed damage distributed to the various affected urban areas, it has been concluded that soil conditions contributed significantly to the amplification and increased duration of strong shaking with longer periods, and these factors in turn were the main reasons for the high level of damage. Significant surface faulting was observed, with a maximum displacement of 2 meters and a length of about 12 km. The EQ triggered perhaps thousands of landslides. Some of the rockslides and landslides caused severe damage to lifelines. Although some soil liquefaction was observed in the form of sand boils, this effect is not considered significant.

**Performance of Structures.** As indicated earlier, one of the most important features of this EQ was the catastrophic collapse of relatively modern multistory residential buildings (Figs. 6 and 32). A very large percentage of composite-frame stone buildings with four and five stories suffered heavy damage. In Spitak, 87% of the structures collapsed or suffered such heavy damage that they had to be demolished. In Leninkan, about 30% of the engineered structures suffered severe damage: 72 modern 9-story precast concrete frame buildings collapsed, and about 60 more have to be demolished. From analysis of the statistics available regarding the structures that collapsed or suffered heavy damage [28], the following conclusions were drawn: (1) precast-panel buildings performed well; (2) precast-frame buildings performed poorly. Of the total number of precast-frame buildings in Leninkan (133), 95% collapsed or had to be demolished. A large number of these buildings were nine to 12 stories. These buildings lacked ductile details and the quality of the field workmanship was poor (Fig. 6). Except for a 9-story hotel and a couple of high-rise buildings that were under construction, no buildings of more than five stories survived the EQ. On the other hand, in Kirovakan, out of total of 108 RC precast-frame buildings of which the majority have 5 or fewer stories, none collapsed or had to be demolished.

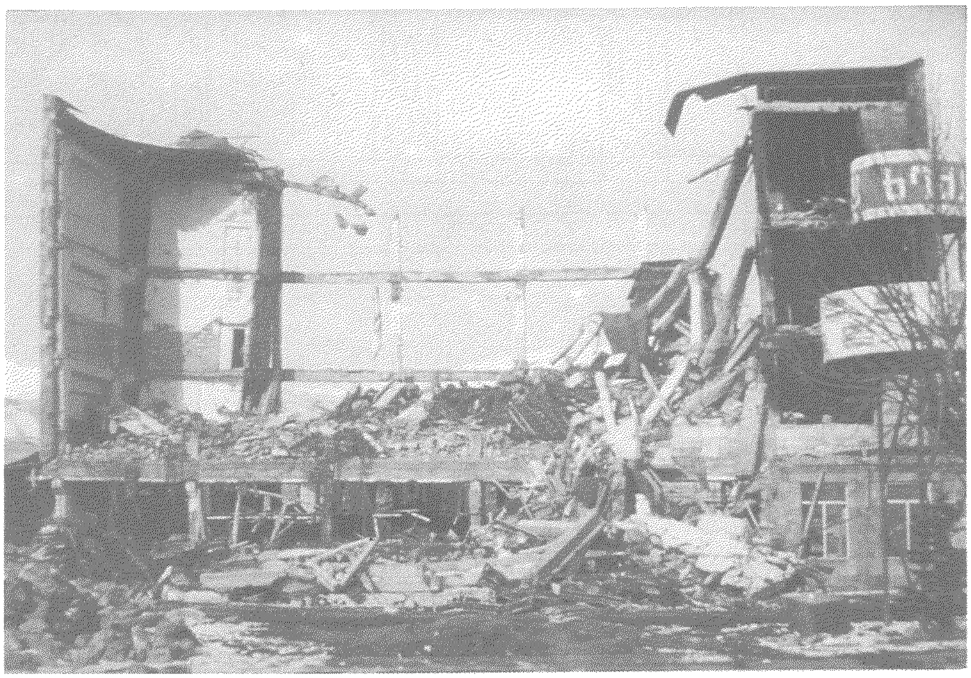


**Fig. 32 COLLAPSE OF A FIVE-STORY PRECAST FRAME BUILDING IN SPITAK [28]**

An analysis of percentages of damaged buildings suggested that in Leninkan this percentage increased with increasing period of the building, and in Kirovakan the percentage decreased with increased period [28]. This conclusion is consistent with the conclusion that, due to the geological setting, the EQGMs in Leninkan had a higher predominant period than those in Kirovakan. The above main features of the recorded EQGMs, geotechnical effects, and performances of structures point out clearly the importance of the geological setting (site conditions) in establishing the design EQs and in the selection of the structural systems; the need for reliable zonation and microzonation of urban areas; and the importance of providing ductility through proper sizing and detailing and of good field construction practice (quality control of materials and workmanship).

Comparing the behavior of the RC precast-panel with that of the RC precast-frame, and considering that in both of these two types of construction the quality of the connections was very poor, it becomes clear that the seismic response of the frame structure is more sensitive to the behavior of the connections than the all-precast-walls system.

**THE OCTOBER 17, 1989 LOMA PRIETA EARTHQUAKE.** The following information about the Loma Prieta EQ is a summary of the material presented in a public briefing on the preliminary investigations of the EQ on October 25, 1989, on the Berkeley campus of the University of California, and published in *Report No UCB/EERC-89/14*, October 1989, by the Earthquake Engineering Research Center at the University of California at Berkeley [12].

The epicenter of this EQ, located in the Santa Cruz Mountains, was about 16 km northeast of Santa Cruz, 30 km south of San Jose, and nearly 100 km south of San Francisco and Oakland (Fig. 1). The Richter magnitude, $M_L$, was assessed as 7.0, and the average surface wave magnitude was estimated as 7.1. Although the strong shaking lasted only a few seconds (less than 12 seconds in the epicentral region, less than seven seconds in the Bay Area), the EQ induced damage throughout an area of about 8,000 square km, causing economic losses due to physical