

THE 1999 QUINDIO EARTHQUAKE, COLOMBIA

- Investigation into Damage to Civil Engineering Structures -

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An earthquake of magnitude 6.2 (M_b) occurred in west-central part of Colombia on January 25, 1999. This earthquake is officially called Quindio Earthquake from the name of the most affected province. The earthquake caused disastrous damage to a large number of buildings resulting in significant casualties. In Armenia City and its neighboring villages close to the epicenter, over 1,000 people were killed by the earthquake and the total monetary loss reached US\$ 2 billion. Armenia City, which has an approximate population of 280,000 people, apparently suffered the worst in terms of casualties and damage to the buildings.

The present paper focuses on the causes of damage to houses and buildings in Armenia City. First, the evolution of the urban area of the city was investigated using historical features available maps from each era. Then a correlation between building damage and topographical features of the city was studied. The effects of geological features and amplification of ground motion were also investigated.

Keywords: building damage, earthquake damage, topographical and geological effects

1. Introduction

An earthquake of magnitude 6.2 (M_b) occurred in Quindio Province, Colombia at 13:19 local time on January 25, 1999. According to the technical report of the Ministry of Interior (RCMI,1999), the total number of dead was 1,171 and injured 4,795. Among the damages to tangible assets, 21,178 dwelling and non-dwelling buildings collapsed completely, and over 32,000 buildings collapsed partially.

The city of Armenia which is located approximately 13 km to the north of the epicenter, suffered the worst human and structural damage among all cities affected by the earthquake, even though the earthquake was of moderate magnitude ($M_b=6.2$). The effect of sediments and

/or ground topography seemed to be significant. Therefore, the evolution of the urban area of Armenia City was investigated by using old edition maps in various eras to study the relation between the damage to buildings and topographical features. Further, effects of geological features and ground motion on the damage to buildings were also investigated.

2. Outline of earthquake and damage

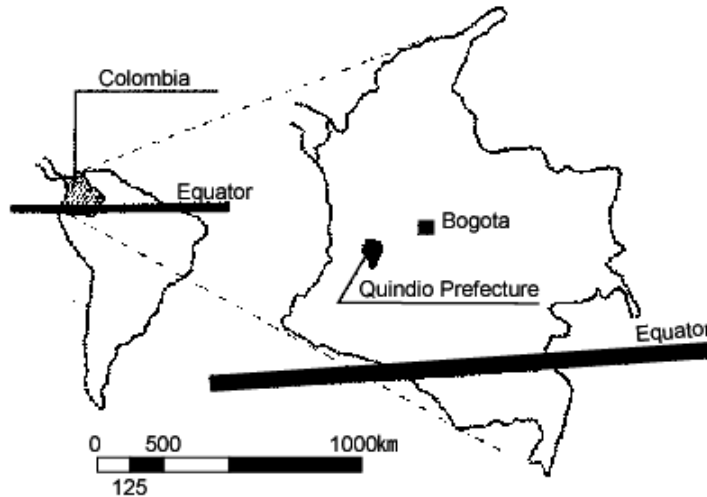


Fig.1. Location of Quindio Prefecture, Colombia

Colombia is a low land country surrounded by the Andes mountain range in the west and the upper Amazon river in the east. Since the Nazca plate of the Pacific Ocean had sunk below the South American plate thus forming the Andes mountain range, western Colombia is rich in volcanic eruptions and seismic activity.

Fig.1 shows the location of Quindio Province. The epicenter is located 13 km south of Armenia City, having a latitude 4.41 degrees north and longitude of 75.72 degrees west, with a depth within 10 km. The earthquake fault was in the direction of NNE to SSW with left lateral slip. Major parameters of the earthquake are listed in Table 1.

Table 1. Parameters of the main shock and maximum aftershock
(after INGEOMINAS,1999a)

	Main shock	Aftershock
Date	25 Jan. 1999	25Jan. 1999
Origin time	13h19m(18h19mUT)	17h40m(22h40mUT)
Longitude	4.41N	4.39N
Latitude	75.72W	75.72W
Depth	+/-10km	+/-10km
Magnitude	6.2	5.8
Moment	1.8E18Nm	—

Accelerations were recorded in Quindio University, located in the north of Armenia: a maximum horizontal acceleration of 580.0 gal in NS direction, 518.1 gal in EW direction, and a vertical acceleration of 446.7 gal.

Table 2. Damage statistics(after INGEOMINAS,1999a)

Province	Injured	Dead	Dwelling Buildings		Non Dwelling Buildings	
			Total	Partial	Total	Partial
Quindio Province	3,744	1,033	18,691	24,303	390	417
Risaralda Province	761	51	174	1,209	1,225	1,952
Valle del Cauca Province	240	85	278	2,531	0	140
Tolima Province	50	2	394	1,357	2	71
Caldas Province	0	0	24	107	0	0
Total	4,795	1,171	19,561	29,507	1,617	2,580

Table 3. Damage statistics of major cities

City	Distance from epicenter(km)	Population	Dead	Injured	Death rate per 1,000persons
Armenia	13	283,842	800	2,300	2.8
Calarca	15	71,149	116	334	1.6
Caicedonia	15	50,534	48	80	1.5
Pereira	48	434,267	50	650	0.1
La Tebaida	9	26,078	33	280	1.3
Montenegro	17	38,133	19	350	0.5
Circasia	24	24,459	12	142	0.5
Total			1,078	4,136	

Table 2 lists the damage statistics for human lives and structures in the affected provinces. Table 3 summarizes the damage statistics in major cities. Fig.2 shows the relation between death rate per 1,000 persons and the distance from the epicenter. Armenia City with the severest damage has the highest value of 2.8 persons per 1,000 persons. This value is much less than the values for Higashi Nada, Nada, and Nagata wards in the 1995 Hyogoken-Nambu (Kobe) Earthquake (more than 5.0 persons per 1,000 persons), but is almost equal to that of Hyogo ward (3.0 persons per 1,000 persons). The overall scenario indicated that the further the city is from the epicenter of earthquake, the smaller the death rate is.

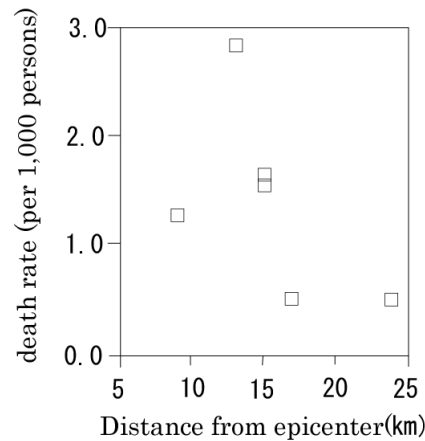


Fig.2.Relation between death rate (per 1,000 persons) and the distance from the epicenter

3. Evolution of the urban area of Armenia City and its relation to building damage

Foundation soil in Armenia City includes a soft foundation layer sandwiched between finger-like formation of hills which is a typical representation of the topography of the city. Fig.3 makes a comparison of architectural damage, in terms of damaged buildings, encountered in the central and northern parts of the city. (INGEOMINAS [1999b] Terremoto del Quindio (entro 25 de 1999) Informe Tecnico Preliminar, No.2, Armenia-Quindio.) In the northern area, where most buildings conform to the building standards of 1984, only 8 buildings were completely destroyed in the earthquake, whereas in the central area that has so many old buildings suffered severe damages. Provincial government buildings, city government buildings, hospitals, fire department headquarters, police department headquarters, and shopping district all suffered heavy damages due to the earthquake. Out of the extent of architectural damage, 10% were completely destroyed, 40% were severely damaged but not completely destroyed, 30% suffered medium level damages, while the rest of 20% had minor damages. To the west of this area, the Armenia Fault runs from north-northeast to south- southwest, and although the fault did not move itself, the weak foundation area to the west of the fault was associated with indicated the greatest degree of damage. In the southern area, where low-income dwellers are concentrated and the buildings are old, due to the poor foundation soil, the amount of architectural damage was in the range of 40-70%(see photo 1). Most of these low rise structures were self-constructed with bricks, but among them were some houses made of thick bamboo reinforcements called *Gaudoa*; the low-cost single story structures were not severely damaged due to their light weight. However, in the northern Lobidensia, the damage rate was 30%, the central Centro area this was 90% while the southern Brazilia area had 95% damage ratio.

Fig.4 shows a comparison of urban growth of the central area in which the damage due to the earthquake was most severe, from 1948 to 1998. In 1948, the urban area was only a small but high plateau, which would have had minimal damage due to an earthquake. In the course of the city growth to 1998, it is observed that urban sprawl has set in here. It accelerated in 1957, causing urbanization up to the areas of cliff slopes and those of soft soils. The urban area of 1985 quite resembles that of 1957. And urban sprawl has shown a tree-like growth. As a result, the area of growth within this period has matched that of the area of damage in this earthquake. Thereafter, since the urban growth was in the direction of southwest towards hills,

the damage in this area was minimal. In the central and southern parts of Armenia City, there was a good correlation between the filled area and disaster damage. In the filled area, the damage was great, and this included the fire department as well.

Summarizing the above content, it is revealed that the initial urban development of the city was confined to a safe plateau area, and spread due to urban sprawl that was unplanned into the areas of hills and those with soft soils showing a high degree of damage in this disaster. In the period, building standards were regulated in 1984 but this was not mandatory. Since most of buildings did not conform to the standards, the design level of buildings was low and invariable in this period. So the damage to houses and buildings did not relate to the evolution of design standards but difference of ground conditions. Further, the fresh growth of the city into the safe areas of hills in the southeast and ended there had minimal damage. However if the urban sprawl takes place into soft soil areas in future, it is necessary to think of remedial action against damages expected due to earthquakes.

Fig.5 shows cross-sectional topography and architectural damage distribution of Brazilia and San Tandel, where the most severe damage was reported. This figure revealed that the building located up to a distance of 1.0-1.5 times the height of slope, from the foot of it, were completely destroyed. This will be discussed in the next chapter.

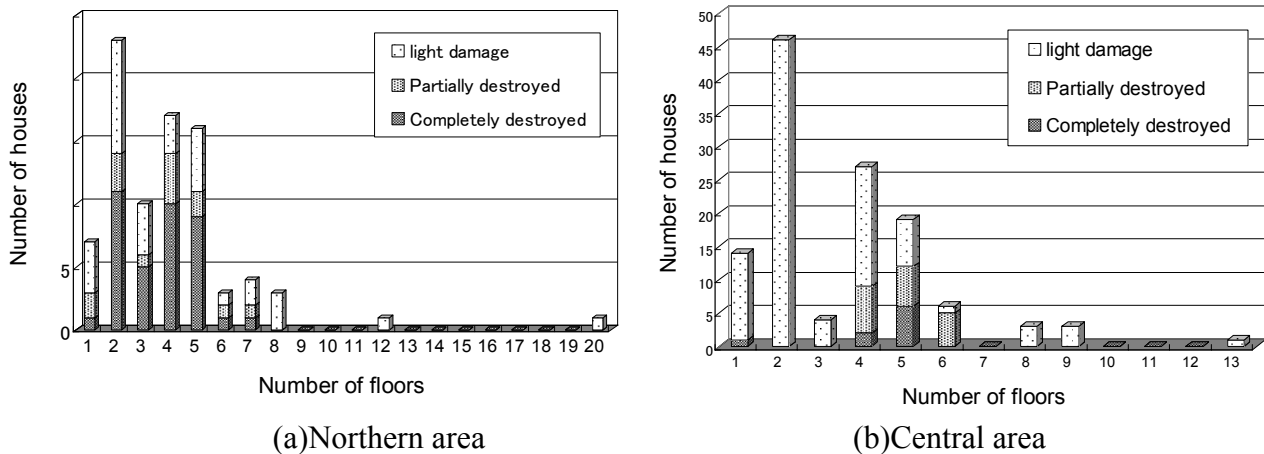


Fig.3. Damaged houses in northern and central parts of Armenia City



Photo 1. Worst damaged area of Armenia City (Courtesy: by E.Rodriguez Grandos)

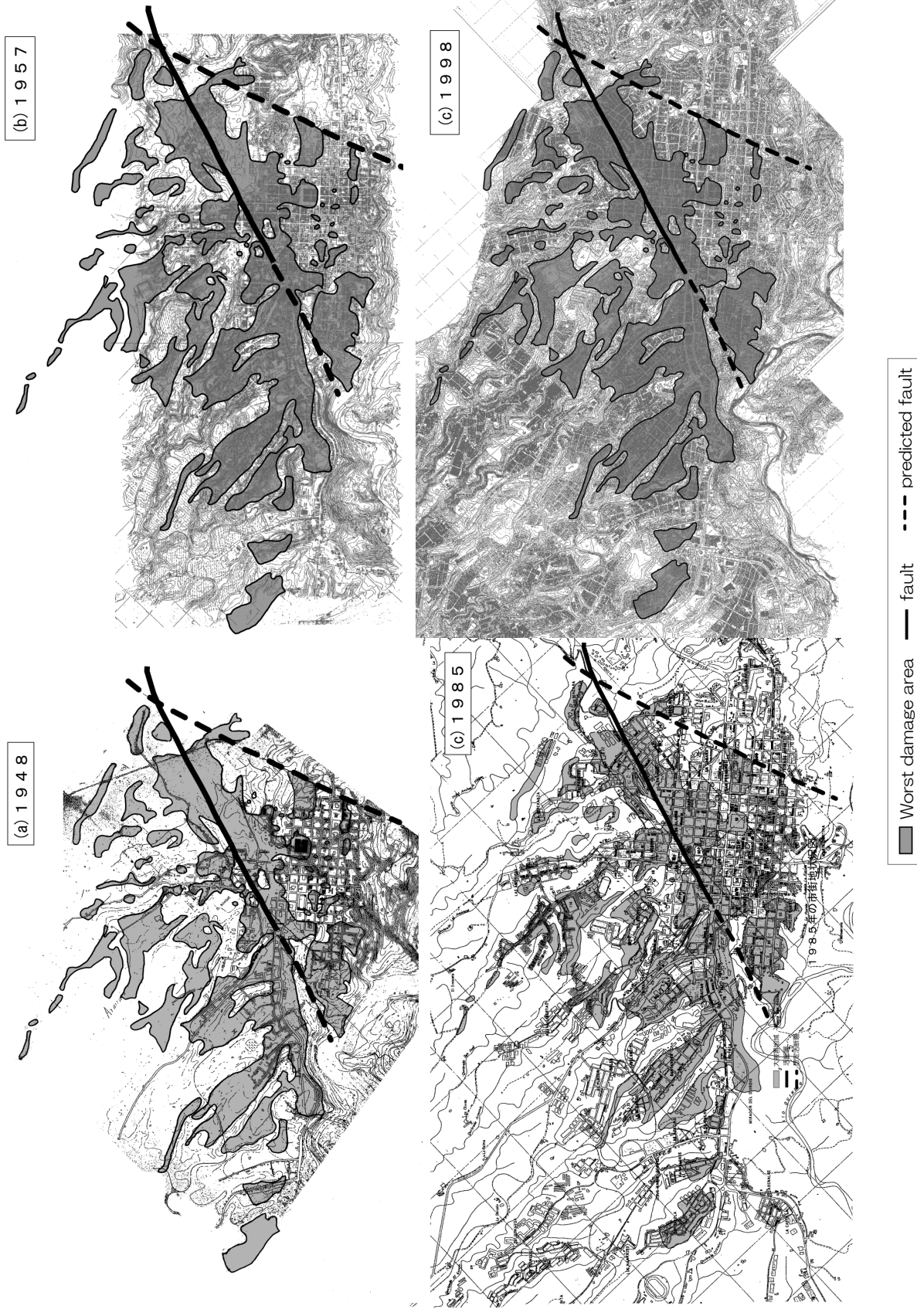


Fig.4. Evolution of urban area of Armenia City 1948-98.

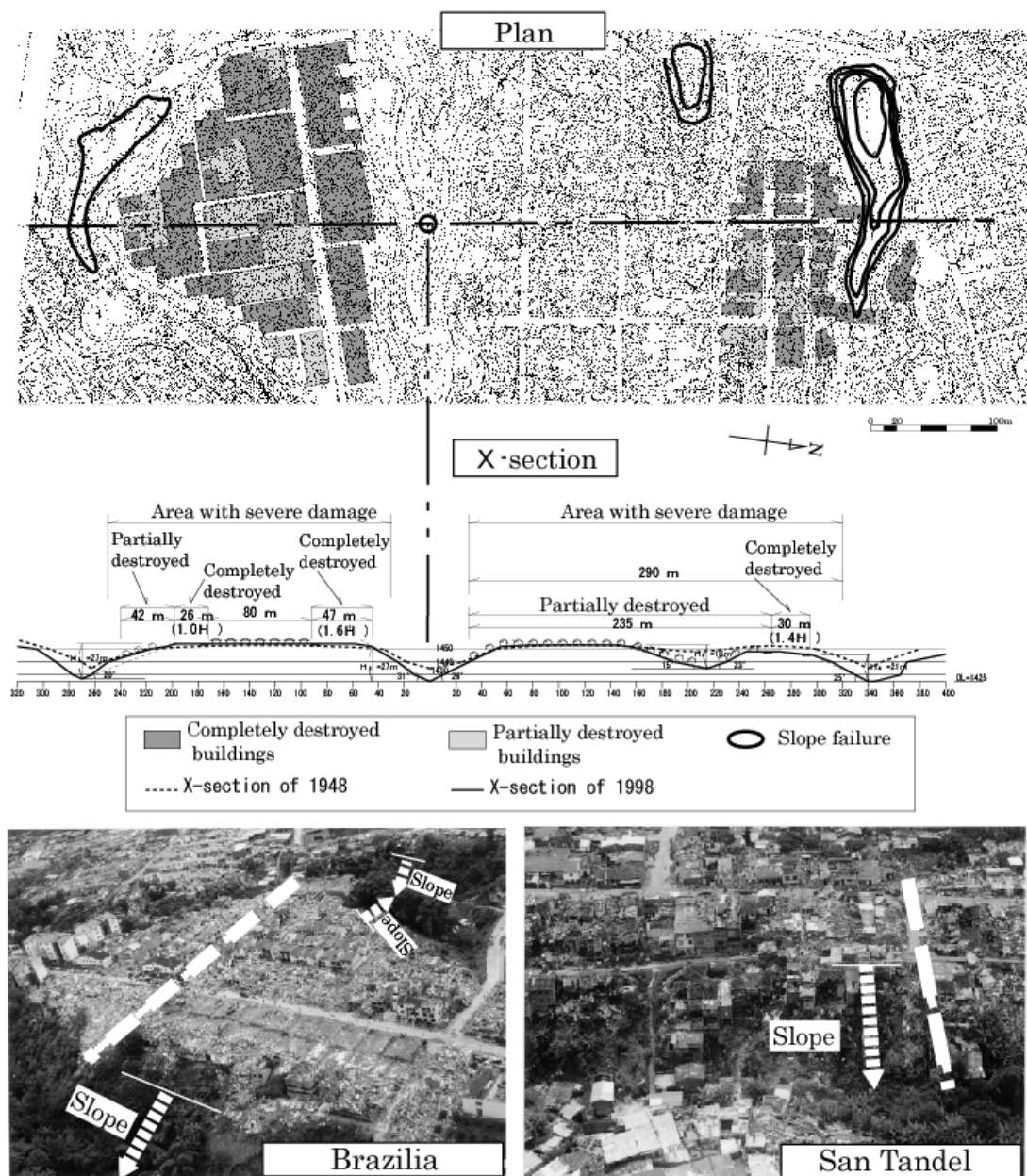


Fig.5. Cross-sectional topography and building damage distribution of Brazilia and San Tandel

4. Causes of damage to buildings

4-1 Effect of topography

To analyze the damage in the worst affected areas, the effects of topography (①~⑥) and foundation soils (A to J) were investigated. Lines of cross-sections considered are shown in Fig.6 In areas where severe damage occurred slope failure and tension cracks etc. were observed due to topography of slopes (see photo 2). In Fig.7, cross-sections at slope failure locations are shown. These locations were affected severely by the topographical conditions. Fig.8 shows relation between width of damage area and height of cliff. Damage area is defined as the places where severe damage to houses and buildings was caused in this paper. According to distribution map of damage level presented by INGEOMINAS [1999b], all areas of the Armenia City are classified into severe and moderate damage levels. The severe damage level area is adopted here as the maximum damage area. Therefore, there was no big difference in the damage level in the area. It was possible to observe that an upper boundary of L is 1.0 to $1.5H$, where L and H are width of maximum damage area and height of cliff respectively. In locations like cross-section ⑤ where it is surrounded by a valley, the damage was observed to be $L > 1.5H$. Fig.9 indicates relation between slope and L/H . L/H increases in an increase of slope and the upper boundary of L/H is 1.5 . There is almost no study that investigates width of damage area during earthquake with respect to the height and/or angle of cliff. Hirai et al. investigated the damage to building foundation in relation to an angle, height (H) and distance from the edge of cliff (D) in the 1995 Kobe Earthquake. They clarified that the number of damaged buildings increased when the slope exceeded 30% and no building damage occurred in the areas of $D > 1.5H$ (Hirai et al. 1996). These show good agreement with our observation in Colombia. Since the soil type is, however, different in each site, further study is needed.

In Japan, landslides due to rainfall may be in the area from 0.5-1.0 times the height of the cliff from its top or the area 2.0-3.0 times the cliff height from the bottom (Ministry of Construction in Japan (edit.) 1996). This is designated as the landslide prone area and cliff ordinance restrictions for houses and buildings. Since there is, however, no regulation for landslides during earthquake, the observations in this paper is important for the future regulation.

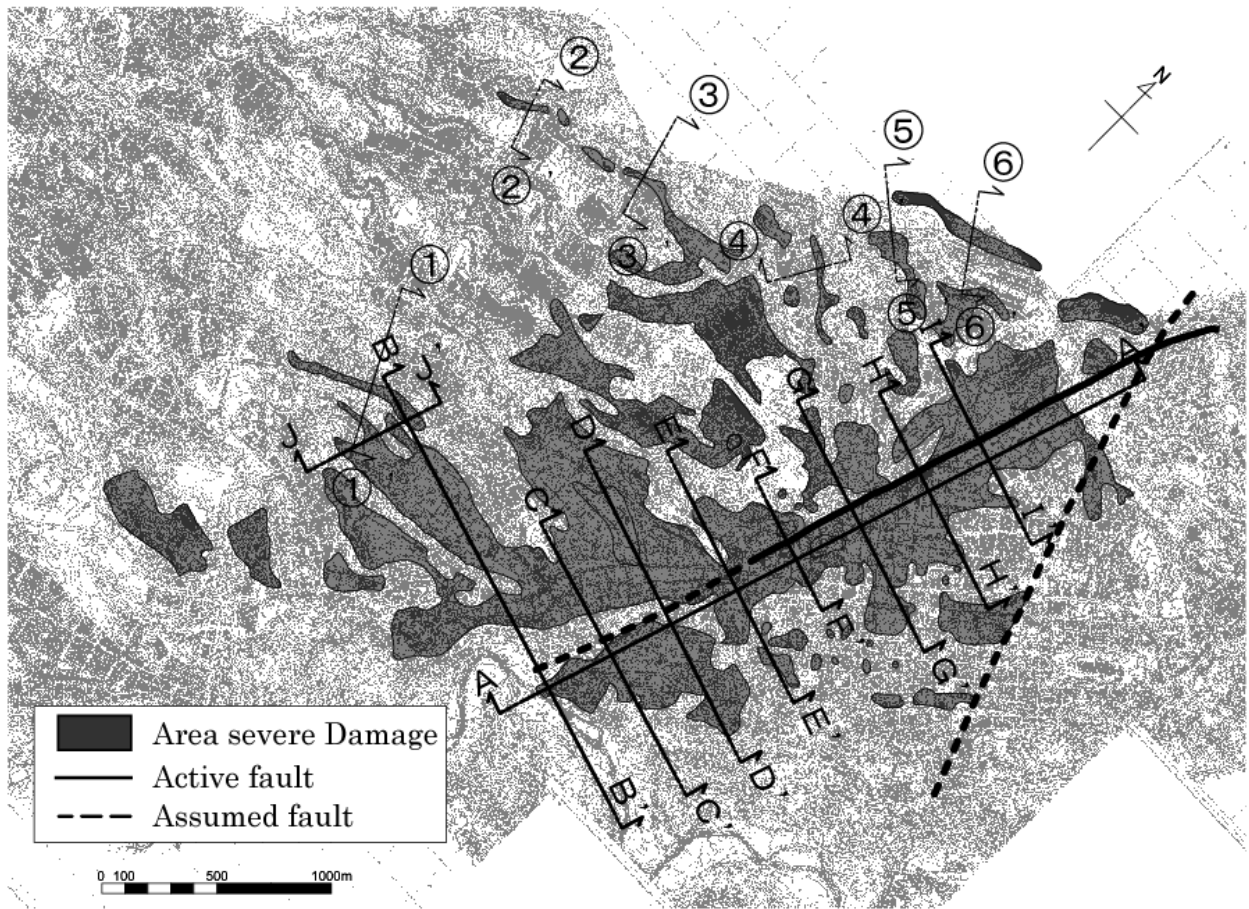


Fig.6. Area of severe damage and fault locations



Photo 2. An example of slope failure

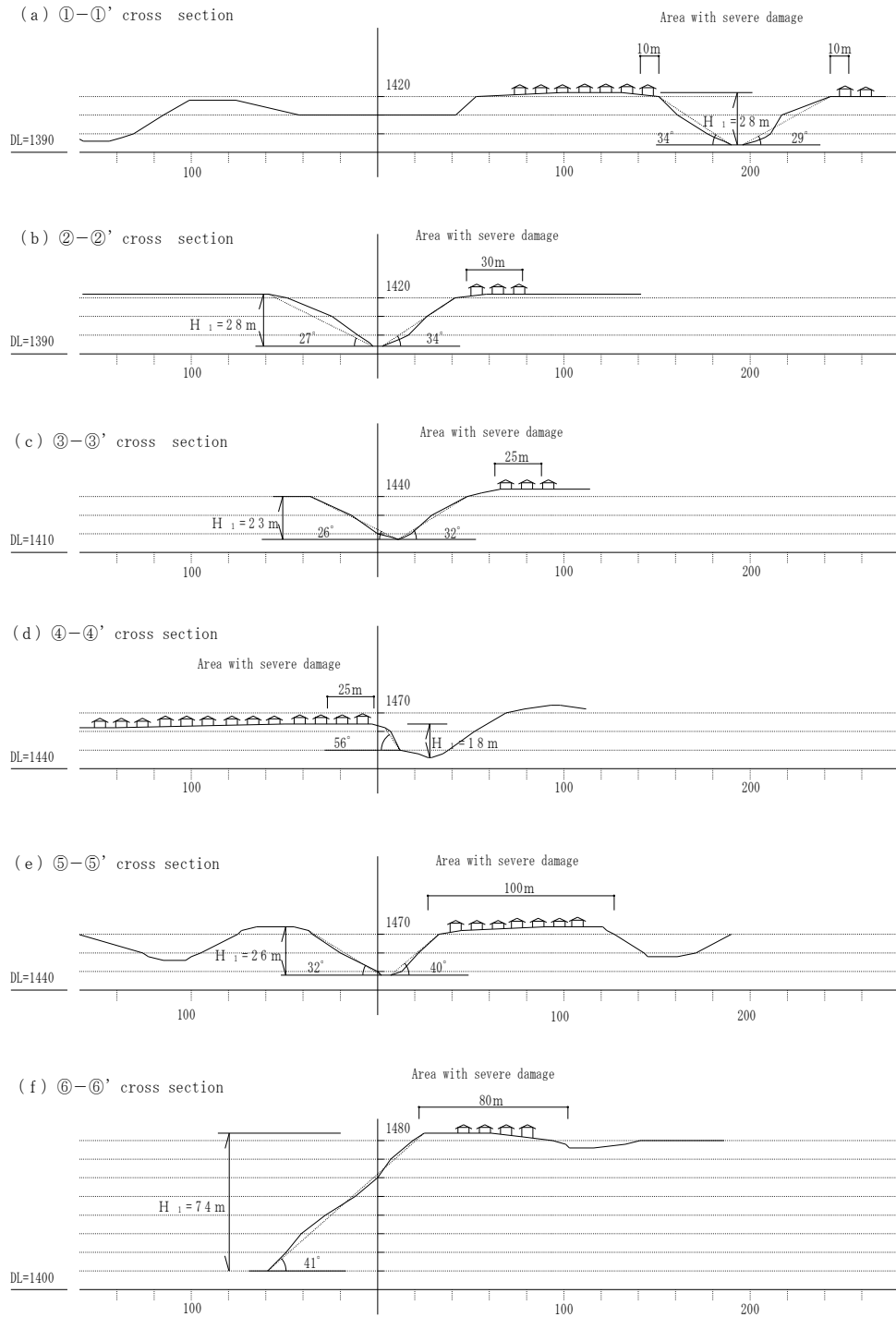


Fig.7. Cross-sections at failure locations

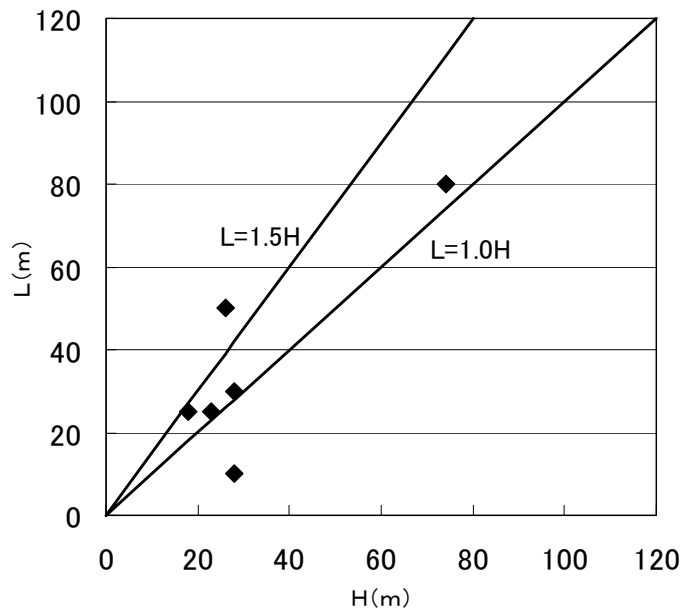


Fig.8. Relationship between width of damage area and height of cliff

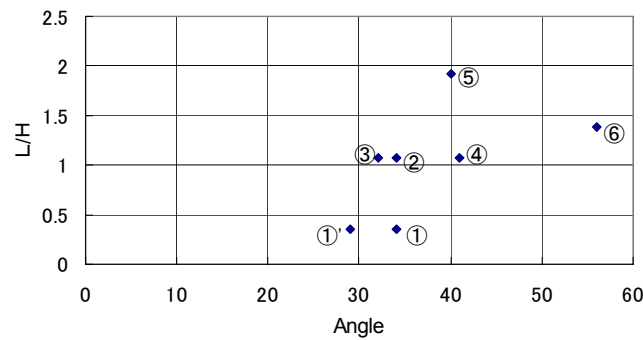


Fig.9. Relationship between slope and L/H

4-2 Effects of foundation soil conditions

Since soil investigations have not been conducted, maps of 1948 and 1998 were overlapped as shown in Fig.10. It was observed that urban sprawl was quite minor in the area illustrated in Fig.10 during this period, therefore assuming that this difference in topography is fills, each cross-section was analyzed. This fill area, as seen in typical cross-sections from F to H, is in the western (left) part, including the fault.

In cross-section H, a damage area exists in the eastern (right) part including the fault. According to the soil maps of INGEOMINAS [1999b], large deformations in cross-sections were observed and in comparison to the upper western part, the eastern part has considerable sediments of loam, which are as thick as 50 m approximately at the fault. Therefore, it is concluded that (right) areas east of the fault have been affected by fill while western (left) areas have been affected by soft loam. Further, it is considered that ground motion amplification could have occurred on either side of the fault owing to the soft soils.

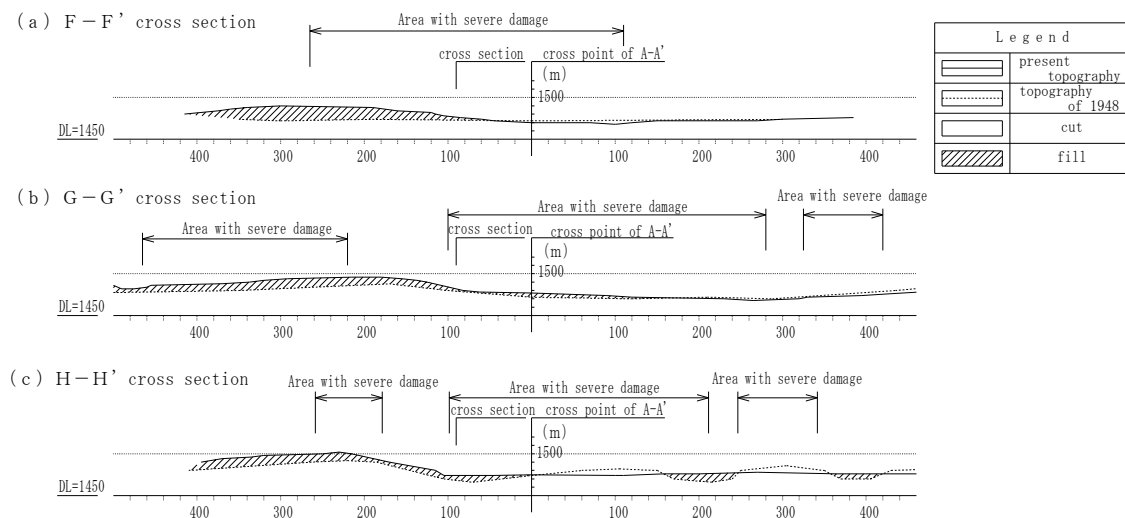


Fig.10. Effects of foundation soil condition

4-3 Effects of ground motion amplification

In Armenia City, INGEOMINAS has installed an accelerometer in the Quindio University located at the north of the city. Fig.11 shows the time histories, Fourier spectra and response acceleration spectra of the accelerographs of the main shock. The details of stratigraphy of this site were evaluated by the CRQ and the Los Andes University (1997) survey as listed in Table 4. The natural period of ground vibration was evaluated as a function of the thickness of the soil deposit, the soil density and shear modulus by using Table 4. According to this evaluation, the natural period of this site was obtained as 0.68 sec. This period coincides with the peak of response acceleration spectrum in N-S component as shown in Fig.11.

Although the natural periods of buildings in this area were not determined, they can be roughly estimated from a function of the number of stories (n) as $0.1 \times n$. When the natural period of building is close to the peak period of the response acceleration spectrum, the resonance effect is strong. The five to seven story buildings are likely to be affected by resonance effects in the north of the city where the accelerograph was obtained. According to Fig.3(a), the number of completely destroyed buildings was greatest in five stories. The resonance effect seems to be one of causes of building damage in this area. Only a preliminary investigation was conducted here, more detailed soil data are needed for proper study of the amplification of ground motion.

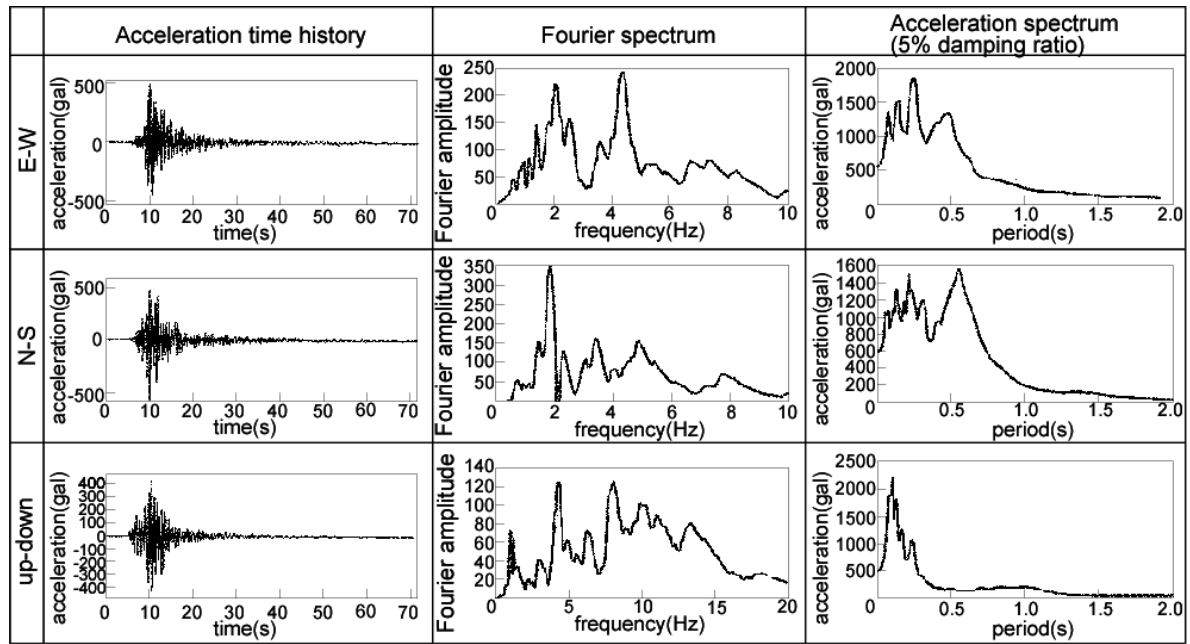


Fig.11. Acceleration time histories, Fourier spectra and acceleration spectra of main shock in Armenia City

Table 4. Geotechnical Profile at the Quindio University

Layer	Depth (m)	Description	W _n (%)	LL (%)	LP (%)	IP (%)	Unit Weight (tf/m ³)	Shear Modulus* G _{max} (tf/m ²)
1	0-4	Sandy silt, Yellowish color	30-35	40-45	25	15-20	1.60	2000-3700
2	4-6	Sandy silt, Yellowish gray	35-45	40-50	20-25	20-25	1.60	1500-3500
3	6-8	Sandy-clayey silt, Yellowish gray	45-110	50-120	10-25	25-110	1.50	3500-4500
4	8-10	Sandy silt, Yellowish color	80-100	100-125	40-50	60-75	1.40	1200-1500
5	10-13	Sandy-clayey silt, Yellow	50-150	80-180	50-70	30-110	1.40	1800-2000
6	13-16	Silty clay with gravel, Yellow	65-75	75-85	50-55	25-35	1.40-1.60	2700-9800
7	16-19	Silty clay with reddish and yellow gravel	50-70	50-75	45-50	5-25	1.60	4000-11000
8	19-22	Silty-gravelly sand, Yellow	25	40	25	15	1.60	10000-18000
9	22-24	Sandy-clayey silt, Yellowish gray	115	125	90	35	1.60	8000-12000
10	24-30	Sandy-clayey silt with reddish and yellow gravel	75-80	85-90	45	40-45	1.50-1.60	13000-14500

* Obtained from Bender Element Tests

5. Conclusions

An outline of the damage to buildings from the 1999 Quindio Earthquake, Colombia was presented and the relationship of the damage to ground conditions was discussed. The

following conclusions are drawn based on the present study.

- (1) The evolution of the urban area of Armenia City was investigated using old edition maps in various eras. The initial urban development of Armenia City was confined to a safe plateau area. The urban area, however, spread due to urban sprawl into the hills and areas of soft soils, which showed a high degree of damage in this earthquake in urban areas developed from 1950s to 1980s.
- (2) The relation among the width of damage area (L), height of cliff (H) and angle of slope was investigated from the cross-sections at slopes where the damage to buildings was severe. It was possible to observe L/H increases in an increase of slope and the upper boundary of H/L is 1.5. This is a good agreement with the results in Kobe Earthquake. Therefore, this is an available information for practical purposes.
- (3) It is conceivable that areas east for severe damage of the fault in Armenia City have been affected by fill while the west areas have been affected by a soft soil stratum of loam.

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