THE QUINDÍO, COLOMBIA EARTHQUAKE OF 25 JANUARY 1999

A FIELD REPORT BY EEFIT

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August 2000

ISBN 1 874266 56 5

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ACKNOWLEDGEMENTS

The authors would like to express their thanks to the many individuals and organisations who have assisted with the EEFIT mission to Colombia and the preparation of this report.

We would particularly like to thank the University of the Andes in Bogotá, Colombia, for their assistance; especially Mauricio Sanchez-Silva for making practical arrangements and providing contacts for the team in Colombia, and Filipe Contreras and Ana Maria Millan for their help in the field. We also very much appreciate the willing assistance of Jhon Gilbert Arias as a local guide.

We also thank the UK Engineering and Physical Sciences Research Council, WS Atkins, Alan Baxter and Associates and the European Joint Research Centre at Ispra, Italy, which provided funding for John Macdonald, Christophe Junillon, Graham Parker and Fabio Taucer each to join the team.

We thank our EEFIT colleagues Chris Bolton, Zygmunt Lubkowski, Robin Spence, Antonios Pomonis and Ian Smith, and also our New Zealand counterparts, Hugh Cowan and Jose Restrepo, for their review of the draft of this report.

We also acknowledge Ingeominas (the Colombian Geological Survey), for providing data on seismological aspects of the earthquake and damage surveys.

Finally we thank the University of Bristol for providing resources for the preparation of this report.

1 INTRODUCTION

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1.1 The earthquake

At 13.19 local time on Monday 25 January 1999, an earthquake of magnitude 6.2M_w (USGS) hit the cities of Armenia and Pereira and the surrounding area in the main coffee growing region of Colombia. It caused 1,171 deaths and approximately 5,000 serious injuries, and left up to 250,000 people homeless.

The earthquake was among the most devastating recorded in the history of the country, although many much larger magnitude events have occurred. The combination of a shallow focus, the proximity to the city of Armenia, local ground conditions and poor construction contributed to the scale of the disaster.

The Colombian seismic design code only came into legislation in 1984, so many of the buildings in the area predated it. Also, a large proportion of the population of the area is poor, living in non-engineered buildings, for which there is very little regulation. The worst devastation was in the poor housing areas in the south of Armenia, which were often on low quality land, as well as being inadequately constructed. However, the buildings designed in accordance with the code generally performed well structurally, although there was widespread damage to masonry infill panels and other non-structural components.

Another notable feature of the event was the poor initial management of the disaster. There was severe disruption to services and land transport links following the earthquake, and distribution of emergency supplies was slow. A breakdown of law and order followed in some areas, with looting and violence occurring. This was partly due to the desperation of some of the affected people, but greatly inflamed by troublemakers descending on the area from elsewhere in the country. The army was called in to restore order and it was over a week after the earthquake that the situation started to improve in some areas. [1,2]

1.2 The EEFIT mission

The EEFIT team consisted of four members; John Macdonald of the University of Bristol, Christophe Junillon of WS Atkins Science and Technology, Bristol, Fabio Taucer of the European Joint Research Centre at Ispra, Italy, and Graham Parker of Anthony Hunt Associates, London (formerly of Alan Baxter & Associates, London, at the time of the mission).

The team visited the affected area for five days from 6 February, almost two weeks after the earthquake. By this time order had been restored and the clear-up operation was well under way. Many buildings which had been damaged in the earthquake had already been demolished so for many of the more severely affected buildings there was little evidence remaining of the original failure.

The team was based in Pereira, which was only affected in limited areas. By the time of the visit most activities there were back to normal. The team spent three days in Armenia and the epicentral area to its south, and two in Pereira to study specific buildings. In addition to inspecting buildings and other facilities in the area, the team met with various engineers and officials at the emergency headquarters in both Armenia and Pereira.

Despite the extent of the damage and the problems immediately following the earthquake, the team was very well received, by officials and householders alike. Order had been restored and the people were generally very positive, starting to rebuild their homes and their lives.

1.3 General description of the affected area

The epicentre of the earthquake was 200km to the west of the capital, Bogotá (Figure 1.1). It was in the centre of the small Department of Quindío, just 16km to the south of its capital, Armenia. 30km north of Armenia is the capital of Risaralda, Pereira, which was also affected in some areas (Figure 1.2).

The area is in the westerly foothills of the Cordillera Central, the central of three ridges of the Andes Mountains that cross Colombia in a north-north-east / south-south-west direction. The mountains are volcanically active and rise to over 5,000m just 35km east of Pereira. In 1985 the nearby Nevado del Ruíz Volcano erupted and killed 22,000 people in Armero, on the east side of the ridge.

To the west there is the Cauca Valley, dropping below 800m at the Cauca River, approximately 30km from the cities. The area affected by the earthquake is at approximately 1,500m above sea level so it has a temperate climate, with a high rainfall. The area is very hilly, with many small rivers crossing the area in steep-sided valleys (Figure 1.3).

Just to the east of Armenia, at La Línea, there is a pass through the mountains, carrying one of the main east-west roads across the country. Much of the traffic between Bogotá and the main west coast port of Buenaventura uses this route and it also forms part of the Pan-American Highway, linking to Cali to the south-west.

The area frequently experiences earthquakes, normally associated with the subduction zone of the Nazca Plate. The most recent damaging earthquake was in 1995 ($6.8M_s$), a little to the north, when Pereira was badly affected. As a result there is much more new construction in Pereira than Armenia, which was hardly affected on that occasion. At the end of 1997 there were two significant earthquakes in the south of Quindío, but they caused little damage.

1.4 References

1 The Daily Telegraph, 28 January 1999

2 Semana magazine, Edition 874, 1-8 February 1999, Bogotá

Figure 1.1: Map of Colombia showing location of the epicentre

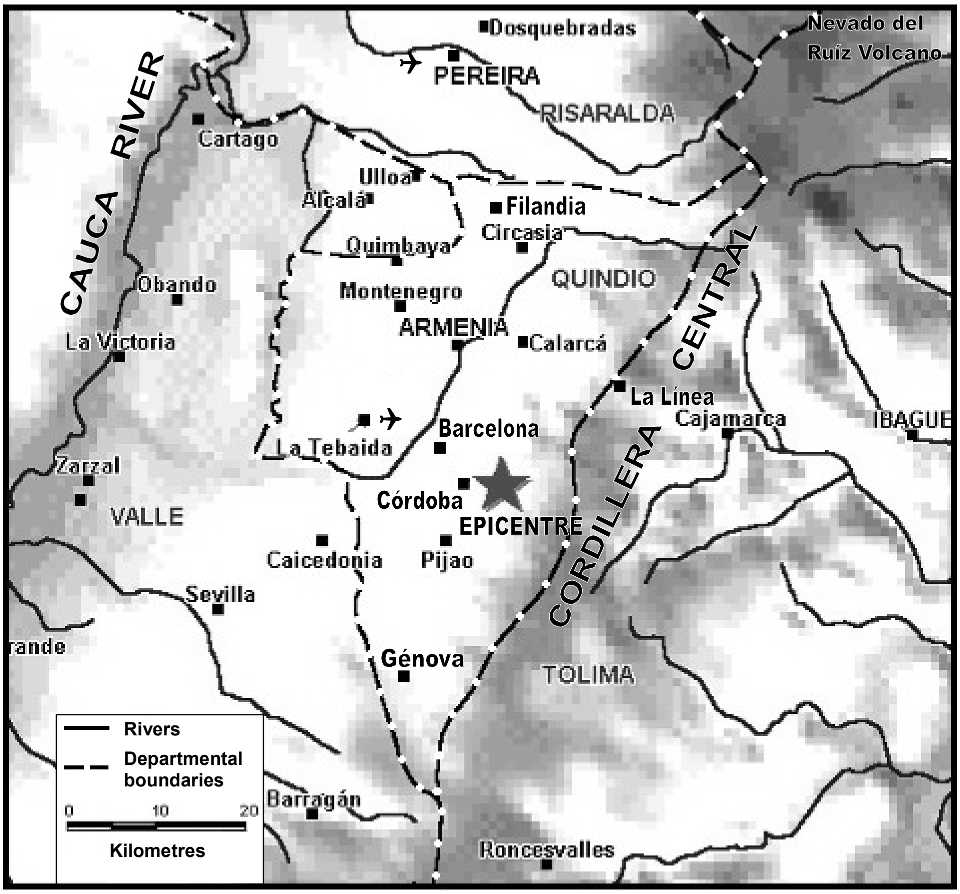

Figure 1.2: Map of the local area, showing location of the epicentre
(from OSSO. The other sources put the epicentre to the west of Córdoba – Section 2.5)

Figure 1.3: Typical topography of the affected area

2 SEISMOLOGICAL ASPECTS

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2.1 Tectonic situation

Colombia is situated on the north-west corner of the South American tectonic plate, in an area of significant seismic activity. The Nazca Plate to the west is moving eastwards with an average speed of 64mm/year and is experiencing subduction under the South American Plate [1] (Figure 2.1). There has also been subduction of the Caribbean Plate to the north-west, and the major Frontal Fault runs north-east / south-west across the country, which it has been postulated may define the edge of a micro-plate, the 'Macondo Plate' or 'North Andes Block' [2]. The subduction of the Nazca Plate is the primary cause of seismic and volcanic activity along the whole of the west coast of South America, but the presence of these other plates makes Colombia a more complex region than elsewhere on the coast.

The subduction boundary is marked by the Peru-Chile Trench approximately 75km off the west coast of Colombia, dipping at an average angle of 30º, resulting in it being at a depth of approximately 160km in the region of Quindío. The variation in depth of the boundary is clearly reflected by the depth of historic earthquakes, shown in Figure 2.2.

The tectonic activity in the region has led to the creation of the Andes mountains, which are divided into three distinct parallel ridges in Colombia. The most easterly ridge, the Cordillera Oriental, follows the western side of the Frontal Fault, and is the setting for Bogotá. Quindío and Risaralda are on the westerly slopes of the Cordillera Central ridge.

2.2 Geological faults

There are many active faults in Colombia, mainly running north-north-east / south-south-west across the country. The Romeral Fault System is one of the main fault systems, over 1,000km long and passing through the Department of Quindío, to the west of the Cordillera Central ridge. It comprises a series of individual parallel faults, which in this region are predominantly left-lateral strike-slip with high dip angle towards the east [3]. The main fault of the system is believed to be the Pijao-Silva Fault (Figure 2.3), but there are more than ten other faults running through Quindío, the most significant of which are the San Jeronimo Fault on the east of the system and the Cauca-Almaguer Fault towards the west [4]. The Armenia Fault, just to the west of the Pijao-Silvia Fault, passes through the city of Armenia, with an escarpment up to 20m high. There are no significant faults of any other orientation in the area that was affected by the earthquake.

2.3 Surface geology

The Cordillera Central mountains, to the east of the affected area rise to 5,000m and are volcanically active. They have to a large extent shaped the recent geology of the region.

The majority of the area affected by the earthquake, including most of the towns, is on a deposit of Glacis del Quindío (Figure 2.3), in some areas more than 100m deep. It consists of poorly consolidated volcanic flows and extends as far as the edge of Quindío to the west and Pereira in the north. It is covered by superficial deposits of between 8m and 12m depth of lightly consolidated tuff, made from volcanic ash and lapilli. To the south and east these volcanic deposits are less deep. [3,4,5]

To the east of the Pijao-Silva Fault and south of Córdoba are various other rock types, which are well consolidated in contrast to the Glacis del Quindío[3,4].

In the many river valleys crossing the region, the volcanic deposits are less deep than elsewhere, but there are some recent unconsolidated alluvial gravels and sands of depth 1-3.5m. However, generally the river valleys are narrow and steep-sided so there is little construction in these areas.

2.4 History of seismic activity

Figure 2.4 shows the distribution of significant earthquakes in Colombia since 1973. A summary of some of the most significant events in the history of the country is shown in Table 2-1 [3,6]. The earthquake in Popayán in 1983 was one of the worst in Colombia in terms of human casualties and damage in recent years. In common with the Quindío earthquake of 1999 it was of modest magnitude but its shallow depth meant that its effects were severe. It was caused by the movement of a fault in the Romeral Fault System, some 250km to the south of Armenia. It was important in the introduction of the seismic design code in Colombia in 1984 [7].

Table 2-1: Significant historical earthquakes in Colombia

Date	Location / Name	Mag.	Notes
16/1/1644	Pamplona		Many deaths
2/2/1736	Popayán		Considerable damage
18/10/1743	Bogotá		Serious damage
12/7/1785	Bogotá		Largest of 18th century, felt over wide area
16/6/1805	Honda, Mariquita		>100 deaths
12/7/1806	Tame		Serious damage, many aftershocks
1826	Bogotá		
16/11/1827	Territorio Nacional		Affected a large area, including Bogotá
20/1/1834	Sibundoy, Putumayo		Serious damage
16/8/1868	Border with Ecuador		70,000 deaths (30,000 of which in Colombia)
18/5/1875	Cúcuta		Destroyed the city, 461 deaths
31/1/1906	Tumaco	8.9	Off Pacific coast, tsunami killed 400
31/8/1917	Bogotá	7.2	Light damage, 6 deaths
13/12/1923	Border with Ecuador		200-300 deaths
5/2/1938	Caldas/Menizales	7.0	Depth 160km, widely felt, 2 deaths
8/7/1950	Arboledas		Severe damage, 106 deaths
30/7/1962	Pereira/Manizales/Sonsón	6.7	20 deaths, depth 59km
9/2/1967	Huila	6.7	98 deaths
29/7/1967	Bucaramanga		
23/11/1979	Antiguo Caldas	6.7	55 deaths, depth 105km, in Pereira/Manizales
12/12/1979	Pacific, south of Colombia	7.8	Tsunami hit Tumaco, 500 killed or missing
31/3/1983	Popayán	5.5	Superficial, 300 deaths, US$300M damage
6/3/1987	Border with Ecuador	7.0	1000 deaths, 4000 missing (many in Ecuador)
17 & 18/10/1992	Murindó	6.6 & 7.2	US$40M damage, much in Medellín, exposed very poor control of construction quality
22/7/1993	Arauca	5.9	Depth 10km, further east than normal
6/6/1994	Páez	6.4	Depth 10km, 100 deaths, many landslides
19/1/1995	Tauramena	6.5	Depth 50km, severe damage in many towns
8/2/1995	Pereira / Calima	6.8	Depth 102km, severe damage in Pereira

It can be seen from Figure 2.4 that the recent earthquake occurred in a particularly seismically active area. However, most of the previous earthquakes in the area have been associated with the subduction (or Benioff) zone and occurred at depths in excess of 100km (Figure 2.2). Of the 19 previous nearby earthquakes of magnitude 5.0M_s or greater for which the depth is known (i.e. since 1922, Table 2-2), only four have been at depths less than 100km, the shallowest being a 6.7M_s event in 1962 of depth 59km. However in the wider area of the Cauca Valley, following the Romeral Fault System, superficial earthquakes of magnitude up to 6.5 have been recorded.

Table 2-2: Earthquakes since 1922 of magnitude ≥5.0M_s in the affected area (3.5-5.5°N, 75-77°W, i.e. within approximately 100km of the earthquake of 25/1/99)

Date	Lat.	Long.	M_s	Depth (km)	Location
27/10/35	4.0N	76.0W	5.5	150	
5/2/38	4.5N	76.3W	7.0	160	Manizales
10/4/50	4.6N	75.4W	6.0	128	
24/5/57	3.74N	76.77W	6.7	60	
20/12/61	4.60N	75.60W	6.7	176	Armenia/Calarcá
30/7/62	5.23N	76.34W	6.7	59	Tado, Chocó, Pereira, Manizales, Sonsón
12/1/63	4.70N	76.70W	5.8	84	
3/4/73	4.70N	75.67W	6.4	146	Venadillo
19/5/76	4.49N	75.77W	5.8	161	El Dovio
23/11/79	4.81N	76.20W	6.7	105	Los Paraguas, Chocó, Pereira, Manizales
25/6/80	4.50N	75.73W	6.0	160	
29/11/88	5.16N	76.55W	5.4	75	
23/11/90	4.75N	75.55W	5.4	136	
15/8/92	5.15N	75.58W	5.4	107	
8/2/95	4.13N	76.74W	6.8	102	Pereira, Calima
19/8/95	5.11N	75.71W	6.6	110	
19/2/97	4.54N	76.52W	5.2	120	
2/9/97	3.96N	75.87W	7.2	230	Génova
11/12/97	4.00N	75.95W	6.2	220	Génova

The earthquake of 20 December 1961 was the closest recorded earthquake to Armenia, occurring just to the east of the city. Although it was of magnitude 6.7M_s and killed over 100 people, it caused less deaths and damage than the most recent event, due to its significant depth (176km) and the smaller population at the time. The Antiguo Caldas event of 23 November 1979 was significant in the loss of life and damage in Los Paraguas, Chocó, to the north-west, and it caused some damage in Pereira, Manizales and Armenia. It also caused many landslides, blocking several main roads in the area.

The magnitude 6.8M_s earthquake of 8 February 1995 caused severe damage in Pereira. However it led to much new construction in the city and retrofitting of several large buildings, the performance of which in the most recent earthquake is discussed in Section 4.3.

The last two significant seismic events in the region both occurred near Génova in the far south of the Department of Quindío at the end of 1997. Both being very deep and further from centres of population, they caused relatively little damage.

Figure 2.5 shows the areas of seismic risk in Colombia adopted in the 1998 seismic design code [8], from a joint study by the Colombian Association of Seismic Engineering (AIS), Ingeominas (the Colombian Geological Survey) and the University of the Andes [9]. The area of high risk to the west corresponds to the subduction of the Nazca plate while the north-east / south-west band is due to the Frontal Fault. Armenia and Pereira are on the edge of the area of high risk. In this area the peak horizontal ground acceleration (on rock) specified in the 1998 code (and previously the 1984 code), based on a probability of exceedence of 10% in 50 years, is 0.25g.

2.5 Characteristics of the earthquake of 25 January 1999

The earthquake of 25 January 1999 struck at 13.19 local time. It was a superficial earthquake of magnitude 6.2M_w (USGS) with the epicentre approximately 16km south of Armenia. Estimates of the magnitude and depth vary slightly according to the different sources (Table 2-3). However, it is clear that the earthquake was shallow, being significantly less deep than any previously recorded event in the area of magnitude 5.0M_s or greater (Table 2-2, Figure 2.2). This would be a contributing factor to the considerable damage caused by this earthquake of relatively modest magnitude. The loss of life and economic cost were the among greatest recorded for any earthquake in the history of the country.

Table 2-3: Magnitude, depth and location of earthquake from different sources

Source	M_L	M_b	M_w	M_{sz}	M_e	Depth (km)	Long.	Lat.
USGS		5.9	6.2	5.7	6.3	17	75.68W	4.29N
Harvard		5.8	6.1	5.8		27.9	75.77W	4.45N
ERI, Japan		5.8	6.1			49	75.70W	4.68N
BGS		5.8				shallow	75.68W	4.29N
OSSO*		5.9				35	75.64W	4.38N
Ingeominas	6.2					<20	75.72W	4.41N

* Colombian South-west Seismological Observatory

In a preliminary analysis, the earthquake was attributed to the Cauca-Almaguer Fault [3], towards the west of the Romeral Fault System. However there are several close parallel faults so the one which caused the earthquake is not easily distinguished, particularly with the lack of strong ground motion sensors in the vicinity. There is significant variation in the estimates of the position of the focus, and the dip angle of each of the faults in the area is not accurately known.

For an earthquake of this magnitude, the expected surface rupture length would be approximately 5km and the maximum surface displacement 0.08m, based on the relationships of Reference 10 for strike-slip movements. Following the earthquake, some cracks were found in various roads in the epicentral region, the largest relative displacements being 60mm horizontally and 35mm vertically [3]. The locations described for some of the most significant cracks - 3km north of Pijao, 3km north-west of Córdoba and 5km south-west of Calarcá (a maximum of 18km apart) - lie on the line of the Pijao-Silva Fault (Figure 2.3), suggesting that there may have been a surface rupture of this fault. However, the cracks did not show a consistent direction of displacement and many are likely to have been due to local soil movements. Also, a surface rupture elsewhere of the expected size could easily be covered by the superficial deposits or could go undetected in such a hilly and well-vegetated rural area, so the evidence of movement of the Pijao-Silva fault is not conclusive.

The moment tensor solutions from the different sources are given in Table 2-4. The strike and dip angles of the first solution are consistent with the orientations of the Cauca-Almaguer Fault (strike 015°, dip >60°) and the Pijao-Silva Fault (strike 021°, dip >60°), although other faults in the area are also roughly parallel. The motion was predominantly left-lateral strike-slip, with a small normal component.

Table 2-4: Moment tensor solutions from different sources

Source	Scalar Moment (10^{18} Nm)	Solution 1			Solution 2		
		Strike	Dip	Slip	Strike	Dip	Slip
USGS	2.2	027°	80°E	-18°	121°	73°S	-169°
Harvard	1.82	005°	63°E	-19°	103°	73°S	-152°
ERI, Japan	1.67	009.4°	79.3°E	-21.3°	103.5°	69.1°S	-168.6°
Ingeominas	1.8	018°	81°E	-9°			

2.6 Strong ground motion records

There were a limited number of seismometers in the affected area, so it is not possible to build up a detailed pattern of the distribution of ground motion. Also, for the measurements that do exist, the ground conditions are uncertain, so it is not possible to clearly distinguish effects due to local conditions from those due to the global characteristics of the earthquake.

The locations of instruments forming the Colombian national accelerometer network, are shown in Figure 2.6, along with the location of the epicentre. The instruments are owned by a number of different organisations but the network is administered by Ingeominas. The instruments closest to the epicentre are in Armenia (CARME), Filandia in the north of Quindío (CFLAN), and two instruments near Pereira (CBOCA and CPER2). All of these are situated in soil, apart from one of the instruments near Pereira (CBOCA), which is in rock.

The strong ground motion record from Armenia on soil is shown in Figure 2.7. The instrument is located at the University of Quindío, approximately 700m north-east of Armenia's central square, on relatively flat ground 200m from a steep-sided valley. It is situated on a depth of at least 30m of the poorly consolidated Glacis del Quindío, which it is thought caused significant amplification relative to the base rock. It is notable that the three orthogonal components are of very similar amplitude and in particular that the vertical component is large, which is consistent with the shallow depth of the earthquake.

Figure 2.8 and Figure 2.9 show the time histories of accelerations recorded near Pereira, measured on base rock and 'soil' (6m depth of fill to smooth the topography). The instruments are 6.4km apart so they are not directly comparable, but they are at similar distances from the epicentre. The difference in the amplitude of motion is marked, indicating high amplification due to local conditions.

The duration of strong ground motion was less than 10s as measured at Armenia and near Pereira on rock. At Pereira on soil and also at Filandia the strong motion lasted 20-30s due to local effects.

Figure 2.10 shows the response spectra for 5% critical damping for the acceleration records from Armenia and Pereira, compared with the design spectra for normal construction from the Colombian seismic design code [8]. For more critical structures the magnitudes of the design spectra can be increased by a factor up to a maximum of 1.3. Two design spectra are shown for each of the horizontal components - for rock and the softest classification of soil. As can be seen, the code allows for an increase in the period for maximum response on soils, but it does not allow for an increase in the maximum response.

Comparing the response spectra for the measurements on rock and soil near Pereira, the significant amplification can be seen. Also, for the horizontal components, the much greater significance of the longer period motions (0.6-0.7s) is clear, as expected for soft soils. However, for the records from Armenia, although the comparable rock acceleration is not available, in addition to the large amplification at periods around 0.6s in the north-south component, there are very large components for short period vibrations (<0.3s). This is particularly exaggerated for the vertical component of acceleration. This could be a result of the shallow nature of the earthquake and the proximity of the station to the epicentre. This large low period / high frequency component of vertical ground motion could go some way to explain the high levels of damage observed in Armenia, particularly to buildings of up to three storeys.

A summary of the peak ground accelerations measured at selected stations on Figure 2.6 are given in Table 2-5. Full details of the accelerations registered by the national network are given in Reference 11.

Apart from the accelerometers in the national network, the only known strong motion instruments in the area were at the cable-stayed bridge in Pereira (Section 7.1.2) and some installed in Pereira by the Risaralda regional council (CARDER), for which the records have not been made available. There were no known instrumented buildings.

Table 2-5: Measured peak ground accelerations (10^{-3}g)

Location	Code (Figure 2.6)	Distance from Epicentre (km)	Ground	East-west	North-south	Vertical
Armenia	CARME	13	soil	518	580	448
Filandia	CFLAN	33	soil	555	478	182
Pereira	CBOCA	42	rock	82.7	49.0	27.5
Pereira	CPER2	48	soil	208	141	95.8
Manizales	CMAN1	76	soil	85.9	103	57.2
El Toche	CTOCH	94	rock	3.58	2.72	2.80
Villahermosa	CVHER	97	rock	6.48	5.42	12.0
Filadelfia	CFILA	100	rock	8.85	9.65	5.27
Calima	CECAL	112	rock	2.37	2.23	1.47
Prado	CPRAD	117	rock	6.94	5.50	5.48
Pensilvania	CPENS	125	rock	21.1	25.0	7.14
Cali	CCALI	142	soil	21.6	17.2	7.95
Arbeláez	CARBE	144	rock	6.71	5.82	2.66
Buenaventura	CBUEN	162	soil	15.3	20.7	3.71

2.7 Aftershocks

A significant aftershock, of magnitude 5.5M_b at a depth of 10km (USGS) occurred at 17:40 local time on the same day as the principal event (i.e. 4½ hours later), causing considerable further damage. Some buildings which were damaged in the initial earthquake were reported to collapse in this aftershock. Peak ground accelerations of 0.142g horizontally and 0.116g vertically were recorded in Armenia (on soil) [11].

A series of further aftershocks followed but no more exceeded a magnitude of 4.5M_L (Ingeominas). Their frequency and magnitude generally decreased with time such that none were felt after two weeks. A total of 138 aftershocks were recorded in the month following the earthquake. Additional temporary accelerometers were installed in the epicentral area to monitor the aftershocks. From the preliminary analysis, there was considerable scatter of the estimated locations of the aftershocks, but they all occurred at depths less than 25km, there appeared to be a general trend northwards with time, and there was an indication that they were associated with the Pijao-Silva Fault [12].

2.8 Conclusions

The earthquake of 25 January 1999 occurred in an area of high seismicity and it had a magnitude (6.2M_w, USGS) lower than many historical events in the region. However, the damage and loss of life it caused were among the greatest recorded for any earthquake in the history of country. It was the shallowest earthquake of significant magnitude recorded in the region, which was an important factor in the extent of the damage. Also the poorly consolidated volcanic surface deposits exacerbated the ground motion. The peak ground acceleration recorded was 0.580g, in Armenia, with a vertical component as high as 0.448g. There was very considerable amplification of accelerations of soils compared with the underlying rock. The most important periods of ground motion on soils were around 0.6s, and below 0.3s close to the epicentre, with particularly large vertical components for the lower periods in Armenia.

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13 United States Geological Survey (USGS), National Earthquake Information Center (NEIC) (http://neic.usgs.gov/neis/epic/epic.html)

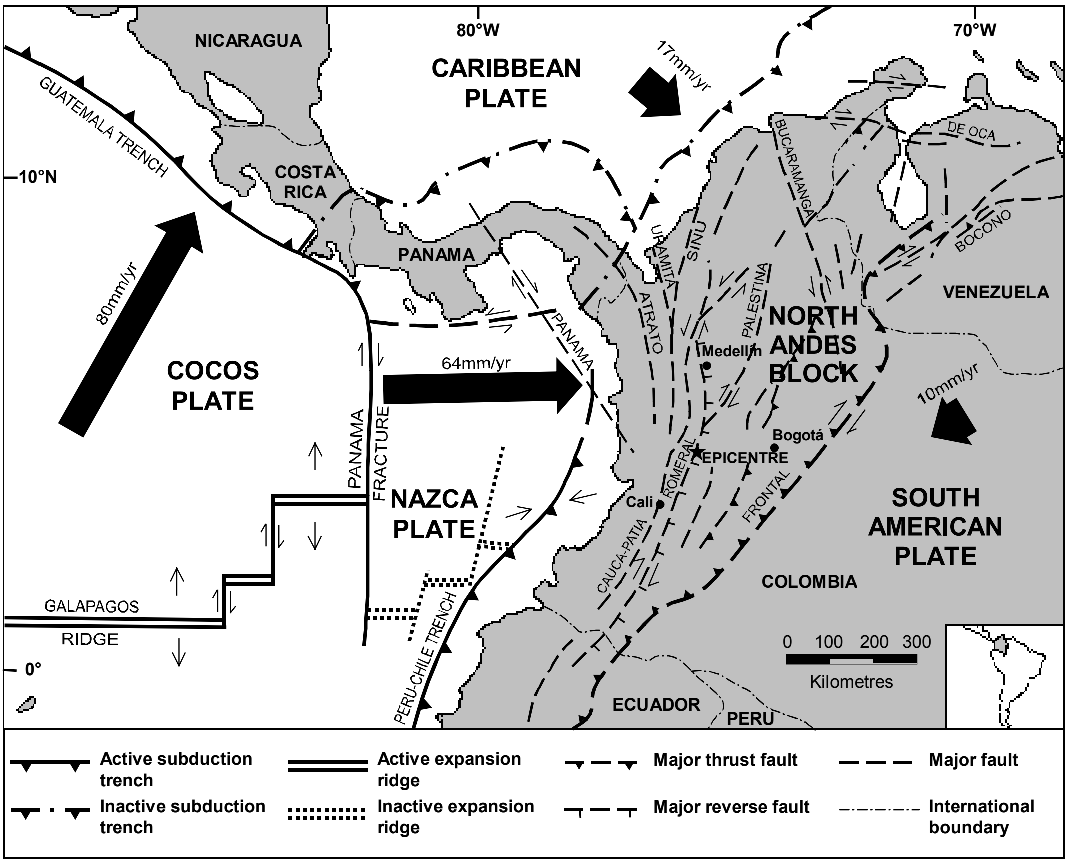


Figure 2.1: Tectonic situation of Colombia (based on Ref. 1)

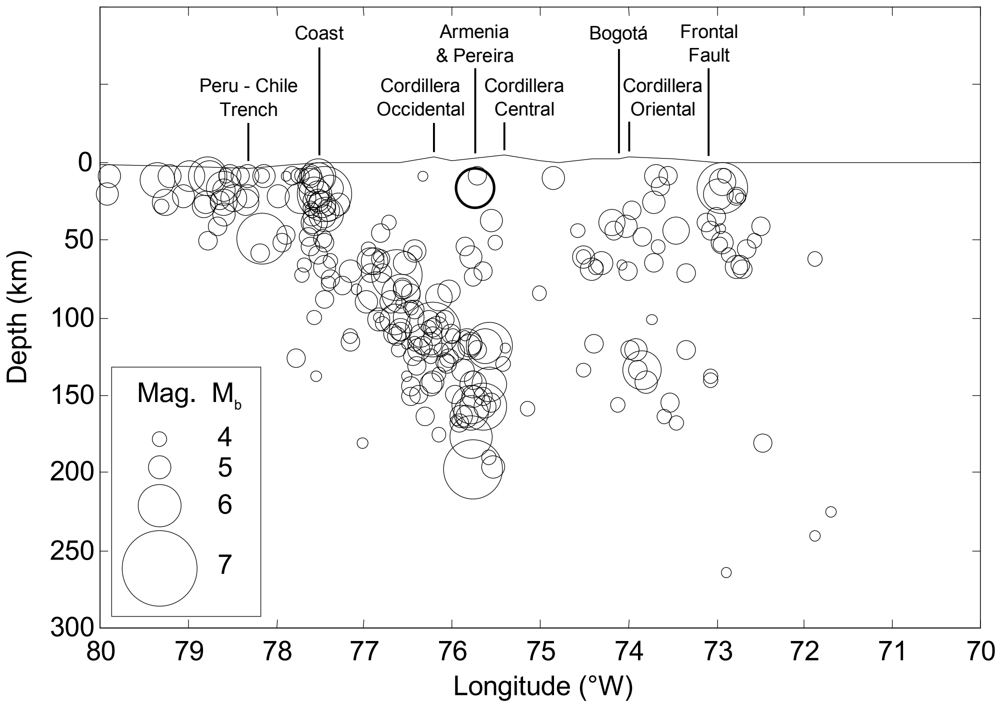


Figure 2.2: East-west cross-section through Colombia, showing earthquakes since 1973, latitude 3-6°N (based on data from USGS NEIC [13], vertical scale exaggerated, earthquake of 25/1/99 in bold)

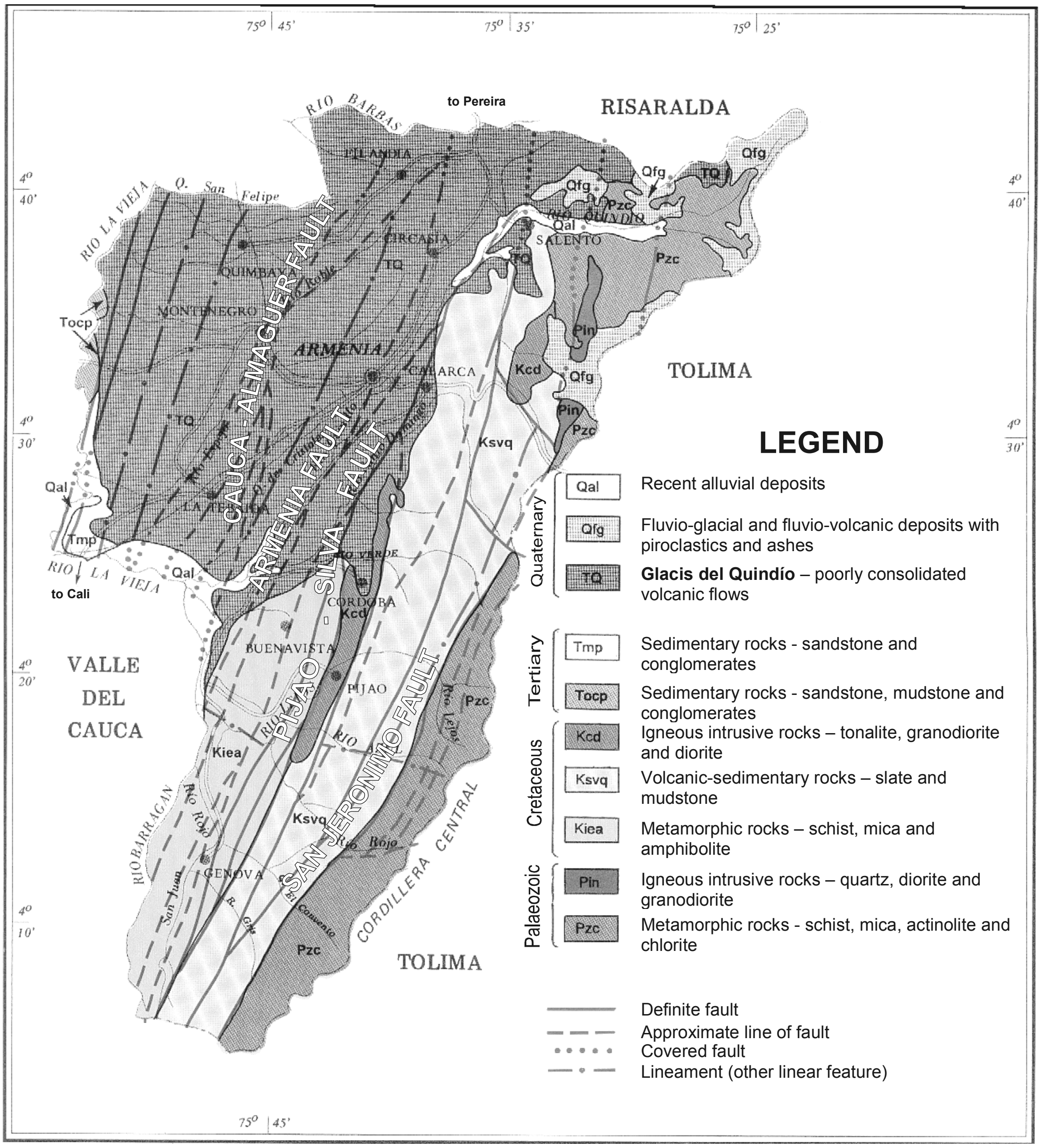


Figure 2.3: Geological map of Quindío (Ingeominas)

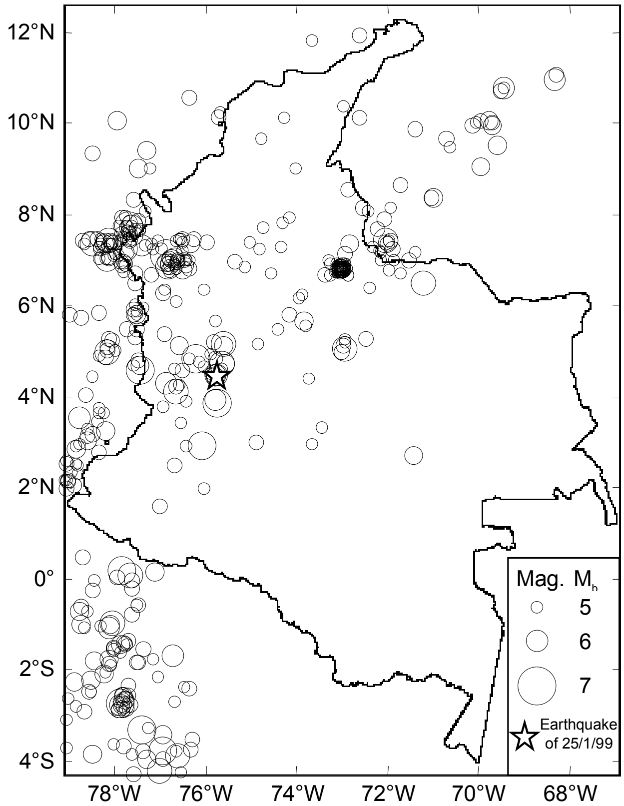


Figure 2.4: Earthquakes in Colombia since 1973 of magnitude ≥ 5.0M_b (based on data from USGS NEIC [13])

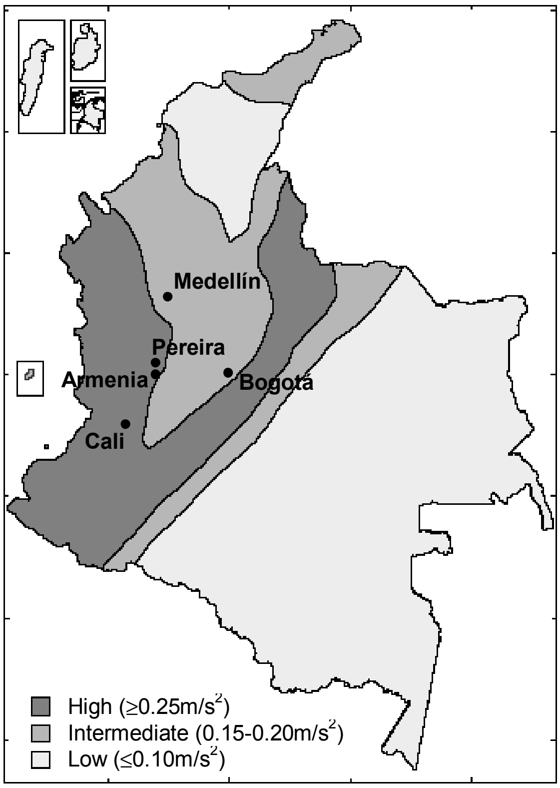


Figure 2.5: Areas of seismic risk in Colombia and design peak ground accelerations for 50 year return period (from Ref. 8)

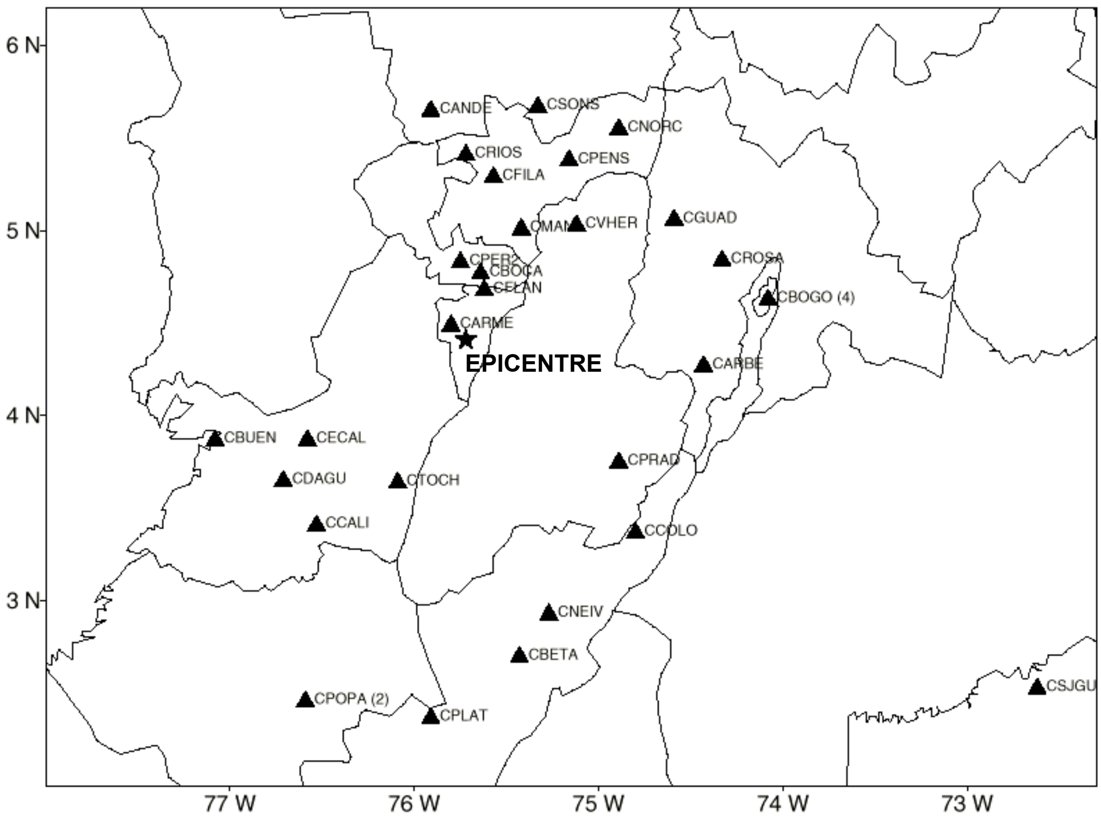


Figure 2.6: Locations of accelerometers of the Colombian national network (Ingeominas)

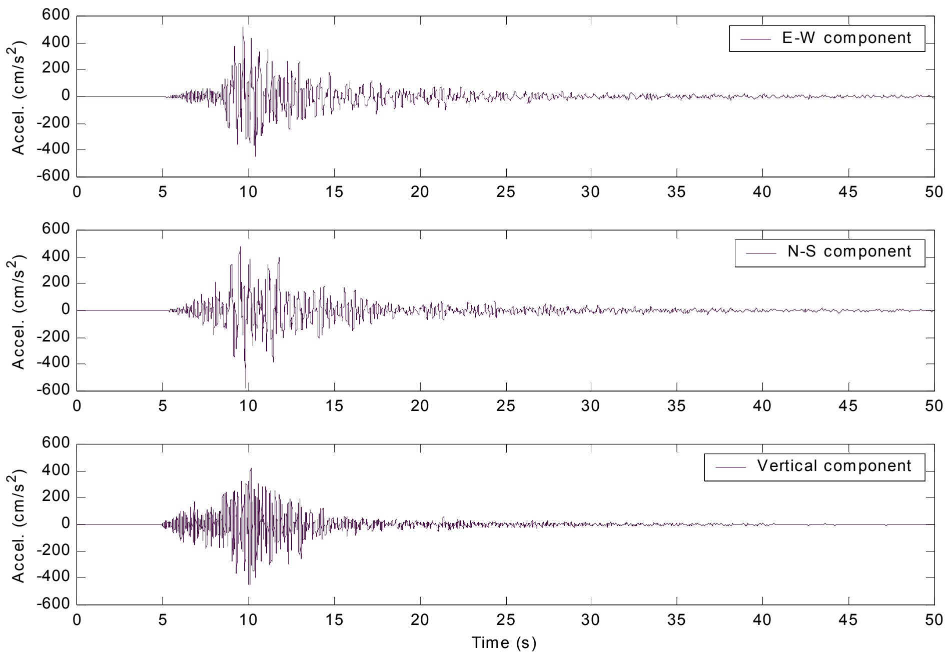


Figure 2.7: Strong ground motion record from Armenia, measured on soil (from Ingeominas National Accelerograph Network)

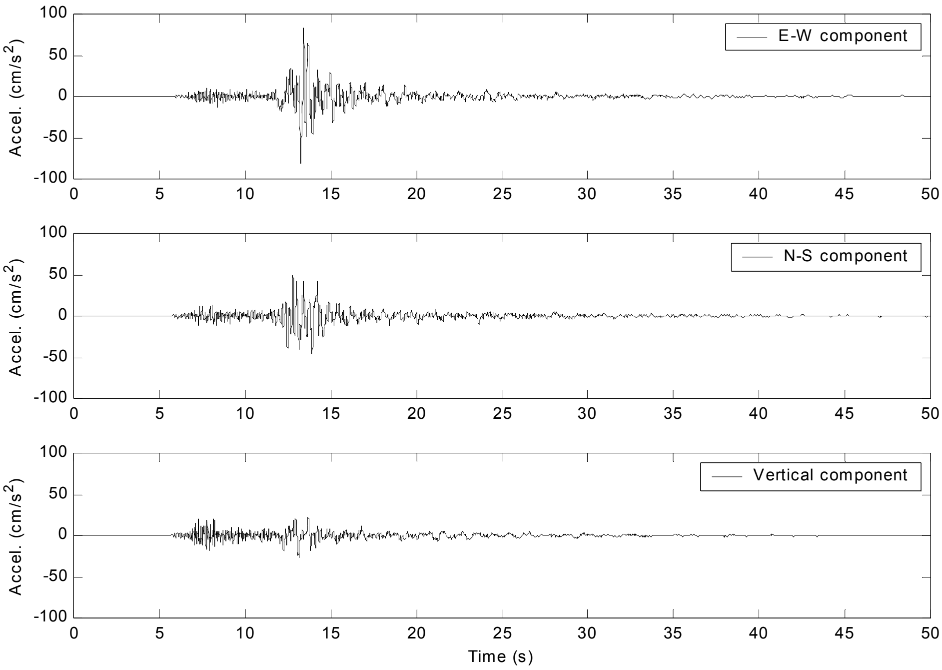


Figure 2.8: Strong ground motion record from near Pereira, measured on rock (from Ingeominas National Accelerograph Network)

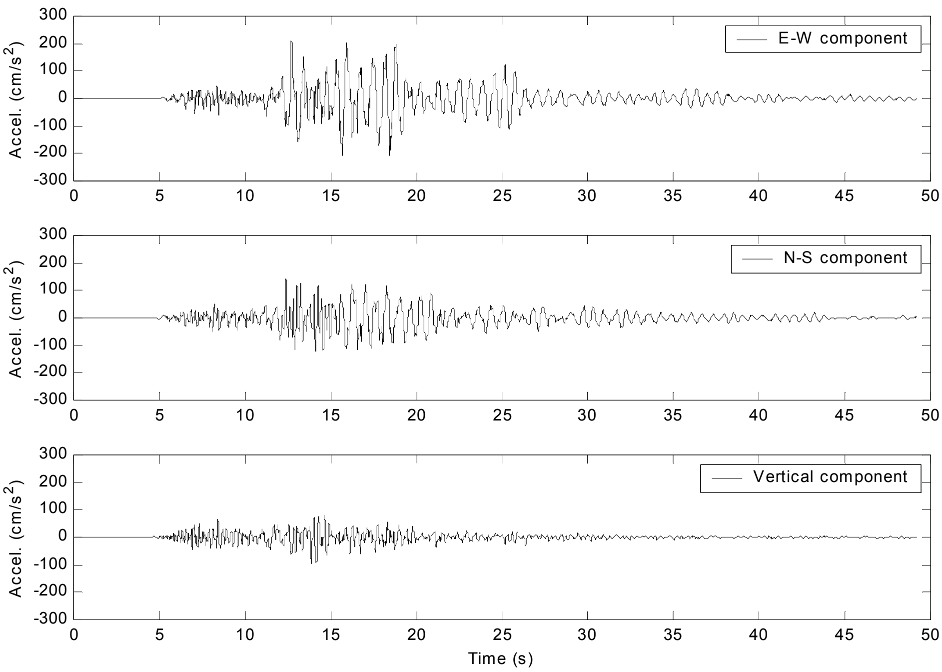
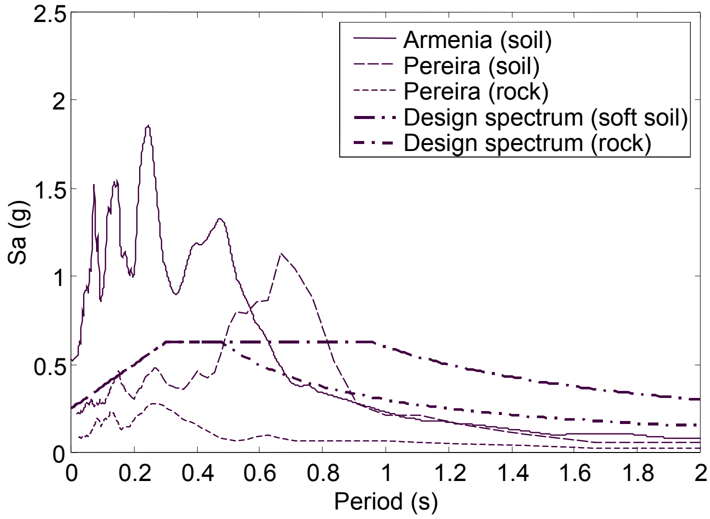
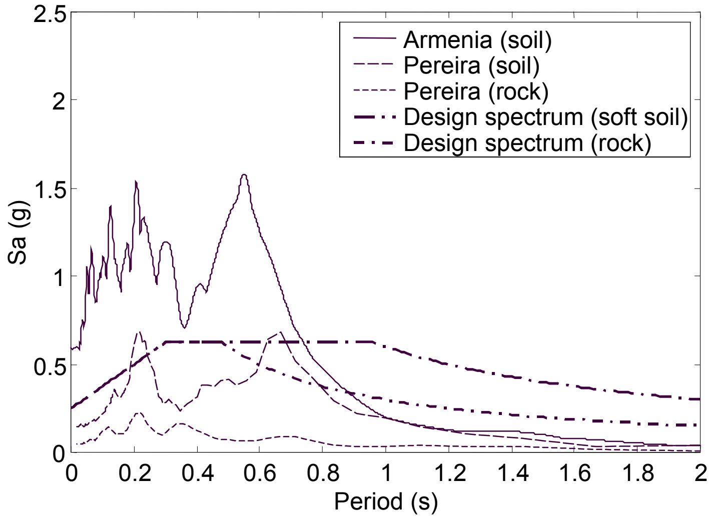


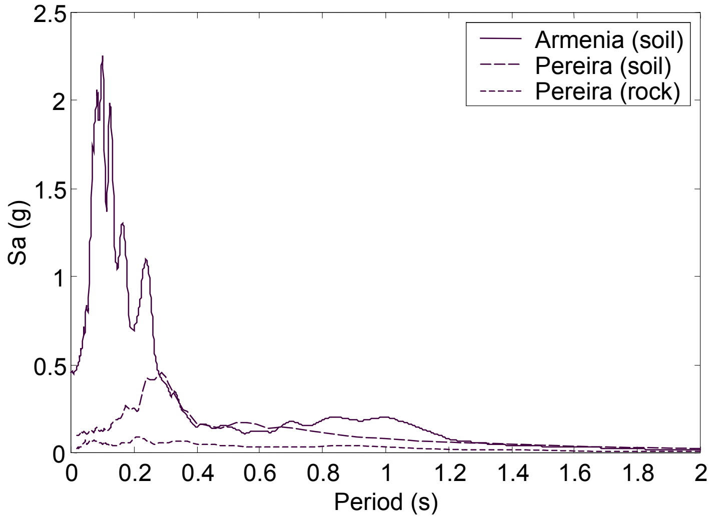
Figure 2.9: Strong ground motion record from near Pereira, measured on soil (from Ingeominas National Accelerograph Network)



(a) East-west component



(b) North-south component



(c) Vertical component

Figure 2.10: Response spectra for 5% critical damping

3 DESCRIPTION OF THE AFFECTED AREA AND OVERVIEW OF DAMAGE

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3.1 Description of the affected area

3.1.1 Population and economy

Quindío is the smallest Department of Colombia after the district of Bogotá and the islands of Archipelago. It covers just $1845km^2$, 0.16% of the area of the country. Risaralda is also one of the smallest Departments, accounting for 0.36% of the area. They are, however, two of the most densely populated Departments outside Bogotá, with population densities over 200 inhabitants/km^2 (similar to the average over the UK). From the 1993 census, 495,000 people lived in Quindío and 844,000 in Risaralda. In each case approximately half of the population lived in the Departmental capital - around 240,000 in Armenia and 410,000 in Pereira. The populations at the time of the earthquake are likely to have been slightly higher. The remainder of the affected area is rural, with many small towns and villages scattered over the area (Figure 1.2). [1]

The main economic activity in the area is coffee production. Quindío and Risaralda have the highest yield of coffee per unit area of any Departments in Colombia. Despite their small sizes they each contribute 8% of the total national production. Although there was a significant drop in production in the early 1990's, coffee is still the largest single export of Colombia, contributing 24% of GDP (1994), and making Colombia the world's second largest producer. The majority of the coffee is grown on small family farms and it is often harvested by hand, making the industry the main employer in the area. Coffee is traded in the cities and the majority is exported as beans. There is some small scale processing, often on the farms, for the domestic market. [1,2]

The GDP per capita in 1992 was US$1,690 in Quindío and US$1,500 in Risaralda, somewhat above the national average of US$1,330, due to the high coffee production in the area. In Quindío the other industries include food production and limited banking, commerce and services. Risaralda has a similar balance of activities but also produces some textiles and paper. Pereira is somewhat more industrialised than Armenia, with significant industry in the neighbouring town of Dosquebradas. [1,2]

3.1.2 Building stock

The building stock in the area affected by the earthquake included a variety of structural forms. The majority of buildings belonged to one of the following categories: reinforced concrete frames with unreinforced masonry infills, load bearing masonry with little or no reinforcement and traditional bahareque structures. Further descriptions of the different construction types are given in Chapters 4 & 5.

As well as varying in type, the constructions varied significantly in quality according to the age of the building and the wealth of the area. Recent engineered structures were of significantly better quality than older ones; in particular those built prior to the introduction of seismic provisions in the 1984 building code. In addition, in poor neighbourhoods a majority of non-engineered low quality structures built by their occupants could be observed, while in more affluent parts of the city well designed and built structures incorporating seismic provisions could be found.

3.1.3 Ground conditions

As described in Section 2.3, the majority of the area affected by the earthquake is on a deep deposit of Glacis del Quindío. It is covered by superficial deposits of between 8m and 12m depth of tuff, with the physical properties shown in Table 3-1, on which most structures in the area are founded. It is believed that these two poorly consolidated materials led to significant amplification of the underlying rock motion in the earthquake.

Table 3-1: Physical properties of surface tuff in Quindío (from Ref. 3)

Depth	Plasticity Index (%)	N SPT	Density	Shear Wave Velocity
8 to 12m	12 to 24	6 to 10	1500kg/m^3	160m/s

The local topography is characterised by high ridges and steep valleys. This is particularly true in the southern part of Armenia, where many of the constructions are located on top of these ridges or in partially filled valleys. The central parts of both Armenia and Pereira have been levelled through cutting and filling, and a large number of structures are located on the man-made fills. Reference 4 quotes for these fills a shear wave velocity in the range of 90 to 150m/s. It is believed that further amplification of ground motion occurred on these fills.

It is worth noting that the town of Córdoba, close to the epicentre, is thought to have very different ground conditions from the other localities to the north and west. Reference 5, states that it is located on bedrock, while Figure 2.3 indicates that it is at the edge of the area of Glacis del Quindío. Pijao, further south, is located on igneous intrusive rock, rather than Glacis del Quindío. No details of the surface deposits are available, but since the town is situated adjacent to a river in a relatively wide valley, there could be alluvial deposits.

3.2 Overview of damage

Despite its moderate magnitude, the earthquake caused very extensive damage in the epicentral area and in the city of Armenia with, in some areas, as many as 80% of the structures collapsed or damaged beyond repair. However, the affected area is limited and most of the damage is located within 30km of the epicentre. This overall level and distribution of damage, which was to be expected in view of the shallow nature of the event, is shown in Figure 3.1.

3.2.1 Damage in the epicentral region

The epicentral area includes a number of small towns and villages such as Barcelona, La Tebaida, Córdoba and Pijao (Figure 1.2). These localities are economically poor and non-engineered structures built by their occupants are prevalent. Only a few kilometres away from the epicentre, these towns and villages are thought to have experienced high ground accelerations and were very extensively damaged with the proportion of structures collapsed or severely damaged as high as 50%. Further details on the level of damage in these localities can be found in References 6 & 7.

The least affected of these localities was Córdoba, although it was the closest to the epicentre. This is believed to have been due to the different ground conditions mentioned above.

The majority of damage occurred to the north-west of the epicentre. This corresponds with the area of the poorly consolidated Glacis del Quindío and surface tuff (Section 2.3), suggesting that they may have been responsible for considerable amplification of the underlying rock motion. The significant level of damage experienced in Pijao, in contrast, could be due to the behaviour of alluvial deposits in the river valley. However, with the area to the south and west of the epicentre being sparsely populated and with little data available on the ground conditions in the towns and villages which were affected, it is difficult to draw definite conclusions.

3.2.2 Damage in Armenia

The city of Armenia is situated approximately 16km north of the epicentre. It experienced large accelerations and contributed approximately two-thirds of the casualties. The level of damage within the city could be observed to be highly variable (Figure 3.2). A number of factors contributed to the variation of level of damage, including the type, age and quality of construction (Chapters 4 & 5), local ground conditions and topography, so it is difficult to determine the significance of each variable.

It has been suggested by Ingeominas [8] that movement of the Armenia Fault, shown on Figure 3.2, may have contributed to the high level of damage observed in its vicinity. However, a number of other explanations could be given to this localisation of the damage, particularly as the rupture is believed to have occurred on one of two other faults, as discussed in Section 2.5. Reference 4, in particular, suggests that it was due to poor ground conditions in the form of anthropic fills adjacent to the fault escarpment.

3.2.2.1 South-western Armenia

The south-western part of the city contains many poor neighbourhoods and the dominant types of construction are non-engineered traditional bahareque and load bearing masonry structures, both described in Chapter 5. They were very extensively damaged with a proportion of buildings severely damaged or destroyed as high as 80% [6] (Figure 3.2 & Figure 3.3).

This part of the city contains many ridges and partially filled steep valleys. The structures located on the ridges experienced particularly high levels of damage. Firstly, this might have been caused by further amplification of the ground motion. Reference 3 calculates the seismic wavelength in the top deposit as approximately 30m, which roughly corresponds to the height of a number of the ridges. In addition, partial ground failure led to damage of foundations of those structures near slope edges as shown in Figure 3.4. These structures would not have respected the local regulation specifying a minimum distance of 10m from the point where the slope exceeds 25º. The downhill part of the foundation would often bear on poor fill brought from the excavation of the uphill part of the foundation. Partial ground failure in that fill often resulted in distress of the structure.

3.2.2.2 Central Armenia

The central part of the city contains a large proportion of medium rise reinforced concrete buildings, built both before and after the introduction of the Colombian seismic design code. As described in Section 3.1.3, this part of the city has been levelled through cutting and filling.

The overall proportion of structures collapsed or damaged beyond repair was approximately 40% [6] (Figure 3.2). All of these severely damaged structures, apart from one further described in Section 4.2.1, had been built prior to the 1984 seismic regulation.

The strong ground motion accelerometer in Armenia was located 700m north-east of the city centre. It indicated high levels of acceleration and a peak in the response spectrum for the north-south component at a period of 0.6s (Section 2.6), which would correspond with the natural periods of buildings of approximately six storeys. This was a typical height for buildings in central Armenia, which would go some way to explain the high levels of damage observed.

3.2.2.3 North-eastern Armenia

The north-eastern part of the city is generally more affluent and contains a large proportion of well designed and built structures, mainly reinforced concrete frame structures. Furthermore, discussions with geotechnical staff of the local authority indicated that ground conditions are thought to be more favourable in this part of the city, although no detailed records of site investigations were available. The level of damage was much lower in this area, with less than 20% of the structures collapsed or damaged beyond repair [6] (Figure 3.2).

3.2.3 Damage in Pereira

Pereira is located approximately 46km north of the epicentre and saw little damage in comparison with Armenia. A general view of the city is given in Figure 3.5.

The accelerations experienced in Pereira were significantly less than those experienced in Armenia, but still quite high on poor soil - approximately 0.2g compared with 0.08g on rock. Only a few buildings were severely affected, all of them thought to have been located on poor soil, in particular fills. An example of this was the comparison of several blocks of flats located on a slope near the airport. Significant damage was observed in a block founded half in cut and half on fill, while other almost identical blocks, founded almost entirely in cut, were only lightly damaged.

Reference 3 suggests that most damage observed occurred along the Egoya sewerage line, a filled valley running east-west south of the city centre. As the line is not confined, the surrounding soils are expected to be fully saturated, which would have led to particularly poor behaviour.

Finally, it is worth noting that, while few collapses were observed, casualties and large financial losses were caused by non-structural damage, often in structures designed to the 1984 seismic design code, as shown in Figure 3.6. This is discussed further in Section 4.2.2.

3.3 Conclusions

Damage caused by the earthquake of 25 January 1999 was very extensive but over a relatively small area owing to the shallowness of the seismic event.

The level of damage was strongly correlated to the quality of construction in a given area emphasising the need for careful seismic design and strict construction control. This will be developed further in Chapter 4.

In addition to the quality of construction, local ground conditions have been observed once more to be important, with large amplifications occurring on lightly consolidated volcanic deposits, poor soils and fills. In addition, local ground failures caused significant damage to structures near the edges of ridges; especially those partially founded on fill used for levelling. Finally, topographical features are thought to have been responsible for additional amplification, further contributing to the damage on ridges.

The increase in the demand on structures arising from local conditions, whether in terms of soil or topography, stresses the need to carry out microzonation studies in the large cities of regions prone to earthquakes. This was recognised by the Colombian government and such a study has already been carried out and implemented in a code for Bogotá. A pilot study is believed to have also been carried out in Armenia a few years ago. Comparing the conclusions of this study with the observed damage would provide a particularly interesting insight, but it is believed that the results of this study have not been published to date.

Finally, it was observed that structures well designed and built, away from areas known to lead to increased seismic demands, behaved well. This clearly demonstrates that damage can be minimised through careful and adequate control. Ensuring such control will be crucial at the reconstruction stage, when it will be made more difficult by the urgency of providing housing and the sheer volume of work ongoing.

3.4 References

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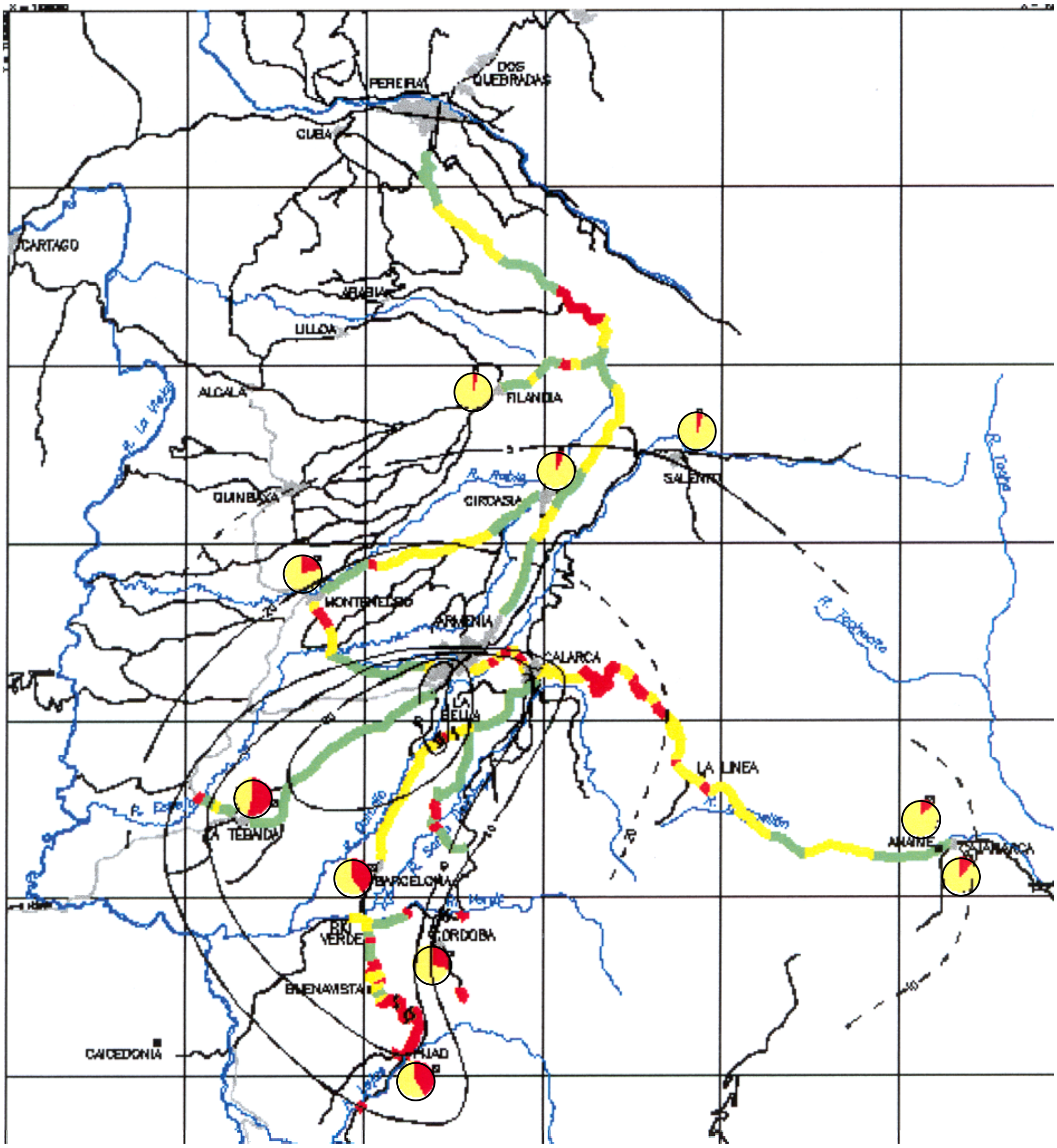

Percentage of buildings collapsed or damaged beyond repair

Zone 2
Intermediate zone with landslides with volume less than 100m^3 on main roads or 20m^3 on secondary routes

Zone 1
Critical zone with landslides with volume in excess of 100m^3 on main roads or 20m^3 on secondary roads

Zone 3
Zone with no significant landslides

Figure 3.1: Distribution of damage in the epicentral region (Ingeominas)

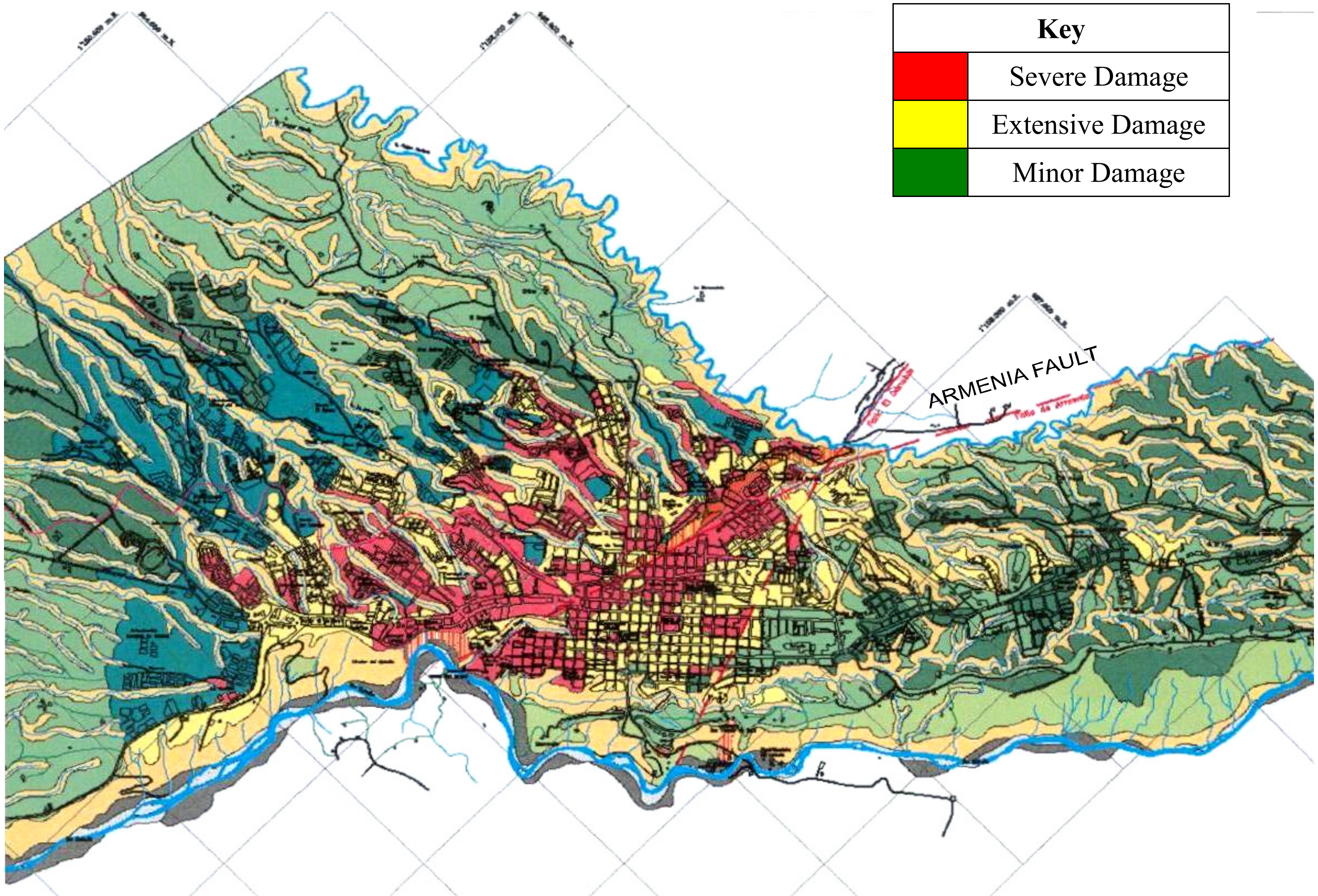

Figure 3.2: Distribution of damage in Armenia (Ingeominas)

Figure 3.3: Traditional bahareque structures – Armenia (south)

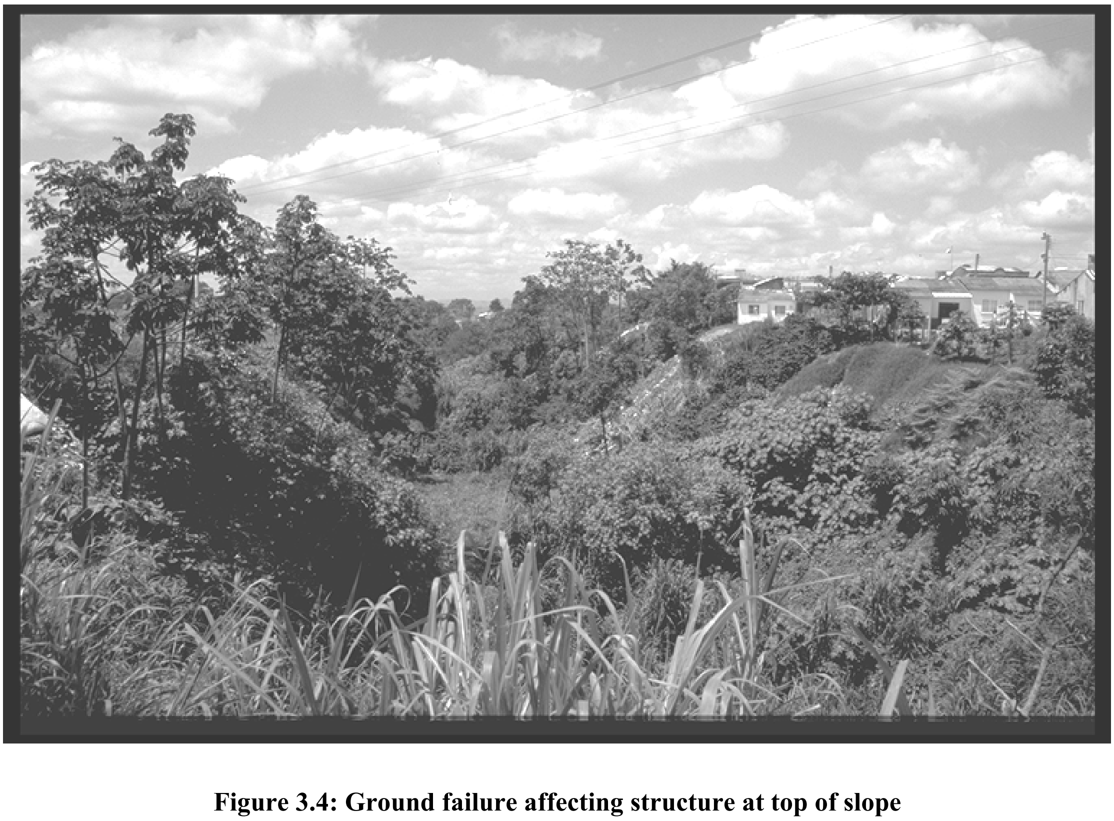

Figure 3.4: Ground failure affecting structure at top of slope

Figure 3.5: General view of Pereira

Figure 3.6: Non-structural damage – Pereira

4 PERFORMANCE OF ENGINEERED BUILDINGS

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4.1 Description of engineered buildings

Most of the engineered buildings observed were 2 to 7 storey reinforced concrete frame structures with masonry infill panels. These panels were made out of clay bricks as well as concrete or clay hollow blocks. In the vast majority of cases they had been erected after the completion of the frame and were not tied into the rest of the structure. Occasionally, reinforced concrete beams had been cast on top of the masonry panels. This was, however, rare for engineered buildings.

In addition to these, a few high rise residential blocks, 10 to 15 storeys high, were observed. However no steel structure of any significance was encountered.

4.1.1 Design codes

Seismic requirements were first introduced in Colombia in the 1984 design code (based on the 1978 Applied Technology Council provisions [1]), following the Popayán earthquake of 1983. However, the observation of the structures erected before 1984 often showed reasonably large section sizes and heavy reinforcement, indicating that designers were aware of the need to consider earthquake loading. It is understood that, prior to the introduction of the 1984 code, references were often made to Californian codes with translations being made available since 1976 [2].

The design spectra given in the seismic design code (both the 1984 and 1998 editions) were significantly exceeded by the earthquake of 25 January 1999. Comparison of the spectra (Figure 2.10) shows an exceedence of 2 to 3 times, up to periods of 0.6 to 0.7s, corresponding to the natural periods of the vast majority of structures found in the area.

However, recent structures behaved well, provided that they were adequately detailed and built. Indeed, only one recent structure suffered complete collapse, thought to be due to particularly poor construction.

At the time of introduction of the 1984 code, it was judged preferable not to introduce unduly stringent rules in a country that had never had a seismic design code. The code was, however, upgraded in 1998 [3] with significant changes including:

- allowable inter-storey drift (calculated from unreduced elastic forces and stiffness) reduced from 1.5% to 1% of storey height
- recommendations on microzonation studies and soil-structure interaction
- introduction of fourth, softer, soil type.

While it is believed that one structure in the area had been designed to this upgraded standard, it was not seen by the investigation team.

4.1.2 Quality of construction

Although materials used on site seemed to be of reasonable quality, very poor concrete was observed in a number of cases, in particular with excessively large aggregates (Figure 4.1). The extensive use of undeformed bars in older structures was also noticed.

However, the main shortcoming in the quality of the building stock was to be found in the detailing. This was observed not only in the older structures designed prior to the introduction of seismic provision, but also in recent structures, highlighting deficiencies in control of design and construction. Typically such shortcomings included lack of shear reinforcement near connections, insufficient anchorage or splice length, location of splices through joints, and poorly closed stirrups. Further details are given in the following section.

No unusual construction practices were observed, with the few exceptions mentioned below.

The use of thin and lightly reinforced slabs with secondary beams, also lightly reinforced, was noticed. A typical arrangement is shown in Figure 4.2. In addition, structures with beams running in only one direction were observed. This was the case, in particular, for a block of flats in Pereira.

4.2 Damage to engineered buildings

As described above, engineered buildings often had reasonably large and heavily reinforced sections but they suffered heavy damage nonetheless. This was due largely to poor detailing and construction control leading to low capacity and brittle failure modes. As such, no new lessons were learnt.

The observation of damage showed in all cases that ductile behaviour had not been guaranteed through adequate design and construction. This was highlighted by the fact that throughout the mission not a single case of beam hinging was observed. It is not known, however, whether the 1984 design code explicitly required the bending moment capacity of the columns to exceed that of the beams. Whenever adequate behaviour was observed, it was due to the frame being able to resist the applied loads without excessive distress, as opposed to being able to dissipate energy through ductile failure modes.

Even though the required detailing was not always fully implemented on site, recent structures, designed in line with the recommendations of the 1984 code, behaved well. Most of the damage was observed in the older structures, built prior to this standard, showing a significant improvement in the quality of the local building stock. This highlights the improvement brought by the introduction of the standard but also the success of the local control organisation in imposing its application. It is understood that the implementation of the 1984 code had to confront considerable initial resistance.

While significant improvement of the construction quality has been achieved, poor detailing was still observed on ongoing sites. This stresses that further improvements have to be made, in particular at the time of reconstruction. This will be made particularly difficult because of the sheer volume of work ongoing.

It is interesting to note that the implementation of good seismic design and construction practices is often met with resistance because of its cost implication. However, significant improvement of the detailing can often be made without unduly affecting cost. This applies in particular to splice length and location, adequate development length at connections and proper closing of stirrups - shortcomings so often observed on site.

Finally, most of the damage observed on recent structures was non-structural. It is understood that the 1984 code concentrated on survival of the structure and did not set, in particular, stringent requirements on the limitation of drift. This might explain the high level of casualties and financial losses caused by falling masonry. However, this has been addressed, at least in part, by the 1998 design code.

4.2.1 Examples of structural damage

Examples of poor detailing could be found on most structures. A few examples are listed below. It is not intended to give a complete list of all the failure mechanisms observed.

Figure 4.3 shows the only observed collapse of a recent structure. As shown in Figure 4.1, the anchorage length provided at the beam-column connection is short and the concrete is of particularly poor quality, with large aggregates.

Figure 4.4 shows similarly poor detailing on a different structure. The bottom bar was virtually unanchored to the column and the stirrups provided were notably insufficient.

Figure 4.5 and Figure 4.6 show another typically poor behaviour with failure of the columns, one abutting a masonry panel, the other away from any panel.

Figure 4.7 shows a compression failure in columns. Such a failure mode was widely observed in the older reinforced concrete frame structures of central Armenia.

While examples of pounding between structures were observed (Figure 4.8), Figure 4.9 shows an unusual arrangement where adequately separated structures were connected through a tie spanning the gap.

Poor detailing was also observed on ongoing construction sites. Figure 4.10 shows a column under construction where all the bars will be spliced through the same section. This was observed on a large proportion of the site.

One unusual structure was observed and will be described further. It was a three storey extension of the municipal building and included a cantilevered section of approximately 10m. The structural members were made of rectangular hollow sections, some 2m deep, with exceptionally heavy reinforcement - 32mm and 40mm bars at 100mm centres. In addition, some pre-stressing tendons were observed. Figure 4.11 and Figure 4.12 show some of these sections. It is not understood why such an approach was used but its inherent flaw was highlighted by the gross collapse of the structure. The high vertical acceleration would have contributed to producing very high loads on structural members that would have failed in a brittle manner, through shear or compression failure of the concrete. Further inherent weakness would come from the large eccentricity between the structure centre of mass and stiffness. Finally, pounding might have occurred between the extension and the rest of the municipal building.

4.2.2 Non-structural damage

A high level of non-structural damage was also observed. It led not only to casualties but also to large financial cost.

Free-standing masonry walls at gable ends often collapsed, as shown in Figure 4.13. Such an arrangement is thought to have been responsible for a large proportion of the casualties.

Severe non-structural damage made the block of flats shown in Figure 4.14 uninhabitable. This structure was built as recently as 1995 and the financial cost, in terms of lost income and repair probably represented a significant proportion of the original cost of construction.

4.3 Buildings retrofitted following the earthquake of 1995

The last earthquake to cause damage in the region was the Pereira earthquake of 8 February 1995 (Section 2.4). It was a magnitude 6.8 M_s event and produced ground motions with a dominant frequency content of between 0.7 and 1.0 Hz, which would correspond to the fundamental mode of vibration for buildings of between 10 and 14 storeys. The earthquake caused severe damage in Pereira, predominantly to these mid-rise buildings.

A number of structures were retrofitted following the 1995 earthquake. An investigation was made by the team to record the techniques used to improve earthquake resistance and to consider their performance in this earthquake.

4.3.1 The Geographical Institute

4.3.1.1 Form

This building is located in Pereira approximately 46km from the earthquake epicentre. It is a five storey reinforced concrete structure with non-loadbearing infill masonry walls with glazed facades on two of the elevations (Figure 4.15). It is founded on concrete caissons with ground beams between the heads tying the whole base together.

The building was constructed in 1985 and so should have been designed to the recently introduced code of 1984. The building was originally constructed as a multi-storey car park. However, at some point before 1995, it was converted into office space. This involved the concrete ramps between floors being removed (Figure 4.16) and replaced with in-situ concrete floor slabs supported on new concrete edge beams. The rest of the structure remained unaltered.

4.3.1.2 Damage caused by the 1995 earthquake

The building suffered substantial damage during the 1995 earthquake: a substantial area of the floor slabs collapsed, shear failures were observed in a number of columns and there was substantial damage to the non-structural masonry infill panels within the concrete frame.

The collapse of the slab elements appeared to have been the result of the changes made to the building prior to the earthquake, as described above, which affected the overall stiffness distribution of the structure. The ramps may have originally provided a structural tie between the floors and their removal would have significantly reduced the lateral stiffness of the building. This would explain to some extent the damage caused to the infill panels due to the increased flexibility of the frame.

4.3.1.3 Retrofitting

Following the 1995 Pereira Earthquake, the retrofitting of the building was carried out in approximately seven months and comprised three main aspects:

- replacement of the collapsed floor area
- relocation of the lift
- introduction of shear walls.

The collapsed slab was replaced by a new floor supported on a steel truss composite with a reinforced concrete slab over (Figure 4.17). The lift was relocated towards the façade of the building. The whole building was then strengthened and stiffened by the introduction of four concrete shear walls placed between the lines of the existing columns, defining a box shape in plan, eccentric with respect to the centre of the building (Figure 4.18). The shear walls run the full height of the building (Figure 4.19).

4.3.1.4 Damage caused by the 1999 earthquake

The building suffered moderate non-structural damage during this earthquake. There were no visible signs of damage to the load bearing structure.

The non-structural damage was on the external and internal infill panels, particularly at the corners. There were numerous cracks on the external infill walls, with sections of the walls that had fallen away, possibly due to out of plane loading (Figure 4.20). The level of damage increased with height. At basement level (below ground), damage was limited to a single crack at the junction of the reinforced concrete structure and the masonry infill panel (Figure 4.21).

4.3.1.5 Conclusion

It appears that the post-1995 retrofitting was successful in mitigating the levels of damage sustained in this event. However, although the building suffered moderate non-structural damage, it can be argued that it would not have been excited as much by this event as by the 1995 earthquake, which was closer to Pereira.

The addition of the shear walls would have stiffened the building significantly. However, the arrangement of the shear walls resulted in an eccentricity of the centre of stiffness with respect to the centre of mass of the building. The resultant torsional effects may explain the damage to the external infill panels, particularly at the corners.

4.3.2 The D.A.S. (National Security) Building

This building is located in the south of Pereira, approximately 45km from the epicentre. The building is vacant except for the top two storeys, which still house tenants.

4.3.2.1 Form

It is a nine storey building (comprising two storeys below ground level and seven above) of reinforced concrete frame construction with non-loadbearing masonry infill walls (Figure 4.22). The floors comprise reinforced concrete beams within the slab depth with 275mm deep concrete ribs at 700mm centres spanning between beams. A 75mm thick concrete topping over the ribs forms the floor slab. Poor detailing of the service penetrations through the floor were noted (Figure 4.23). The building was constructed in 1991 and so would have been built to the 1984 seismic design code.

4.3.2.2 Damage caused by the 1995 earthquake

The building suffered severe non-structural damage and moderate structural damage in the 1995 earthquake. The non-structural damage comprised severe cracking of the brick and block infill panels both internally and externally. The structural damage comprised spalling of the concrete to a number of columns and shear failures to some of the floor beams. The concrete staircase collapsed completely. Further details of the damage were not available.

4.3.2.3 Retrofitting

The building underwent a substantial retrofit in 1998. It was only completed shortly before the 1999 earthquake, so the structure was still exposed, enabling the team to study the works. The retrofitting involved strengthening the majority of the columns and main floor beams between levels 1 (ground level) and 4. Figure 4.24 shows the extent of the strengthening to a typical storey. It appears that two frames in each direction, each of four columns and located near the slab perimeter, have been stiffened and strengthened. Additional part frames spanning in the longer direction have also been strengthened.

The column sections at locations C1 (Figure 4.24) have been built up in size uniformly on cross-section from 400 mm square to 600mm square. C2 denotes columns strengthened about a single axis, while at locations C3 the columns have not been altered. Figure 4.25 shows a typical build up to the columns. Figure 4.26 shows that some column and beam strengthening works were out of alignment, resulting in an overall eccentricity about the centreline of the column. This was not typical, however, and generally the strengthening works lined through with the respective centrelines of beams and columns.

Between level 4 and level 6 fewer columns and beams were strengthened, than shown for the typical floor in Figure 4.24. Above level 6 and below ground level (i.e. level 0) no additional strengthening works were carried out.

The strengthening work to the floor beams involved adding a section 540mm x 135mm deep to the underside of the existing beam. The beams generally offer additional restraint to the columns at each floor, though not always about both axes (Figure 4.27).

No details were available showing the methodology of the strengthening works to the beams and columns. In some cases of this type of retrofit to columns, the concrete is added around the column without effectively connecting additional reinforcement to the beams at the joint. This often results in added stiffness without added strength or ductility. This is very dangerous as the stiffer structure attracts higher forces, which it is not capable of resisting. Similarly, it is difficult to see how the strength of the beam sections has been increased by the retrofit. In order to make use of the new section, the existing beam would need to be propped to take the load off it and the new section added with the additional reinforcing bars adequately lapped into the column reinforcement. The effective depth of the section would only then be increased, thus increasing the strength.

4.3.2.4 Damage caused by the 1999 earthquake

The damage caused in this earthquake was minor. No structural damage could be seen and the only significant non-structural damage was to the blockwork infill panel to the lift shaft at ground floor level (level 1) (Figure 4.28), although minor non-structural damage occurred to some other infill panels at the lower levels. The new steel staircase introduced as part of the retrofit was undamaged.

4.3.2.5 Conclusion

The main strengthening to the building was carried out between levels 1 and 4, as described in Section 4.3.2.3. Above this level there was a reduced level of strengthening. It is possible that the approach used for the retrofit of this building has targeted those areas whose deficiencies were identified by the previous earthquake, and confirmed by analytical methods, to produce an economical solution. The performance-based method for assessing and justifying retrofit schemes advocates such a targeted approach to capitalise on existing strengths.

However, as highlighted in Section 4.3.2.3, in order for the strengthening works to be effective and to provide added strength or ductility as well as stiffness, the new sections of concrete must be adequately reinforced, with the additional reinforcement being effectively tied into the beams at the joints.

This building performed very well in this earthquake, although at nine storeys its fundamental natural frequency would be expected to be below the dominant frequencies of this earthquake, which would target smaller buildings.

4.4 Conclusions

The observation of damage to engineered structures affected by the earthquake has not brought to light any new lessons. It highlighted once more the importance of adequate design and construction control, in particular with respect to detailing.

The vast majority of the badly damaged structures had been built prior to the introduction of the 1984 design code. Structures built in accordance with this standard behaved well, even though some improvement in the control of adequate detailing is required.

Casualties and large financial losses resulted from non-structural damage. The introduction of more stringent drift limitation criteria in the 1998 design code should, at least partially, address this.

There is no doubt that the correct implementation of the 1998 design code would result in a high quality and seismically robust building stock. The main challenge will, however, reside in the enforcement of this standard. This is expected to be particularly difficult at a time of urgent need for new habitations and in view of the sheer volume of work.

The two retrofitted buildings surveyed by the team survived this earthquake well, sustaining minor to moderate non-structural damage to the masonry infill panels only.

The retrofitting to the Geographical Institute comprised the installation of four shear walls between existing columns, forming a box shape on plan. The non-structural damage to the masonry infill panels was possibly caused by torsional effects, due to the eccentricity of the centre of mass to the centre of stiffness.

The retrofitting measures to the D.A.S. Building comprised increasing the section size of existing reinforced concrete beams and columns by casting on additional concrete, although the methodology used is not known, nor the level of reinforcement provided in the new sections. In order for this type of strengthening to be effective though, continuity of reinforcement between the new and existing sections is required, especially at the joints between columns and beams.

4.5 References

1. Applied Technology Council (ATC) (1978), "Tentative Provisions for the Development of Seismic Regulations for Buildings" (ATC 3-06), National Bureau of Standards, Washington D.C.

2. García L.E. (1984), "Development of the Colombian Seismic Code", Proc. 8th World Conf. Earthquake Engineering, San Francisco 21-28 July 1984, Vol. 1, pp. 747-754

3. Asociación Colombiana de Ingeniería Sísmica (AIS) (1998), "Normas Colombianas de Diseño y Construcción Sismo Resistente" (NSR-98), AIS, Bogotá

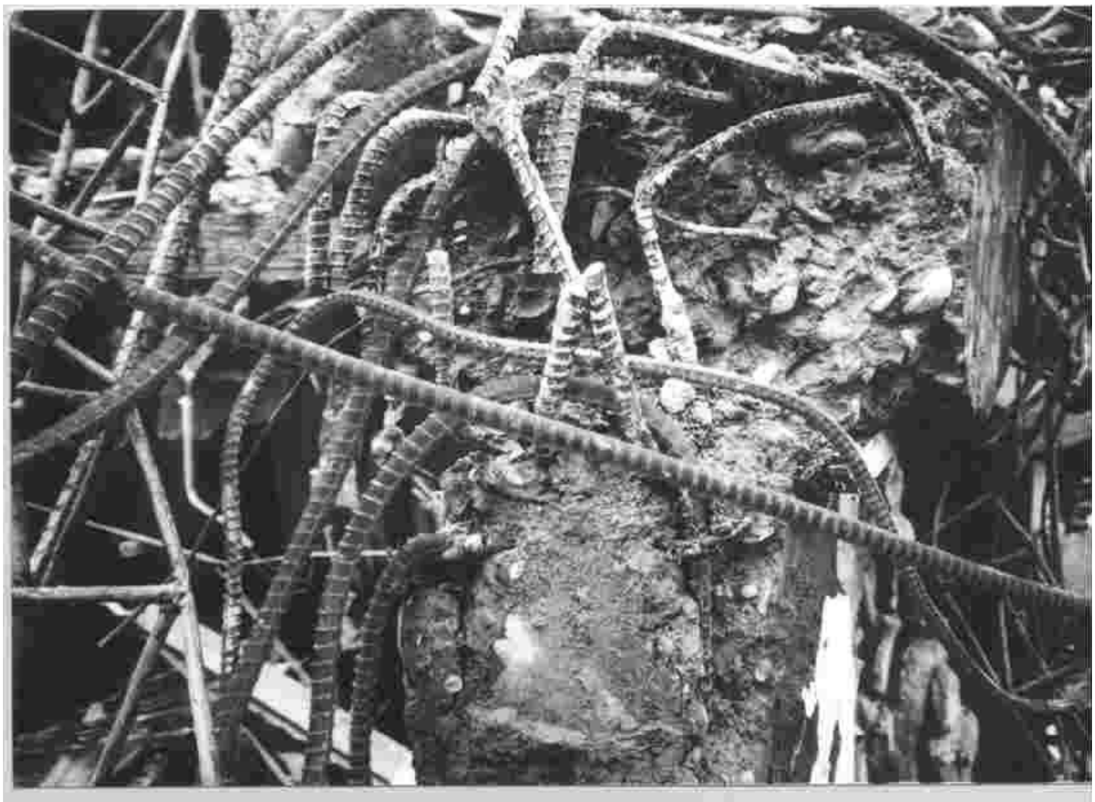

Figure 4.1: Detail of beam-column connection

Figure 4.2: T-shaped slab

Figure 4.3: Complete collapse of post-1984 structure

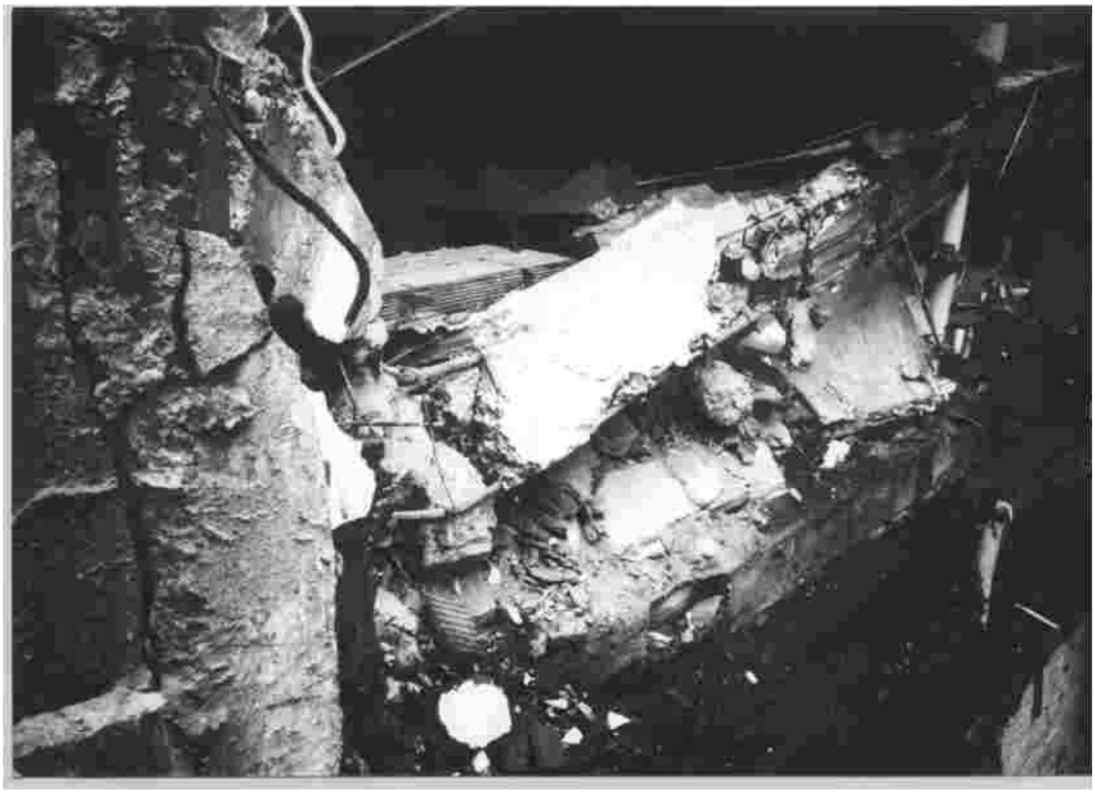

Figure 4.4: Detail of beam

Figure 4.5: Shear failure of column

Figure 4.6: Shear failure of column

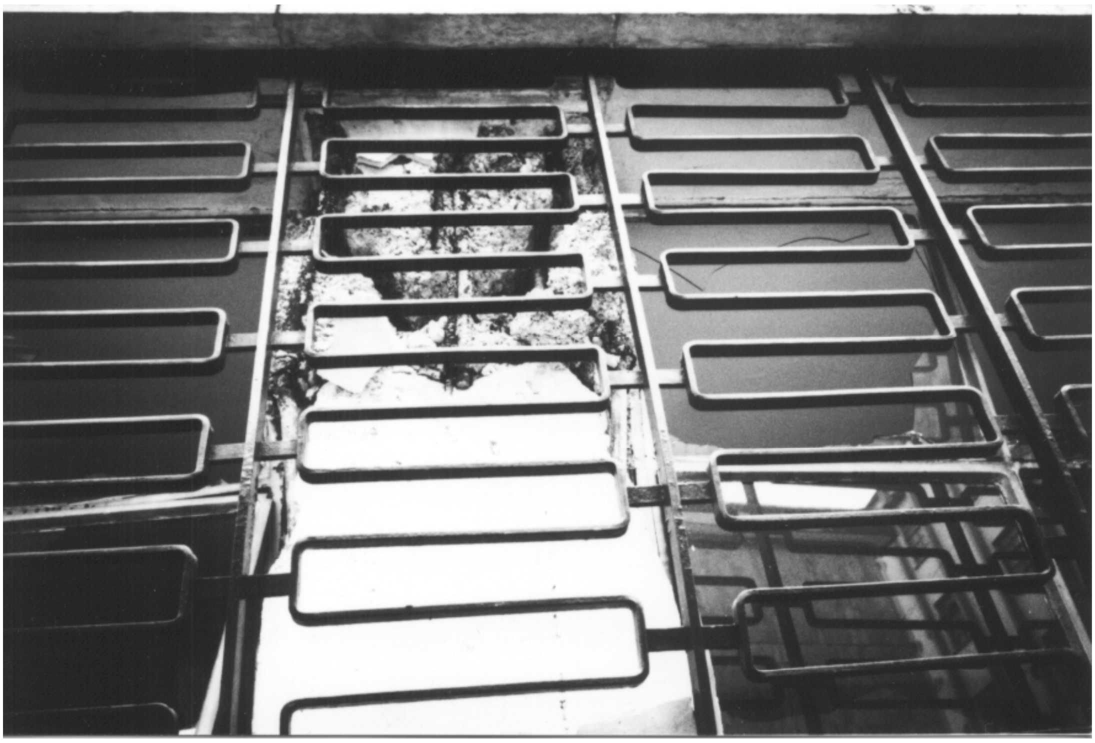

Figure 4.7: Compression failure of column

Figure 4.8: Pounding between adjacent structures

Figure 4.9: Buildings with tie spanning seismic gap

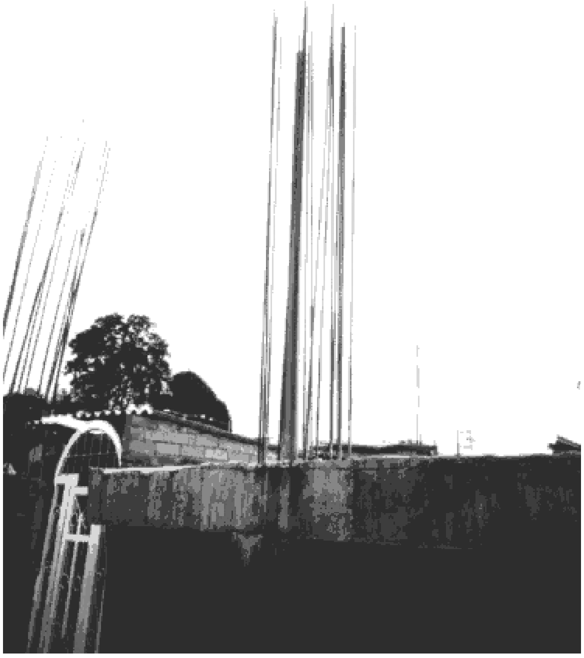

Figure 4.10: Detailing on ongoing construction site

Figure 4.11: Unusual structural design

Figure 4.12: Detail of reinforcement in unusual structural design

Figure 4.13: Collapse of free-standing masonry wall

Figure 4.14: Non-structural damage of recent structure

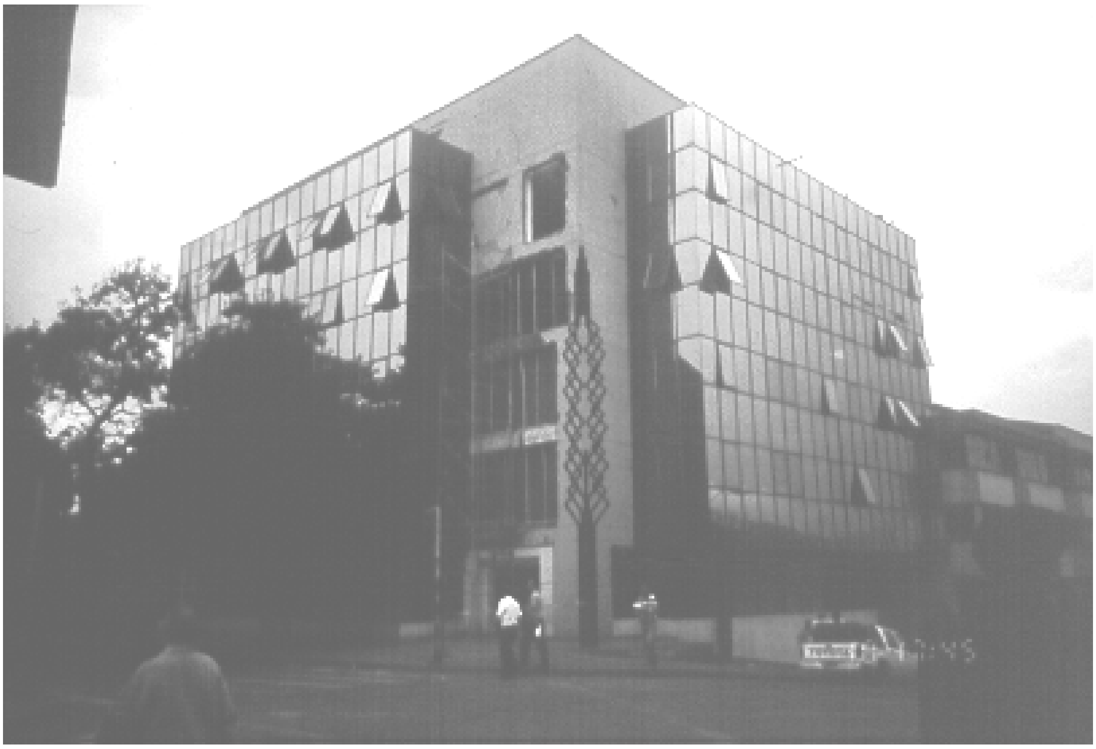

Figure 4.15: The Geographical Institute

Figure 4.16: Location of concrete ramp, now demolished

Figure 4.17: New steel truss floor beam with metal decking and RC slab over

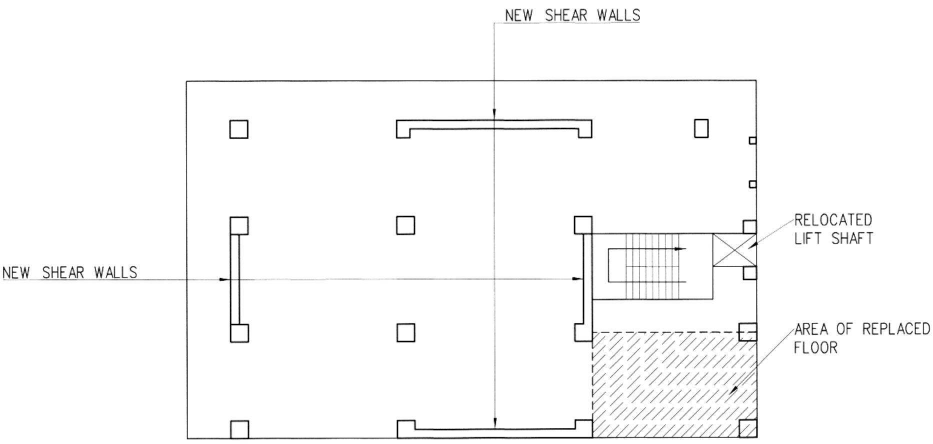

Figure 4.18: The Geographical Institute - Typical floor plan

Figure 4.19: Retrofitted shear wall

Figure 4.20: Cracking to external infill wall panel

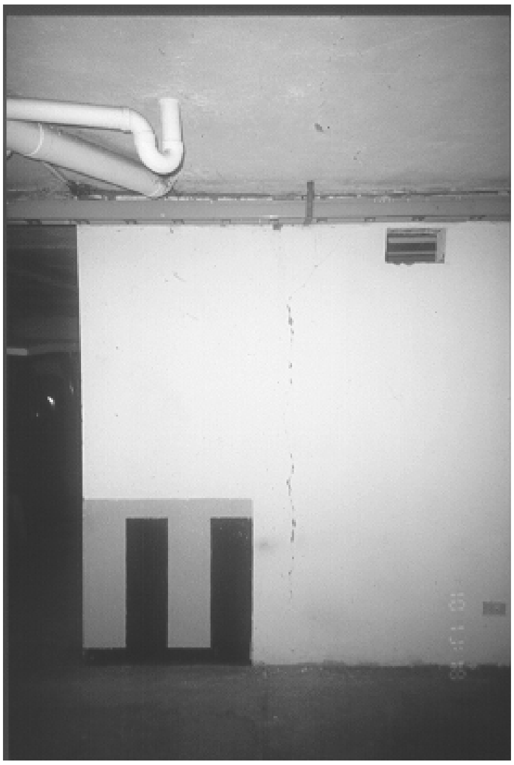

Figure 4.21: Cracking at interface between structural concrete shear wall and masonry partition wall at basement level

Figure 4.22: The D.A.S. Building

Figure 4.23: Concrete floor rib detail, showing poorly located service pipework

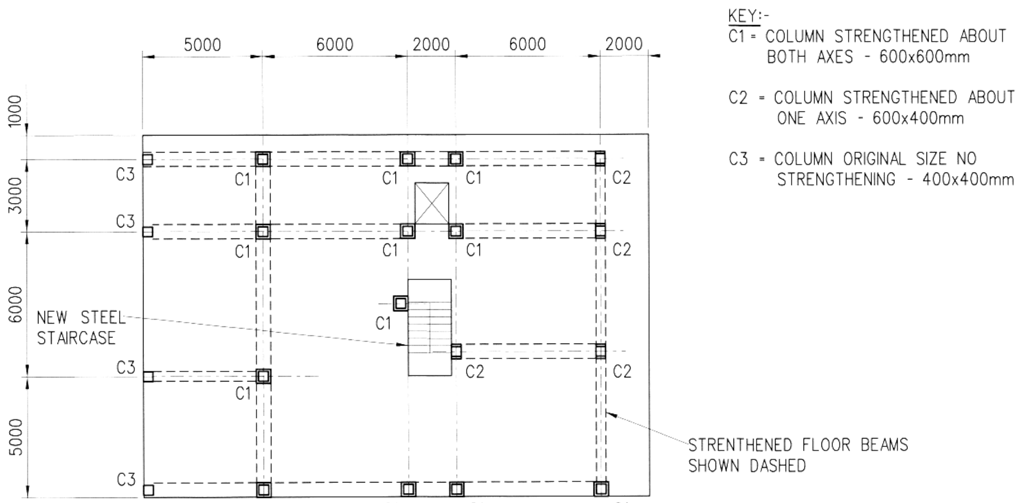

Figure 4.24: D.A.S. Building - Typical floor plan

Figure 4.25: Retrofitted column, type C1

Figure 4.26: Eccentric retrofitted beam and column connection

Figure 4.27: Retrofitted beam and column, with beam only providing additional restraint to column in one direction

Figure 4.28: Shear cracking to internal non-loadbearing wall

5 PERFORMANCE OF NON-ENGINEERED BUILDINGS

Graham Parker
Anthony Hunt Associates

5.1 General description of non-engineered buildings

Non-engineered buildings make up a substantial number of the structures in the region and cover a range of building types**.** These vary from those using the traditional materials and methods of the region to more modern reinforced concrete frame structures with brickwork or blockwork infills. They range in height from one to three storeys. The aspect that these non-engineered building types have in common is that they have not been built to any codes of practice for seismic resistant design. Indeed, due to the nature of materials used in the traditional building types, a code of practice for their design still does not exist.

The building stock in this category can be divided into the following types:

- Traditional bahareque
- Masonry
- Reinforced concrete
- Modern bamboo (guadua)

5.1.1 General description of damage to non-engineered buildings

In general, this earthquake caused high levels of damage to the non-engineered building stock. Due to the shallow nature of the earthquake and corresponding high frequency components (Section 2.6), low-rise buildings (of between one and three storeys) suffered the highest damage levels. This is exactly the range of heights of these non-engineered buildings, and is one of the reasons why such high damage levels were observed.

Local soil conditions also had a significant effect (Chapter 3), together with the observed weaknesses of each building type which are discussed in the following sections.

5.2 Traditional bahareque buildings

5.2.1 Form

This is the traditional form of construction in Colombia. This housing system utilises braced bamboo stud framing forming the wall structure, which is infilled with pieces of tile and brick embedded in clay and mud. Closely spaced laths of bamboo or other materials are nailed to each side of the bamboo studs to reinforce a plaster mortar that covers the mud-filled bamboo lattice (Figure 5.1). The roofs are normally constructed from bamboo rafters covered with either clay roofing tiles or corrugated iron sheeting.

Bahareque construction has been used for centuries and is well suited to the area as it employs materials that are widely available at low cost. It is easy to construct and provides good insulation against the tropical heat. It appears to have been developed as an early form of seismic resistant design. In the 19th century these buildings were referred to as ‘estilo temblorero’ or ‘shaking style’ [1].

Dwellings of bahareque construction have the highest concentration in the smaller towns and villages in the area. In Pereira and Armenia these buildings have often given way to more modern forms of construction such as reinforced concrete, but they are still popular in poorer areas, particularly the south-west of Armenia (Section 3.2.2.1).

5.2.2 Damage to traditional bahareque buildings

Damage to these buildings varied extensively. The level of damage appeared to be dependent not only on proximity to the earthquake epicentre, but also on the ground conditions and quality and age of construction, as discussed in Chapter 3. For instance, in Barcelona which is situated within 5km of the epicentre, a row of terraced bahareque buildings suffered only very low levels of damage. The damage was confined to the spalling of some of the plaster render on the walls and dislodging of clay roof tiles to some buildings (Figure 5.2). In comparison, there was severe damage to masonry and reinforced concrete structures in other areas of the town.

In other areas which were visited, such as the towns of Córdoba, also within 5km of the epicentre, and Calarcá, approximately 15km to the north-east of the epicentre, the damage to bahareque structures was more severe. This appeared to be due to the following reasons:

- Heavy roof in conjunction with a poor connection between the tops of the walls and the roof structure: A good connection between the roof and the tops of the walls has the benefit of stiffening the tops of the walls and enabling the lateral forces to be transmitted into all the available walls through the roof. Where this connection had degraded the loads may not have been so evenly shared through the walls; stress concentrations built up at corners, causing separation of the walls. This then allowed the walls to shake independently and, combined with the heavy vertical roof load, they failed by overturning (Figure 5.3).

- Poor maintenance: Buildings where the mortar and mud fill had degraded and the bamboo infills were visible (Figure 5.4).

- Infestation by insects and the effects of the tropical climate: This undoubtedly affected the performance of these structures, many of which were constructed from untreated bamboo. These effects significantly decrease the strength of the material.

- Alterations to the original design: Some of the designs have been ‘contaminated’ with unreinforced masonry walls. The introduction of these masonry walls as internal partition walls has the effect of changing the load paths in the structure and creating much stiffer local elements. In the earthquake, these stiffer elements would attract more lateral load and could ultimately fail. In some cases this may have led to the collapse of the whole building, as the loads were not being shared evenly in the structure as intended.

When they have been well maintained, these buildings did behave well during the earthquake, such as the street in Barcelona mentioned above.

5.3 Masonry buildings

5.3.1 Form

The masonry buildings observed were generally of one or two storeys, supporting a clay roof on a bamboo frame. Generally these buildings incorporated concrete ring beams at floor and roof levels (Figure 5.5). The purpose of this is to tie the masonry walls together at these locations. This encourages the building to respond to an earthquake as a single unit and helps to reduce the segregation of the walls at the corners.

In some of these buildings the structural floor members were visible from outside the building. These were bamboo sections supported off the first floor ring beam at close centres (approx. 300mm), as shown in Figure 5.5. It was possible to gain access to this building and stand on this floor. Due to the relatively long span of these bamboo members, the floor was very springy underfoot. Being so flexible, this type of floor would provide little restraint to the walls by diaphragm action.

5.3.2 Damage to masonry buildings

The damage observed was mainly to those structures over one storey in height. Figure 5.6 shows a series of one storey brick dwellings in Calarcá. These were uniform on plan and also benefited from a lightweight steel laminated roof. The damage was generally quite minor to this only row of single storey brick buildings in the town. More severe damage was observed to one of these buildings where the front corner of the wall had broken away, however this had not resulted in the collapse of the building.

In those buildings of two storeys the concrete ring beam was seen to be effective in helping enhance the integrity of the structure. The building shown in Figure 5.5 is a good example of this. In Figure 5.7 the ring beam can be seen from inside the structure. On first inspection the ring beam appeared to have performed as intended and provided sufficient restraint to the masonry walls. However, Figure 5.8 and Figure 5.9 show that on closer inspection that the corner connection had started to degrade in the masonry wall. This crack had propagated to the concrete ring beam which had sheared. It was only the tensile strength of the reinforcing bars in the beam which held it together.

The ring beam was very lightly reinforced; it is probable that it may have held had it been adequately reinforced for shear in this corner region. Poor detailing of structural elements was seen repeatedly in many buildings and was a significant factor in the levels of damage experienced (Figure 5.10).

5.4 Reinforced concrete buildings

5.4.1 Form

These were generally buildings of two or three storeys, consisting of a reinforced concrete frame with brickwork or blockwork infills forming the walls. Often, for these non-engineered buildings, the beams had been cast directly on top of the masonry walls. The roof construction was generally of clay tiles.

Most of the residential housing of the low-income population is in this category. Although constructed with a reinforced concrete frame, they have generally not been built to any seismic code. Although there are simplified guidelines in the code for one and two storey buildings, they were very often not followed. There are more rigorous requirements for structures of three or more storeys, but in many cases a third storey was added to houses with no seismic provisions. As a result, many of these buildings are severely under reinforced in key areas and are generally of a poor construction standard.

5.4.2 Damage to reinforced concrete buildings

These buildings suffered the highest level of damage of all the construction types. The central and southern areas of Armenia and certain parts of Pereira suffered extensive damage with hundreds of these buildings suffering total or partial collapse (Figure 5.11). The following factors contributed to the high level of damage experienced by these structures:

- Poor quality of materials and workmanship, poorly compacted concrete with a low compressive strength combined with very large aggregates.
- Virtually no shear reinforcement, additionally main longitudinal bars were in many instances of small diameter and of undeformed bars, thus providing less keying into the concrete.

- Irregularities in plan causing torsional moments in the structure and irregularities in height leading to the sections of varying heights responding differently.
- Connections did not always line up between floors (Figure 5.12).
- Short column failure, where blockwork infills have been added to the structure in order to form an opening for a window. This had the result of shortening the effective length of the column in bending which resulted in shear-induced failures (Figure 5.13 & Figure 5.14).

5.5 Modern bamboo (guadua) buildings

This is a new form of construction using the natural and readily available material of bamboo, of a variety known as guadua in South America. Bamboo has been used as a construction material in conjunction with other materials for many years, such as the traditional bahareque type of construction (Section 5.2), but this is the first time it has been used as the main load bearing structure alone. At present there are no guidelines for the design and construction of these buildings.

Examples of these structures were seen at the National Centre for the Study of Bamboo, which is located near Córdoba, very close to the epicentre. This was established by the Quindío regional council (CRQ) in order to investigate the use of bamboo as a construction material.

In addition, a settlement of social housing of approximately 130 houses has been constructed approximately 3km to the south-west of the centre of Armenia.

5.5.1 Form

The majority of buildings which are located in the social housing settlement are of one storey, with a few two storey buildings. The site is founded on a fairly steep slope, thus the buildings are built up off quite long bamboo stilts (Figure 5.15 & Figure 5.16) on a concrete footing. Unfortunately, it was not possible to gain access to the site to examine the foundation detail further. However in discussion with Juan Guillermo Garces, a promoter of this construction technique, he explained that the foundation consisted of a 0.5m high concrete plinth and a conical steel cup on the end of the bamboo columns to minimise rotting of the base.

The main structure is made up from the continuation of the bamboo stilts forming the main vertical members, with horizontal bamboo sections supporting the floor and roof. Cross bracing is employed in the walls to provide lateral restraint. The roof is constructed from a bamboo frame supporting a lightweight laminated steel sheet.

The connections between the bamboo members are a new innovation which have been developed by a Colombian architect, Simon Velez, working in association with the Zero Emissions Research Initiative (ZERI). The bamboo naturally forms hollow sections approximately 300mm in length. In order to form the joint, the technique is to drill a hole into one of these hollow sections and to fill it with concrete, with the same done to the connecting member. A steel pin treated with pyrolytic acid is then passed through both sections to form the connection. This connection appears to have the advantage of increasing strength without any significant effect upon the flexibility of the bamboo.

The structures at the National Centre for the Study of Bamboo are of an altogether different scale than those discussed above. The buildings there are showpieces of what can be achieved with bamboo. However the same technology as in the social housing scheme is used in these buildings (Figure 5.17). The main differences are in the level of detail and the roof, which is of clay tiles.

5.5.2 Damage to modern bamboo (guadua) buildings

These structures performed very well in the earthquake. In fact they withstood the earthquake forces better than any other building type, either structural or non-structural, in the affected area.

No damage was visible to the social housing development, even though other buildings in the immediate surrounding area suffered relatively high levels of damage.

The buildings at the National Centre suffered very slight damage to their roofs, where some of the clay tiles had been dislodged and fallen to the ground (Figure 5.18). Equally here, it was possible to compare their behaviour with neighbouring buildings. A two storey masonry building constructed on the same site received moderate damage (Figure 5.19).

One reason why these structures survived the earthquake with so little damage is probably due to their low weight and high strength. The buildings in the social housing development are especially light. With lightweight wall construction, the lateral loading induced in the members from the earthquake was not sufficient to cause failure of any of the structural members. Bamboo itself is a very strong material, with a higher strength to weight ratio than steel. The new connection technique also appears important to the overall performance of these buildings.

Another factor which is important is the age of these buildings. The settlement was only established within the last 5 years, and it is therefore unlikely that the load bearing ability of the bamboo members would have been impaired yet due to infestation or rotting, as discussed in Section 5.2.2. The bamboo in these houses has been treated with chemicals to preserve it, but the chemicals required are expensive. It is foreseeable that this is an area of the construction which may be omitted in order to construct a cheaper dwelling.

This is something which is currently being addressed in Colombia. The Zero Emissions Research Initiative (ZERI) has developed techniques for preserving the bamboo. Essentially this involves smoking the bamboo with smouldering bamboo shavings. The bamboo shavings exude a natural pyrolytic acid which preserves the bamboo. This system is much cheaper than the normal chemicals required to perform the same function. The system is now operational and the first plant was recently installed in Armenia [2].

5.6 Conclusions

The non-engineered building stock suffered high levels of damage in the earthquake. The damage levels were particularly high due to the high frequency content of the event, effectively targeting these low-rise buildings.

The traditional form of construction, bahareque, was seen to perform well when it was well maintained. However, many of these buildings suffered extensive damage due to lack of maintenance and also the introduction of masonry partition walls. Heavy roofs, combined with deterioration of the corner connections, contributed to the out of plane failure of the bahareque walls.

For masonry buildings, concrete ring beams were seen to be effective in limiting the degree of damage to these structures.

Poor construction quality and detailing was observed in many of the concrete framed buildings.

The new construction technique using bamboo has shown itself in this earthquake to be capable of withstanding seismic loads. Virtually no damage was observed to these structures. The use of the new connection detail, combined with the preservation of the bamboo, appears to be key to the earthquake resistance of these lightweight structures. The development of design and construction guidelines, and the implementation in the local community of techniques for preserving bamboo appear to be the first steps towards making this type of construction a viable alternative for the local population.

5.7 References

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2 Pauli G. (1999), Personal communication, July 1999, Zero Emissions Research Initiative (ZERI) (http://www.zeri.org)

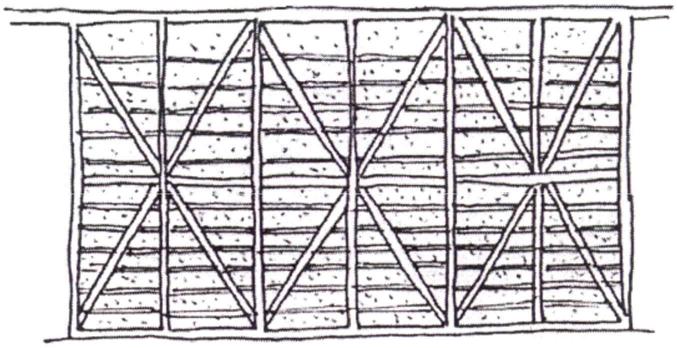

Figure 5.1: Typical construction of a bahareque wall

Figure 5.2: Terrace of relatively undamaged bahareque buildings in Barcelona

Figure 5.3: Separation of walls and roof of a bahareque construction in Córdoba

Figure 5.4: Wall construction of a bahareque building, showing tiles embedded in mud infill

Figure 5.5: Masonry building with ring beams at first floor and roof level. Note bamboo sections above ring beam forming the main structural floor members.

Figure 5.6: Single storey masonry buildings. Note section of wall missing in nearest building.

Figure 5.7: Internal wall of house shown in Figure 5.5

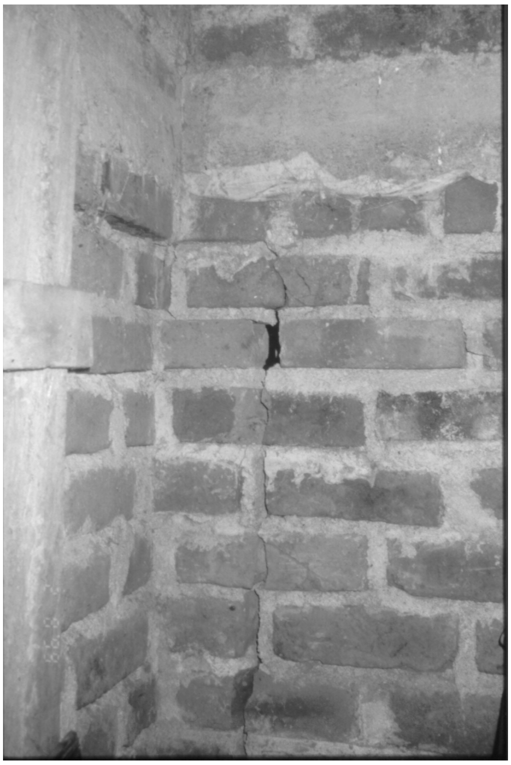

Figure 5.8: Ring beam at roof level, successful in halting the propagation of cracking in the corner of the masonry wall

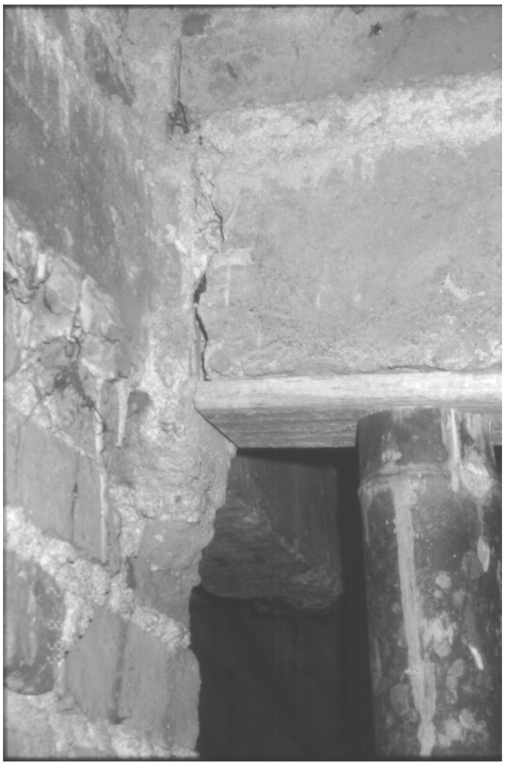

Figure 5.9: Concrete ring beam has sheared here. Note bamboo used as a temporary prop.

Figure 5.10: Example of poor quality control. Concrete lintel with barbed wire being used as the main tension reinforcement.

Figure 5.11: The fate of many concrete framed buildings

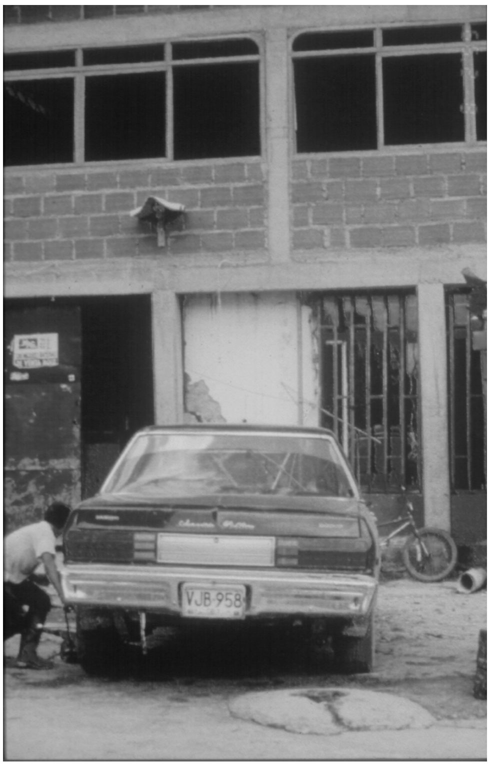

Figure 5.12: Non-coincident beam and column arrangement. Column transfers load to the centre of the beam.

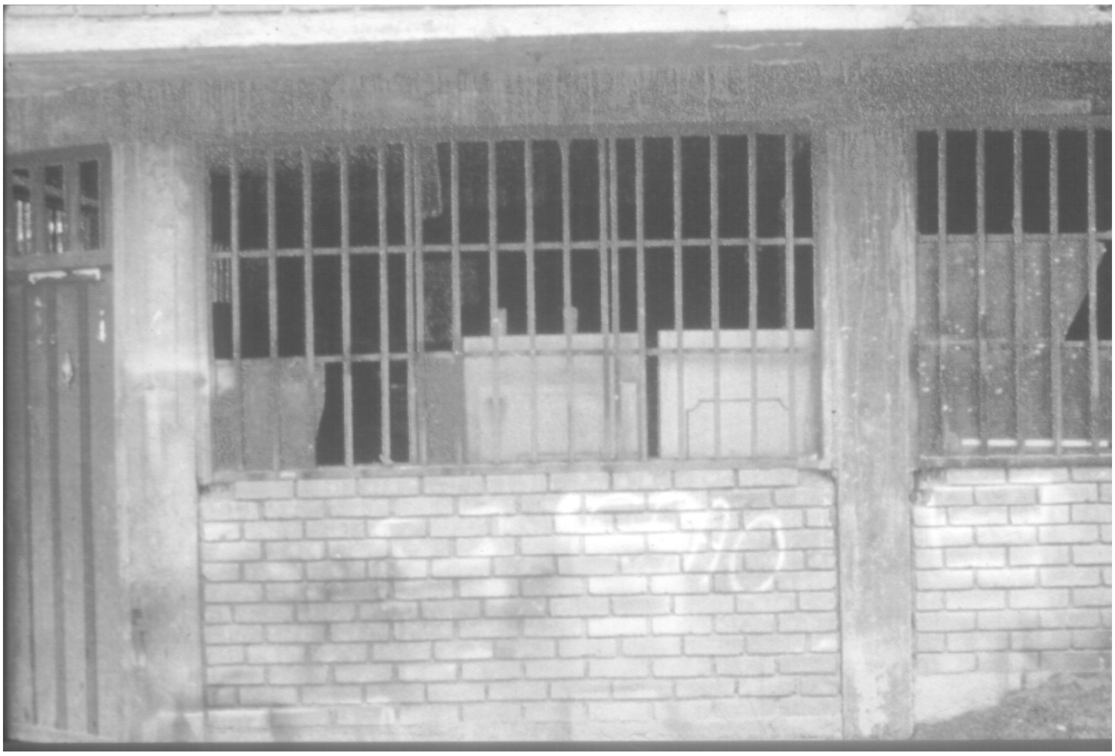

Figure 5.13: Masonry wall built between columns to half storey height to form window

Figure 5.14: ‘Short column’ shear failure

Figure 5.15: Social housing development of new bamboo houses in Armenia

Figure 5.16: Close-up new bamboo houses in Armenia

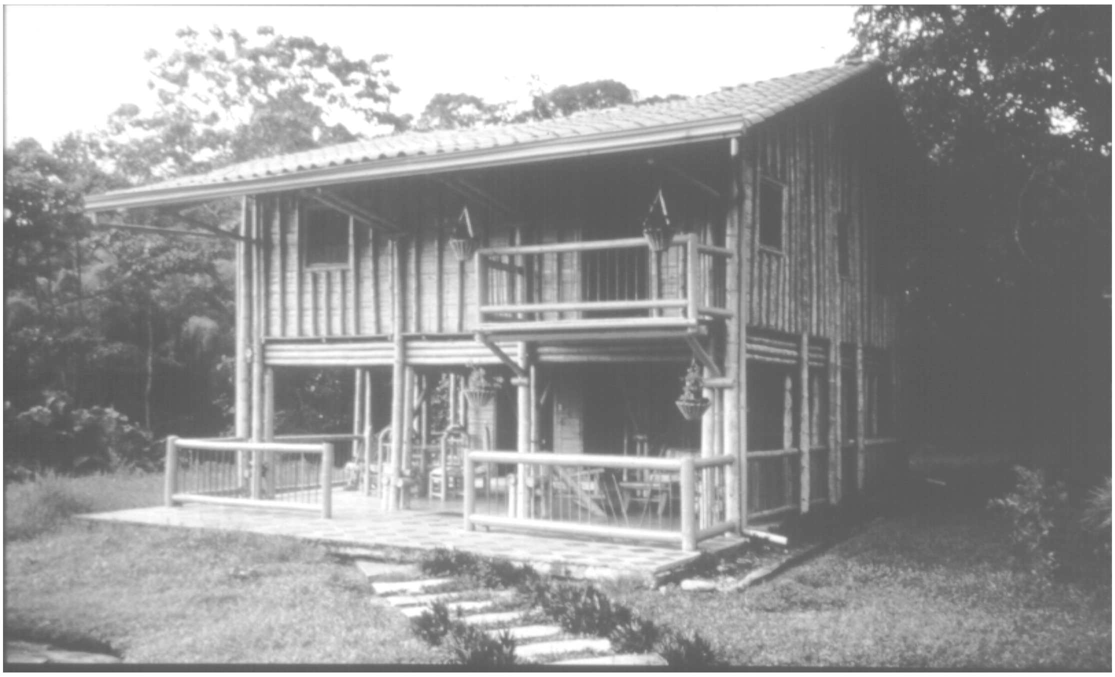

Figure 5.17: Typical house on display at the National Centre for the Study of Bamboo

Figure 5.18: Displaced tiles from the roof of a house at the bamboo centre

Figure 5.19: Damage to a masonry building at the bamboo centre

6 MANAGEMENT OF THE DISASTER AND SOCIO-ECONOMIC EFFECTS

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6.1 Statistics of earthquake losses

The coffee growing area of the Andean region that felt the earthquake has a total population of more than 3 million, living in 30 towns and cities across five Departments [1,2]:

> Department of Quindío: Armenia, Calarcá, Barcelona, Filandia, Montenegro, Circasia, Pijao, La Tebaida, Córdoba, Quimbaya, Salento, Buenavista, Génova.
>
> Department of Risaralda: Pereira, Dosquebradas, Santa Rosa de Cabral, Marsella.
>
> Department of Valle del Cauca: Alcalá, Obando, Ulloa, Caicedonia, Sevilla, Argelia, Anserma, Nuevo Tulua, La Victoria.
>
> Department of Tolima: Cajamarcá, Fresno, Roncevalles.
>
> Department of Caldas: Chinchina.

Pereira and Armenia were the most affected areas [2,3], with populations of approximately 410,000 and 240,000 respectively. In the five days following the earthquake, 32 people were brought out alive and 215 bodies were extracted from the rubble [4]. 180,000 people required immediate relief assistance, with the situation aggravated by heavy rainstorms [5]. By 19 February, 1,171 people were reported dead and 4,765 injured [6] and one month after the earthquake, 250,000 people were reported homeless [7]. About 90% of the causalities occurred in the municipalities of Armenia, Calarcá and Pereira [3].

More than 50,000 structures were destroyed or damaged in the Departments of Quindío and Risaralda [3], with 8,000 structures affected in the coffee growing agricultural areas. Damage to public services was severe and most of the churches close to the epicentral area either collapsed or suffered severe damage.

Direct losses of more than US$1.5 billion are expected, in a country with an economic growth of only 0.2% in 1998 [8]. The city of Pereira, that serves as a commercial and industrial centre and is situated centrally between the principal cities of Bogotá, Medellín and Cali, contributes 2.15% of the GNP of the country. It is important to note that in the 1995 earthquake the city of Pereira suffered losses that amounted to US$50 million. In the area around Armenia, that serves as a centre for the coffee growing industry and contributes 1.40% of the GNP of the country, 60,000 hectares of coffee plantations were directly or indirectly affected.

6.2 Emergency and medical services

The emergency response effort was significantly hampered by landslides blocking the majority of roads in the affected area, delaying land access to certain areas for several days (Section 7.2.4).

The first phase of acute emergency operations concluded after ten days on 4 February, and was followed by a transitional assistance phase, to provide basic relief items and medical services to the most vulnerable people. This phase went on to the end of April and was slowly converted to the third and final phase of rehabilitation.

The first phase of the emergency was dealt with by governmental and international agencies, with the constant presence of the Red Cross, and aimed at providing medical and psychological relief to those most affected.

With the participation of emergency medical teams and Non-Governmental Organisations (NGO's), a command post was established by the Ministry of Health to meet health needs and prevent the spread of disease. Emergency basic medicine teams received, sorted, labelled and distributed medical supplies, while health authorities started a vaccination programme. The situation was aggravated by the interruption of the refuse recollection service in Armenia [2]. Special attention was dedicated to psycho-social recovery of 60,000 affected children in Armenia and Pereira.

The national and international organisations that participated in the emergency phase were: Colombian Red Cross (CRC), Corporación Andina de Fomento (CAF), United Nations Office for the Co-ordination of Humanitarian Affairs (OCHA), United Nations Disaster Management Team (UN DMT), FAO, Pan-American Health Organisation (PAHO/WHO), UNHCR, UNICEF, World Food Program (WFP), UNFPA, United Nations Inter-Agency Procurement Services Office (UN IAPSO) and UNFPA [3,5,6,7,9].

6.3 Distribution of food and temporary shelters

The second phase of the emergency plan was centred on the distribution of food and temporary shelter to those most affected. On 28 January the President of Colombia announced US$13.3 million for emergency aid and US$2.7 million was donated by the international community [10].

Most of the relief and food supplies were bought locally. Although the distribution of relief items started immediately after the earthquake, during the first week there were problems associated with transportation, distribution, and storage of food and provisions. This led to a situation where control of public order was lost, exacerbated by troublemakers from elsewhere in the country descending on the area. In the days following the earthquake, two people died, one was injured and 140 were arrested in looting and violent riots in Armenia (Figure 6.1) [2,11]. Similarly, 13 were arrested and two were injured in Pereira. Following these events the disaster area was placed under military control and a 6pm curfew was declared in Armenia and Pereira, with approximately 3,000 soldiers arriving in the area to secure food distribution points [2,7,9].

One of the problems addressed in the distribution of food supplies was associated with the preparation by the Colombian Government of "cestas familiares" or family baskets, containing essential food and relief items. The Government held these baskets until all items were available, which in some cases took more than a week.

The Colombian Government provided 150 tons of food per day to the disaster area, and there were 50 food distribution points by 3 February [7]. It was estimated on 5 February that food requirements for 180,000 people and housing for 35,000 families were still needed [5]. For this, public facilities, sporting areas and health centres were identified and equipped to provide temporary shelters. By 22 March, the Colombian Red Cross (CRC) reported that a total of 1,000 tons of relief items were sent from Bogotá to 15 Red Cross operational distribution centres and 15 government centres [4].

By 12 February, of 250,000 homeless, 30% were placed in 123 temporary shelters, while 70% were still living in improvised shelters (Figure 6.2) in rural and urban areas [3]. Although the initial difficulties of the emergency were resolved, outstanding immediate relief items were still required. A week later, on 19 February, it was estimated that 67,539 people were still living in make-shift shelters, with 30,000 new shelters needed for the period of reconstruction of at least a year and a half [6].

The role of international organisations was crucial during this period, namely: UNICEF, WFP, FAO, UN IAPSO, UNHCR, HABITAT and UNDP [3,5,6,7,10].

6.4 Technical evaluation and demolition of structures

Another important aspect of the management of the disaster was the technical evaluation of structures, in order to determine their level of safety and the need for demolition or retrofit. The Quindío regional council (CRQ) and many other structural engineers in Armenia and Pereira were active in performing structural assessments. To this aim, the South-west Seismological Observatory (OSSO), with the collaboration of the University of Valle in Caicedonia and Sevilla, produced a reference guide on how to assess the condition of structures based on the following categories of damage [2]:

> Low: damage of non-structural elements. Cost of repair up to 15% of the total value of the structure (not inclusive of land value)
>
> Moderate: repairable damage of the structural system. The structure may need to be evacuated due to severe damage of non-structural elements. Cost of repair up to 30% of the value of the structure.
>
> Severe: failure of the structural system, requiring major retrofitting or demolition and reconstruction. The structure must be immediately evacuated. Cost of repair up to 65% of the value of the structure.
>
> Collapse: Total or partial collapse of over 50% the structure, requiring complete demolition.

The technical evaluation of structures started immediately after the earthquake, and gave priority to those structures with severe levels of damage, in order to proceed with their evacuation and their subsequent demolition if immediate peril was posed to the public.

Six days after the earthquake it was reported that in Pereira alone, 385 structures were destroyed by the earthquake and 522 were to be demolished [11,12]. In the city of Armenia, where much of the city centre suffered considerable levels of damage, only 20% of debris was cleaned away during the first three days following the earthquake, with the result of the city centre being cordoned off [10]. The situation was similar in other towns in Quindío, where the percentage of cleared debris was up to 35%.

The role of the private sector was invaluable for the emergency operations, by supplying heavy machinery (Figure 6.3) and special equipment for the demolition and clearing of debris (Figure 6.4). Much of the equipment had been idle due to the depression of the construction industry, so was immediately available. However, demolition and clearance of debris were still major needs by 19 February [6].

Unfortunately, in some cases the demolition of structures was too rapid, meaning that the opportunity to investigate failures by structural engineers was lost.

6.5 Control of reconstruction

The day after the earthquake, the President of Colombia declared a “state of disaster” with the aim of enabling special measures for handling the emergency and to activate a plan of reconstruction of the area. A special fund was created for the reconstruction of the area by defining measures to facilitate subsidised low interest credits for the reconstruction and rehabilitation of buildings. For the first phase of the reconstruction plan of the disaster area, US$360 million was allocated as an additional part of the National Development Plan [8]. The Government also announced special credit lines for export companies in the affected municipalities.

An emergency loan was approved by the Inter-American Development Bank (IDB) for US$20 million for the rehabilitation and reconstruction of the affected areas [5,6]. On 2 February, four additional loans, totalling US$120 million were allocated by the World Bank [5].

According to the Government, reconstruction of public infrastructure will cost US$50 million [5]. For this the Colombian Government negotiated credits with the Inter-American Bank and the World Bank to re-establish water and sewerage systems and to preserve the environment in the disaster zone. The Ministry of Health made US$5.5 million available for the reconstruction of health centres in Barcelona, Córdoba, Buenavista and Pijao and the hospital in Calarcá [7]. In co-operation with the Ministry of Development, UNICEF rehabilitated the water system in Barcelona (serving 10,000 people) and engaged a contractor for the reconstruction of the sewerage system in Armenia [7]. The Ministry provided the materials, while UNICEF provided for labour and technical assistance. The Corporación Andina de Fomento (CAF) formulated the principal goals in the reconstruction of the physical and social infrastructure of the region [5].

Urban reconstruction will take at least a year and a half and 35,000 homes will have to be rebuilt or repaired [5]. The central authorities promoted an adoption scheme of the affected communities by other municipalities in Colombia, to provide for technical and financial assistance for their recovery and reconstruction. The collaboration of international agencies was also important: HABITAT co-operated with the authorities for urban reconstruction, while the ICRC focused on the repair of existing houses and on community and health social problems. They decided not to focus on the construction of new housing for the homeless, as past experience showed that this creates social tensions by drawing outsiders into the area [5].

A report from the University of Valle in Caicedonia and Sevilla estimated the total repair costs for the cities of Caicedonia and Sevilla at US$2.3 million, based on an average value of US$5,800 for a bahareque house (Section 5.2) for a family of five [2]. It is important to mention that for the reconstruction of bahareque and modern bamboo (guadua) structures, there are no provisions in the seismic design code. To this aim, CRQ has implemented a research program at the National Centre for the Study of Bamboo (Section 5.5). Recommendations concerning the seismic design and construction of modern bamboo structures should be produced and then enforced by local authorities, in order to improve the safety of structures and to promote the use of this natural material. However, a well designed and maintained modern bamboo house has a higher cost than a traditional bahareque house, although all the materials are produced locally and the cost is lower than for reinforced concrete.

The Government has planned to give to each family made homeless compensation funds of US$2,000. Very few householders had insurance or significant savings, so many will not be able to afford to reconstruct well-built homes.

The National Federation of Coffee Growers made US$20 million available for the reconstruction of the rural areas in the coffee growing region, including the activities of rural tourism that are important to 1,500 farms in the area [6]. A National Fund was created for the reconstruction of the coffee-growing region headed by Luis Carlos Villegas (Executive Co-ordinator of the Presidency) [5]. A plan for long-term low interest credit was implemented for reactivating the coffee growing region. FAO supported producers and workers in the recovery of the coffee growing installations [5].

Although the reconstruction will give a welcome boost to the construction industry, it will be difficult for the authorities to keep control of standards, considering the large number of structures that will be built in a very short time. Companies from elsewhere will move into the area to take advantage of Government funding and consequently the whole economy of the area will change, creating an adverse effect by shifting the interest of workers from the more traditional and long term activity of coffee growing into the construction industry. In addition, contractors moving from elsewhere in the country may bring their own workforce, so that the people from the earthquake area, who have lost their jobs, will remain unemployed, while others from outside the region will benefit from the governmental funds.

6.6 Socio-economic problems

The UN Economic Commission for Latin America produced a report on 30 April to estimate the socio-economic aspects of the damage caused by the earthquake [13]. It was reported that at a national level the earthquake affected directly and indirectly 1% and 4% of the total population of Colombia. The total cost of damage was estimated at US$1.5 billion, with more than 90% quantified as direct costs. The most affected was the social sector, with 73% of the cost concentrated in housing. Losses in the production sector represented only 12% of the cost, while in the manufacturing sector the loss was only 1.2%. The damage to the environment, quantified in terms of loss of soil and forests due to landslides and the use of land to relocate affected people, for the deposition of debris, and for management of sanitary fills, amounted to US$3.2 million.

Although the damage represents only 2.2% of the GNP of Colombia for 1998, it is estimated that the indirect losses due to the alteration of the economy of the country will amount to 17% of Colombian exports for 1999, representing 10% of the gross economic growth [13]. The indirect economic effects of the earthquake will last for a period of at least four to five years.

It was estimated that of 35,000 displaced families, one third had left or moved with family and friends, another third was living in damaged homes and the final third (about 68,000 people) were still in need of temporary shelters during the weeks following the earthquake [14]. Food and non-food packages for 20,000 families (approximately 130,000 people), and 1,000 pre-fabricated homes were needed for the first three months following the earthquake. Assistance in health educational programs (to prevent epidemics) and psychological support (especially to children) was a priority during all the emergency phases.

The region, highly dependent on agriculture and related services, suffered a loss of 50% of the homes of small farmers, and large coffee estates were damaged. Heavy rains threatened the coffee harvest, which was due to start in the month of February. Unemployment, at 12.1% before the earthquake, rose to 34.3%, with 87,000 people without work in Quindío. To aggravate the problem, urban dwellers started moving to small rural towns, that were unprepared to receive the new influx [15].

As a step towards solving the unemployment problem, the President of Colombia signed the Pacific Coast Railway project, that will generate 6,900 new jobs in the Departments of Valle del Cauca, Risaralda and Quindío. The reconstruction of the coffee growing area will reactivate the employment sector, generating, according to government predictions, 140,000 direct and indirect jobs. In Armenia alone, it is anticipated that 30,000 direct jobs will be created [6].

6.7 Conclusions

The earthquake of 25 January directly affected more than 200,000 people in the Departments of Quindío and Risaralda, with a death toll of 1,171 people and 4,765 injured. More than 50,000 structures were destroyed, with direct economic losses of US$1.5 billion. It is expected that the economy of the area will be affected for the next four to five years, with the highest impact on the activities related to agriculture and coffee production.

The emergency response was focused on three phases of action: the first phase of rescue and medical attention of the most affected people, a second phase of provision of relief items such as food and temporary housing and psychological assistance to pregnant women and children, and the third phase of rehabilitation through social programs and reconstruction of infrastructure and housing.

The immediate action of the government, through the allocation of special funds for distribution of relief items, and the presence of the military police for controlling the riots that arose during the first week following the earthquake was essential in handling the crisis. Furthermore, the presence of the Red Cross and of international agencies such as the United Nations and the Pan-American Health Organisation played a crucial role in assisting the most affected families, by co-ordinating the distribution of relief items and organising social programs.

It may be concluded from this earthquake that it is important have in place local agencies capable and prepared for managing disasters and to plan, at city level, the mitigation of seismic risk through technical planning, education and public information. In the event of large scale disasters, it is also necessary to rely on the support and participation of institutions at a national and international level.

6.8 References

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Figure 6.1: Arrested looters in Armenia (La Tarde newspaper, 1 February 1999, Bogotá)

Figure 6.2: Make-shift shelter in the central square in Barcelona

Figure 6.3: Demolition of damaged buildings in Armenia city centre

Figure 6.4: Piled debris in Armenia city centre

7 OTHER EFFECTS OF THE EARTHQUAKE

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7.1 Performance of bridges

7.1.1 Road bridges

The area of the earthquake, being in the foothills of the Andes Mountains and having a high rainfall, is crossed by numerous small rivers, often in steep-sided valleys. There is therefore a significant number of bridges over these rivers. There is now no railway in the area and there are no significant pipe bridges, so all of the bridges over the rivers carry roads. It being a predominantly rural area, the majority of the bridges were the only crossing points of the rivers for a considerable distance.

There was no damage observed or reported on any road bridges in the area, despite the major damage to buildings and widespread landslides. This could be in part due to some provision for seismic loading in their design, even for the bridges constructed before 1984, although many of the bridges did not appear to be well maintained.

The majority of the road bridges were of reinforced concrete of a very similar design. Many were single span of approximately 20m at right angles to the river, for example as over the River Quindío on the road between Armenia and Calarcá (Figure 7.1). Others were of multiple simply supported spans of a similar design, for example the two-span bridge in Pijao (Figure 7.2). There were three similar bridges on the main road between Pereira and Armenia, and several more in the area. The largest bridge of this type is the four-span bridge over the River Quindío to the south of Armenia near Barcelona, carrying the main east-west through route across the region (Figure 7.3). This bridge is slightly curved on plan (Figure 7.4), but it is otherwise very similar.

For the bridges of this design there were four longitudinal beams of approximately 1.5m depth and 0.3m width carrying a 7m wide carriageway on a 0.3m deep concrete deck. In most cases the beams were cast in situ but in some cases shaped precast beams were used. The beams sat directly on the abutments and piers with no bearings or expansion joints, but apparently with no definite connection. Taking them to be simply supported, the fundamental natural frequency (vertical bending mode) of the single span bridges has been calculated to be approximately 8Hz. For the multiple span bridges the first transverse natural frequency would also be around 8Hz for 4m high piers, dropping to about 4Hz for 6m high piers. Thus, for the single span bridges and those with short piers their natural frequencies were above the range of frequencies of significant excitation, except for on the soft soil in Armenia (Section 2.6). Only for the bridges with higher piers would there be significant excitation of their first mode in the transverse direction.

Although, as stated, the majority of the bridges over rivers were of concrete, there was a small number of single span steel plate girder bridges, for example in Pereira (Figure 7.5), close to the cable stayed bridge mentioned below.

All of the above bridges were in the bottoms of valleys, where the depth of the poorly consolidated volcanic material was less than elsewhere (Section 2.3), and there would not be any significant amplification of ground motion due to topographical effects. There are some alluvial gravels and sands in these valleys but they are of shallow depth so the bridge foundations should not be supported on these. The seismic excitation at the locations of these bridges is therefore likely to have been considerably less than elsewhere in the affected area. This is supported by the observation that there was very little damage observed in the vicinity of any of these bridges, with the one exception of the bridge in Pijao, where it is thought that many of the buildings may have been built on alluvial deposits (Section 3.2.1). Also, this particular bridge has just two spans and a relatively short central pier, so its first natural frequency would be quite high, above the range of frequencies of significant excitation.

There are few road bridges in the area other than those over rivers, although in Pereira there were a few overpasses at major road junctions. One similar bridge had recently been constructed, but was not yet open to traffic, in the south-west of Armenia (Figure 7.6). This was of a similar size to the single span river bridges and was also of concrete, but it was of higher quality construction. Precast shaped beams were used and there were bearings at the abutments (Figure 7.7). There was no observable damage of the bridge, although in this case it was in an area with substantial damage to buildings, as seen the foreground of Figure 7.6. The similar bridges in Pereira also were undamaged, but there was little damage to buildings adjacent to them either.

One major bridge in the area was the steel arch bridge just to the south-east of the centre of Armenia (Figure 7.8). It carries the main road from Armenia to Calarcá and the mountain pass at La Línea over the deep valley of a small tributary to the River Quindío. It has a main span of approximately 100m, with two side spans each of half this length. Slender concrete piers support the steel arch form the valley floor. Again there was no observed damage, although there was evidence of slope instability adjacent to the bridge on the Armenia (west) side, and there was serious damage to buildings in Armenia within a few hundred metres. The small approach bridge on the east side over a road (Figure 7.9) is similar to the single span river bridges, except it has a significant skew and it has more longitudinal beams. Again it experienced no damage.

7.1.2 Cable-stayed bridge in Pereira

The largest bridge in the affected area is the cable-stayed bridge crossing the valley of the Otun River to the north-east of the centre of Pereira, towards the industrialised town of Dosquebradas (Figure 7.10 & Figure 7.11). It carries a dual carriageway and has a main span of 210m, with a concrete deck supported on steel plate girders. The bridge did not suffer any damage in the earthquake, nor did the approach viaduct on variable height piers on the south-west side of the bridge (Figure 7.12). The bridge was under construction during the earthquake in Pereira in 1995, at which time the pylons and part of the deck had been erected, but again no damage was caused then.

The cable-stayed bridge is of particular interest since it is the only known instrumented structure in the earthquake region, with 29 accelerometers installed on the superstructure [1]. Also, there are at present very few records of the behaviour of cable-stayed bridges in actual earthquakes world-wide.

The peak ground acceleration recorded at the base of one of the pylons was 0.175g and analysis of the records from the superstructure yielded, for the first mode, a natural frequency of 0.488Hz and a damping ratio of 1.5% of critical [1]. Although this level of damping is higher than is typical for cable-stayed bridges for low amplitude wind-induced vibrations (around 0.5%), it is somewhat lower than the value of 5% generally assumed for seismic design. However, the results are consistent with a recent study of data from the Suigo Bridge, Japan, in an earthquake with peak ground acceleration of 0.12g, for which damping ratios of 2% and lower were found [2]. The results from these two bridges suggest that the common assumption of 5% damping for the seismic design of cable-stayed may be too high.

7.1.3 Footbridges

The only observed damage to any bridges was to three footbridges over roads in Armenia, all of the same design (Figure 7.13). They all suffered the same type of damage, indicating a fundamental flaw in the design. They were clearly very recently constructed, and indeed at least three more of the same design were under construction elsewhere in the city.

The bridges had precast prestressed T-beam decks with end details as shown in Figure 7.14. The bearings were designed to allow longitudinal movement, apparently at both ends of the deck. Shear keys were intended to limit the displacement both longitudinally and transversely. Since the deck was not fixed relative to the piers, it was able to slide and impact the shear keys, causing failure. The damage on one bridge was as shown in Figure 7.15, where there had been longitudinal displacement causing failure of the shear keys on one pier on both sides of the deck. On another bridge of the same design the failure was similar, but this time in the transverse direction and at both piers (Figure 7.16). A third bridge experienced the same type of failure in the transverse direction.

It is interesting to note that in each case the direction of relative displacement coincided with the direction in which the steps led up to the platform on the pier. This would indicate that the failure may have been associated with the additional stiffness in that direction from the steps. This emphasises the importance of the stiffness of secondary elements, such as stairs, which may not have been considered in the original analysis.

Fortunately, in all cases the shear keys, although badly damaged, did in fact restrain the bridge decks from falling off the piers.

The one other footbridge seen in Armenia, close to one of the bridges described above, was of a different design. It did not have the movement joints, and suffered no damage.

7.2 Lifelines

The infrastructure of the Departments of Quindío and Risaralda was severely affected by the earthquake. The damage to electricity supply, water distribution, sewerage, telecommunications and transport networks is described in detail below. There was no damage related to gas pipelines, as the little gas used in the area is distributed by tanks.

Although some public services were re-established within a week of the earthquake, most of the infrastructure was still not completely restored one month later.

7.2.1 Electricity supply

The supply of electric power was affected by the failure of equipment at substations and the collapse of electricity poles along the streets. Most of the problems were solved within two weeks of the earthquake [3], by re-routing and using services of other sub-stations. By 3 February it was reported that 80% of Armenia had access to electricity [4].

Armenia was for several days without electricity in the central and southern parts [5], due to damage to the Regivit substation, operational at only 50% capacity during the week following the earthquake [6]. Members of the team visited the substation and confirmed that one of the transformers, mounted on wheels and supported on reinforced concrete walls 1.2m high, had tipped down in the transverse direction (following the axis of the wheels). This was due to shearing of the edge of the wall. The electric transformer replacement is shown in Figure 7.17, where the damage to the concrete wall can be seen to the bottom right. No measures to prevent similar failures had yet been adopted at the time of the visit, however it is recommended that the thickness of the concrete wall be increased, with inclusion of shear keys to provide restraint in the transverse direction. In addition, one of the ceramic electrical isolators, mounted vertically over a steel structure, sheared off at the base (Figure 7.18).

Damage to electric distribution lines was reported in the towns of Filandia, Montenegro, Circasia, Pijao, La Tebaida, Córdoba and Salento [7,8,9].

In the city of Pereira it was reported that the electricity supply was interrupted immediately after the earthquake but within days the service was operational at full capacity [6,9].

7.2.2 Water distribution and sewerage

Water distribution suffered many problems due to the damage inflicted by the earthquake, associated with failure of the power supply and damage of treatment plants and of distribution pipes. It is important to note that the damage caused to the house intake connections was responsible for many of the problems associated with the disruption in service. Being an integral part of the water distribution system, the house connections should have been checked by the water company to function properly in the event of an earthquake.

The city of Armenia was for several days without potable water in the central and southern parts [5], while it was only available in a few neighbourhoods in the north [9]. The sewerage system in the south of the city was severely damaged and as a result part of the town became rat-infested [4]. By 3 February, 65% of the city had access to a water supply [4] while by 12 February, 90% of the damaged distribution pipes were repaired [3]. Where the water service was not restored water trucks made regular distributions after the first few days [10].

Damage to the water supply system was reported for most of the towns of Quindío and debris often blocked the road drainage system [3,8,9,11,12,13]. The main distribution pipe to Barcelona, was reported severely damaged [9,13]. The treatment plant suffered severe damage in Pijao [7].

In the city of Pereira there was also significant damage to the water distribution system. On 31 January it was reported that the main distribution pipe was at risk from potential landslides [5,13]. The service was almost completely restored to the entire city two weeks after the earthquake [6].

7.2.3 Telecommunications

The telecommunication system went out of service due to damage of the structures housing the communication centres. The Telecom building in Armenia was reported partially damaged [9] and the central and southern parts of the city had no service for several days [5]. The Telecom office of Córdoba suffered severe damage [7], while telephone communication with the city of Caicedonia was practically impossible six days after the earthquake [9]. Telephone services were restored three weeks after the earthquake [3], with the mobilisation of special mobile equipment and temporary satellite communication stations [11]. In the experience of the team the mobile phone service was operational throughout the area two weeks after the earthquake.

7.2.4 Roads

In the days following the earthquake many roads in both rural and urban areas were blocked. Most rural roads became impassable due to landslides that occurred either at the time of the earthquake or later due to heavy rain and aftershocks, affecting slopes destabilised by the initial earthquake. The affected stretches of roads are shown in Figure 3.1. These landslides significant hampered the emergency operation (Section 6.2). In Armenia, for the first few days following the earthquake many streets were blocked by collapsed buildings and the debris of demolished structures, further inhibiting emergency access [5,9]. By 12 February the main roads were mostly cleared, but access to some rural areas was still difficult due to landslides still partially blocking many roads [3].

The road to the east of Armenia and Calarcá through the Cordillera Central mountains to La Línea was blocked by 15 landslides [9]. This pass carries the main road from Bogotá to the south-west of the country, including Cali and the main Pacific port of Buenaventura. It also forms part of the north-south Pan-American Highway [7]. The road was blocked for at least two weeks following the earthquake, having a significant economic impact on the whole country.

There were some landslides near Filandia that blocked the Pereira-Armenia road [9], with still only one lane open on some stretches of the road two weeks after the earthquake. Fortunately the Cali-Pereira and Cali-Armenia roads remained functional after the earthquake [9]. On the Calarcá-Armenia road two cars were buried by landslides on the day of the earthquake [9].

Road access to Pijao was completely severed (Figure 7.19) and was only partially restored on the afternoon of 28 January [7]. The main road to the town was cut into the side of a very deep steep-sided valley. In a distance of about 20km, approximately 15 landslides had blocked the full width of the road and 40 more had covered one lane. Also two gabion retaining walls below the road had partially failed, causing the edge of the road to fall away (Figure 7.20). The only other road to the town still remained blocked three weeks after the earthquake. Road access to Córdoba was also affected by 15 landslides of 50 cubic metres [7].

7.2.5 Airports

Flights from Armenia airport, close to La Tebaida (Figure 1.2), were suspended following the earthquake due to problems with the control tower and damage to the terminal structures [5,9,14]. The runway did not suffer any damage, so service was restored for emergency flights after two days.

The airport at Pereira suffered only minor damage, and suspension of services was only brief [5,9]. No damage was reported affecting the runaway.

7.3 Public infrastructure

7.3.1 Fire and police stations

Fire and police stations were severely damaged by the earthquake. Most of the structures were of old design, prior to the enforcement of seismic codes, with soft storeys at the base floor for permitting the entrance of fire and police equipment. This resulted in complete collapse of some buildings due to the formation of a soft storey mechanism.

In the city of Armenia the fire station collapsed completely (Figure 7.21), causing the deaths of eight firemen. The fire station was a three storey reinforced concrete structure of pre-1984 construction. It had previously been identified as vulnerable, but no action had been taken to improve it. The central block of the police station in Armenia also collapsed and there was significant damage to the remaining two wings (Figure 7.22).

The police and fire stations in the towns of Pijao and Caicedonia also suffered severe damage, as did the municipal buildings in Pijao, La Tebaida, Córdoba and Quimbaya [7,9,14].

The fire station at Caicedonia, a three storey reinforced concrete construction with infill walls, was damaged at the beam-column joint at the third storey, causing the failure of the central 0.6 m diameter circular column. Some infill walls were severely damaged and will have to be demolished, but the structure was not evacuated [9].

The Pereira fire station, a three-four storey reinforced concrete structure with a steel front canopy, remained in good condition except for some minor masonry cracking (Figure 7.23). However, the open plan ground floor may have made it vulnerable had the earthquake excitation been greater at this location. It acted as well co-ordinated centre for disaster management for the city.

7.3.2 Hospitals

The hospital infrastructure suffered major damage: of 15 hospitals surveyed in the Departments of Quindío and Risaralda, seven became inoperational, and overall 18 health centres were destroyed in the region [3]. Although most of the hospital buildings were designed before enforcement of seismic codes, their structural damage was often less than for other types of building, probably because of the higher factors of safety adopted in their initial design. Nonetheless, in many cases the damage was sufficient to render the hospital infrastructure inoperable, forcing their closure to the public (Figure 7.24). It is important to note that under the new seismic regulations of 1998 these structures are required to be upgraded to the new standards; in fact the main hospital in Armenia had been partially retrofitted prior to the earthquake [5]. It normally provided 303 beds with 90 physicians [6], but had to be partially closed due to lack of water and non-structural damage that prevented its functioning at normal capacity [9]. It was being retrofitted by means of external moment frames being added to the main structure (Figure 7.25 & Figure 7.26) and by jacketing of internal columns, but work had stopped in December 1998 due to lack of funds.

A large percentage of health centres was also affected, and some had to be evacuated and partially or completely demolished [11,14]. In Calarcá the hospital was reported severely damaged, with the exception of the emergency area. A temporary hospital was installed in the stadium [9,13]. In the town of Circasia the hospital collapsed [9], while in Pijao 60% of the hospital collapsed and the Red Cross building suffered severe damage [7,8]. The hospital in Córdoba was reported to have suffered severe damage [7,9]. The hospital in Barcelona did not suffer significant damage.

In Pereira there was only minor damage reported to the hospital infrastructure [14].

The hospital in Caicedonia was affected in certain sections, through cracking of infill panels and the collapse of the front wall, apparently out of plane. However there was no need for evacuation [9].

7.3.3 Schools

A large number of schools (about 75%) were damaged by the earthquake, forcing children out of school for long periods of time [5,8]. The importance of these numbers cannot be disregarded, as a disruption in the education of children can have long lasting effects. As explained in Chapter 6, UNICEF was present to attend the needs of children following the earthquake, implementing social programs to re-integrate children into school activities as soon as possible.

In Armenia 35% of public schools were severely damaged [11], with medium to minor damage in the towns of Córdoba, Alcalá and Caicedonia [7,9].

In the town of Pijao the school suffered cracking of columns at the level where the masonry infill stopped to make way for windows (Figure 7.27).

Ten schools were reported affected in Dosquebradas, adjacent to Pereira [9].

7.4 Industrial facilities

Most of the industrial facilities in the area were located in Pereira and Dosquebradas. It was difficult for the EEFIT team to survey damage, as permission was seldom granted to enter these facilities. What was evident was that most of the infrastructure dated from before the enforcement of seismic codes and had the ground motion been stronger in the area, the damage and the economic impact of the event would had been much greater.

In Dosquebradas five industrial facilities were reported damaged. On 29 January the food processing plant La Rosa, and Industrias Confecciones Nicole reported closure due to damage, with approximately 300 employees temporary dismissed [9].

Figure 7.28 shows damage at the top of columns below the beam-column joint at the second storey of an industrial facility in Dosquebradas. The enlargement of the cross-section at the column end was typically used for shear strength enhancement in the pre-1984 structural designs.

7.5 Conclusions

There was no observed damage to any road bridges in the affected area. For the majority of bridges, which were small reinforced concrete bridges over rivers, this was believed to be due to the lower amplification of ground motion in their vicinity and their relatively high natural frequencies. The two larger bridges in the area, the steel arch bridge in Armenia and the cable-stayed bridge in Pereira, also suffered no damage.

The cable-stayed bridge was instrumented, and analysis of the data has indicated a lower damping ratio than is typically assumed for seismic design. This suggests that the usual assumption of 5% critical damping should be reassessed. Since records of the response of cable-stayed bridges in earthquakes is rare, the data from this bridge may be worthy of further analysis.

Damage was observed to the shear keys at bearings of several footbridges in Armenia. This was due to a poor connection design allowing relative movement of the deck and abutment, causing impact of the shear keys. The effect of the additional stiffness of stairs leading up to the tops of the piers may also have been significant.

The infrastructure of the Departments of Quindío and Risaralda was severely affected by the earthquake. Immediately after the earthquake two-thirds of the city of Armenia was without electricity, which also led to failure of the water distribution system. The emergency operation was impaired by the collapse and damage to fire and police stations, as well as by damage that rendered many hospitals and health clinics inoperable. Furthermore, the lack of water aggravated the problems of the spread of diseases. The airports were immediately closed after the earthquake, with damage reported to some structures, making the arrival of aid by air difficult on the first two days following the earthquake. The main road connecting Armenia with Bogotá was blocked by landslides and the town of Pijao, severely damaged by the earthquake, remained inaccessible for several days. The city centres were also inaccessible, due to the blocking of streets by the debris of collapsed buildings. Telecommunications were also seriously damaged, making the planning of the emergency activities more difficult. Lastly, the school system was severely damaged, causing a long-term problem for the education of children in the region.

The industrial facilities suffered some damage, and it is expected that in the case of a larger event, there would be large economic losses, as these structures are of non-seismic design and have accumulated damage from several earthquakes in the past.

7.6 References

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Figure 7.1: Single span concrete bridge over River Quindío on Armenia-Calarcá road

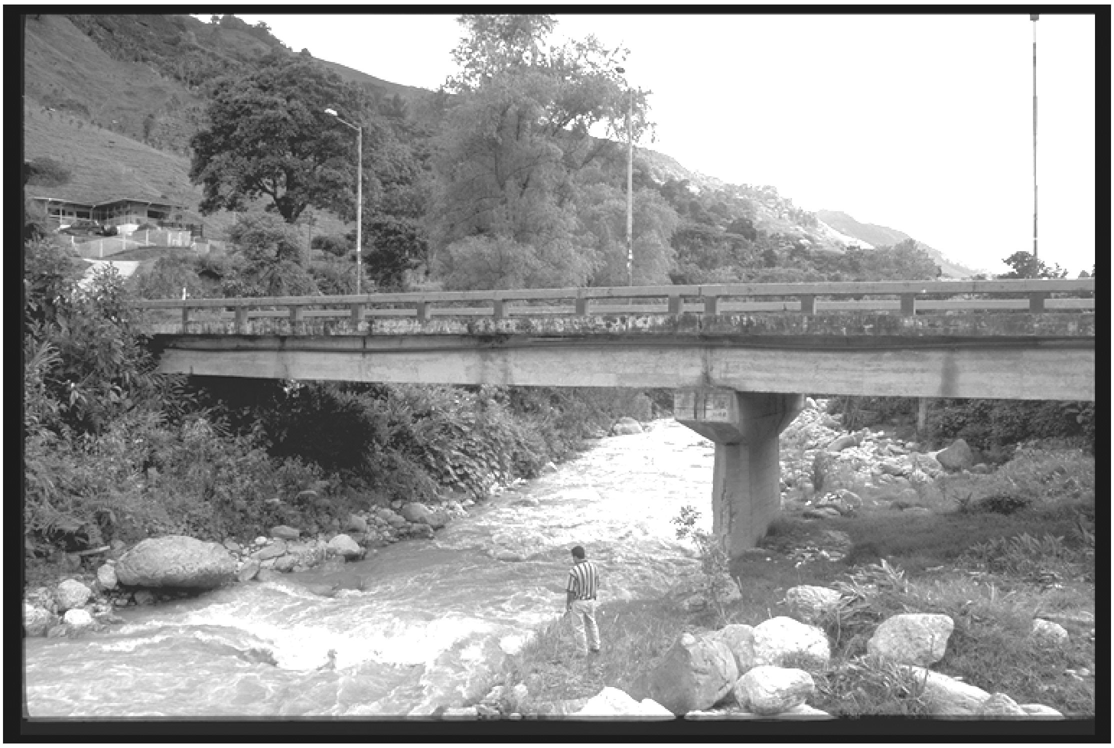

Figure 7.2: Two span concrete bridge in Pijao

Figure 7.3: Four-span concrete bridge over the River Quindío south of Armenia

Figure 7.4: Above bridge, showing curve

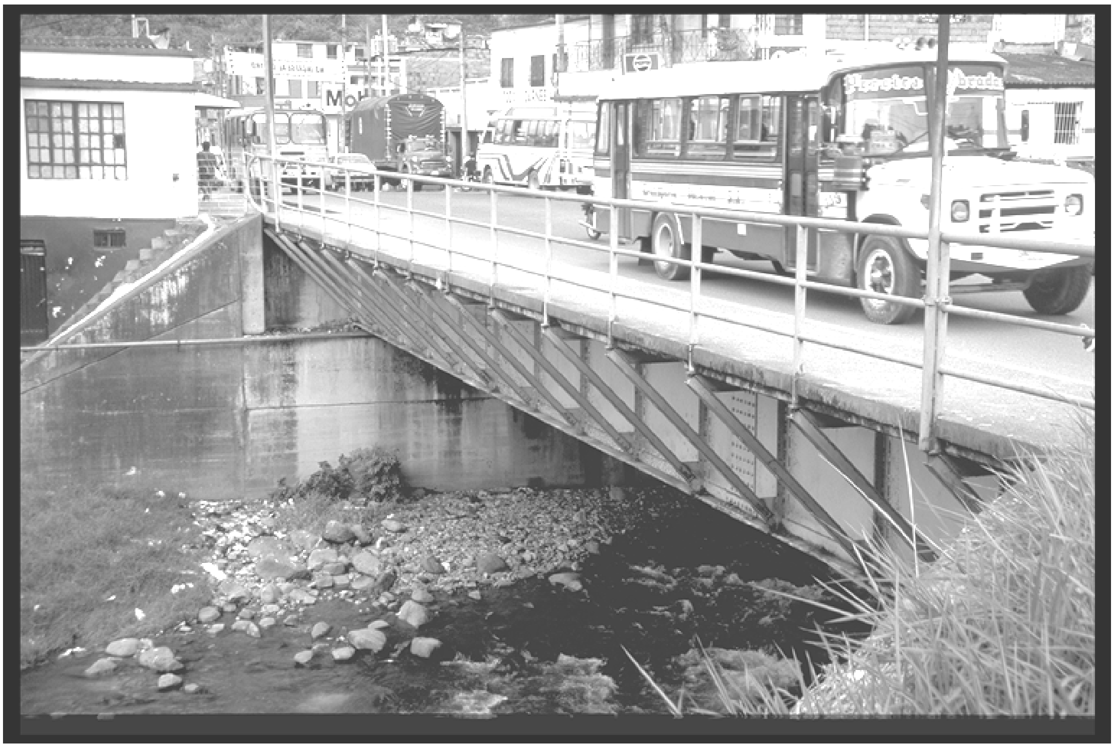

Figure 7.5: Single span steel plate girder bridge close to cable-stayed bridge in Pereira

Figure 7.6: Concrete overpass recently constructed in Armenia

Figure 7.7: Detail of above bridge

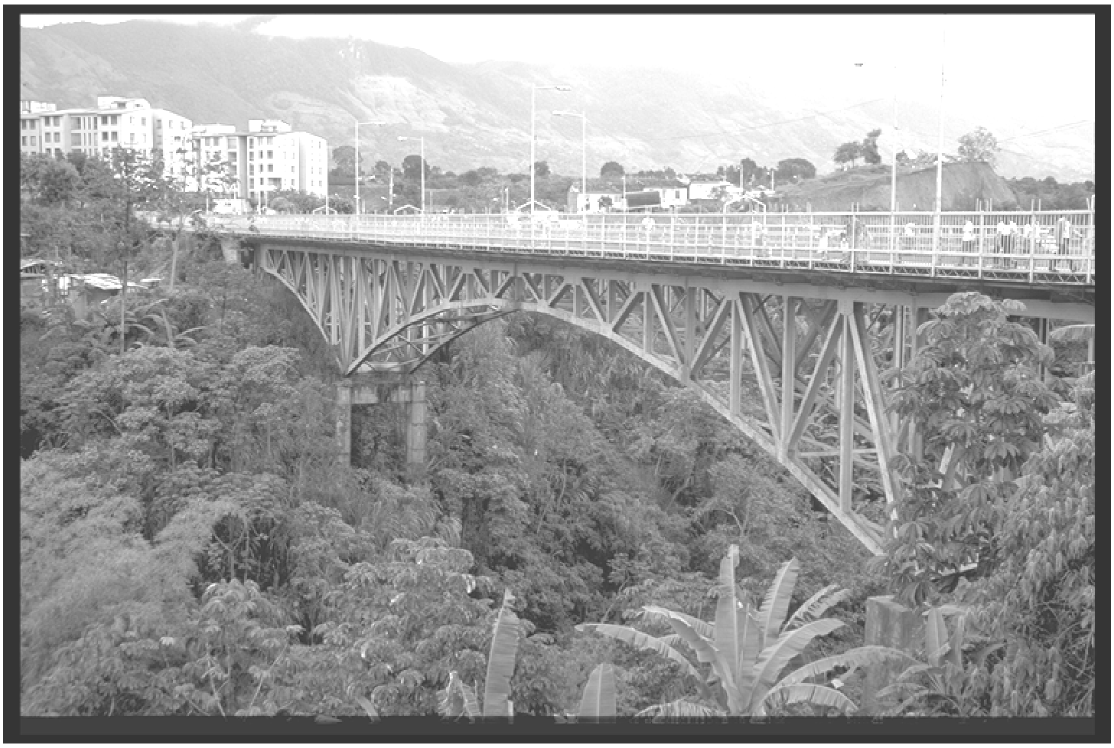

Figure 7.8: Steel arch bridge in Armenia

Figure 7.9: Approach bridge to above bridge

Figure 7.10: Cable-stayed bridge in Pereira

Figure 7.11: View of Pereira cable-stayed bridge from north

Figure 7.12: Approach viaduct to Pereira cable-stayed bridge

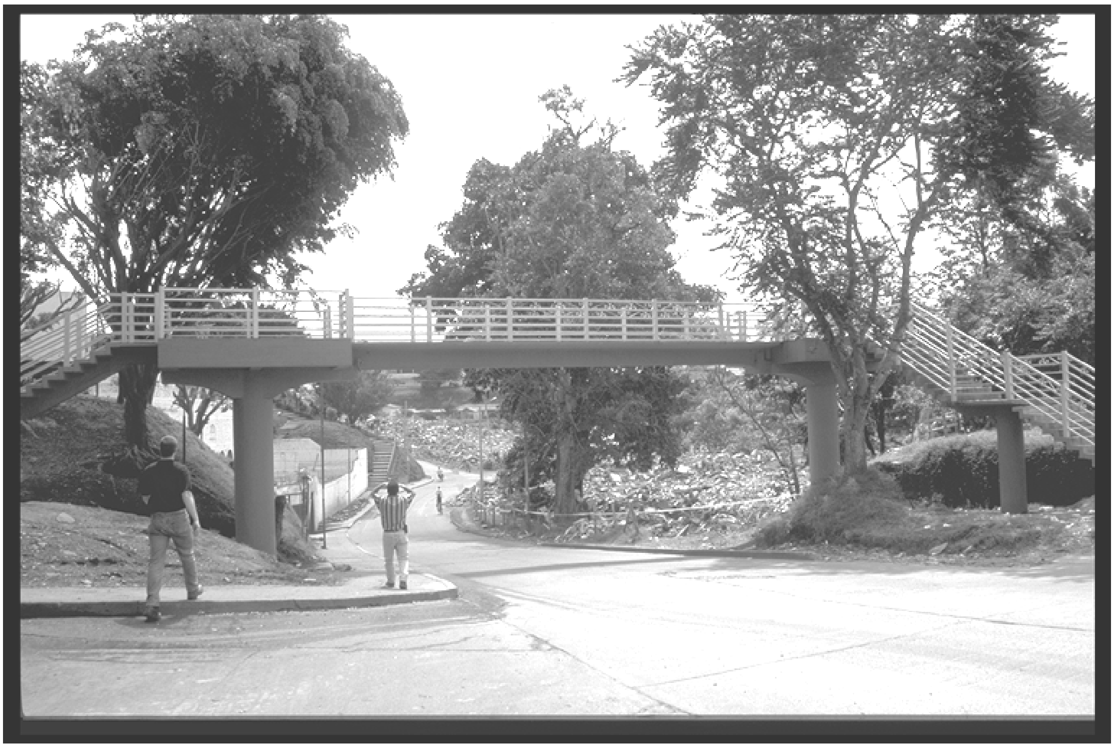

Figure 7.13: Damaged footbridge in south-west of Armenia

Figure 7.14: Undamaged shear key detail

Figure 7.15: Detail of footbridge shear key damage – longitudinal displacement

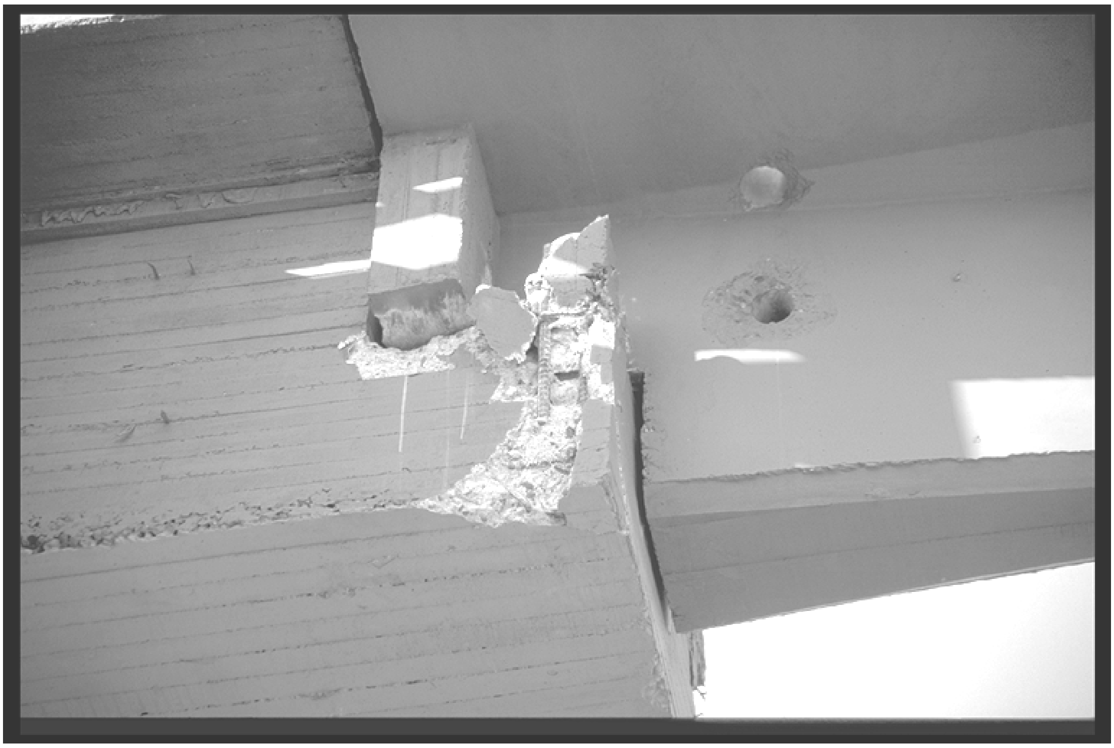

Figure 7.16: Detail of damage of similar footbridge – transverse displacement

Figure 7.17: Replacement of damaged electric transformer of Regivit substation in Armenia, with damaged concrete wall shown on the lower right

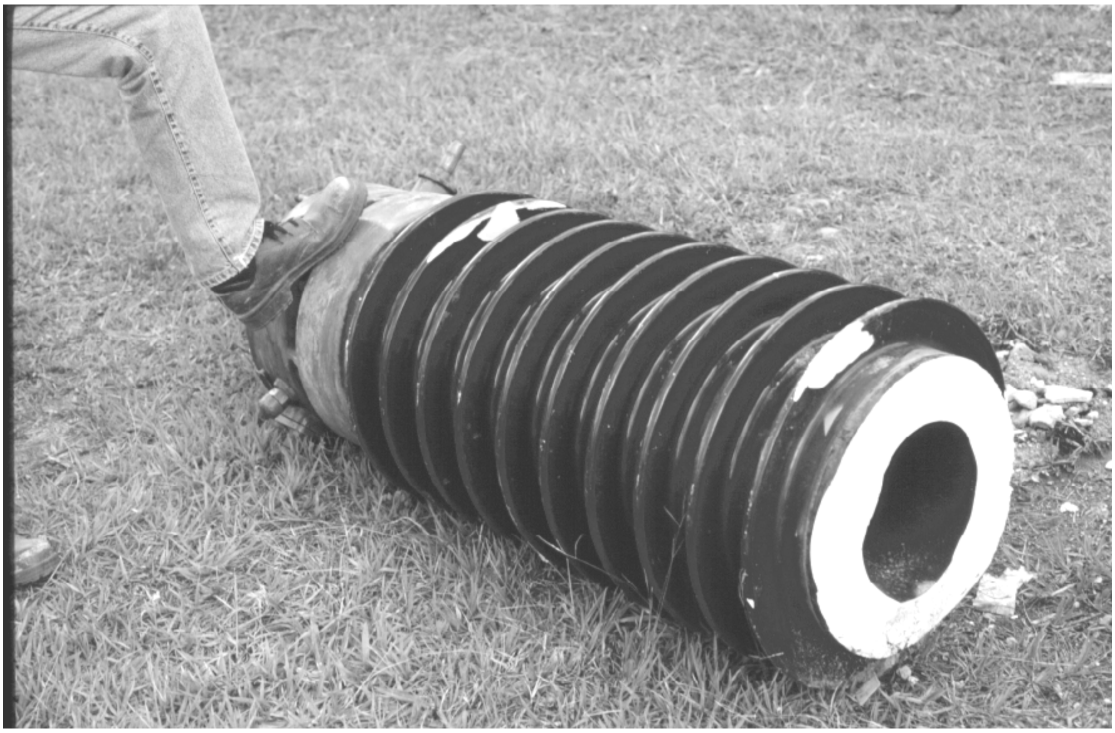

Figure 7.18: Ceramic electric isolator sheared off at the base at the Armenia Regivit substation

Figure 7.19: Landslides on the road to Pijao

Figure 7.20: Partial failure of gabion retaining wall on the road to Pijao

Figure 7.21: Collapse of Armenia fire station, showing heavy damage to equipment

Figure 7.22: The police station in Armenia. The central block (centre of photo) had completely collapsed.

Figure 7.23: The fire station in Pereira, which suffered very little damage

Figure 7.24: Hospital in Armenia city centre (pre-1984 design), closed due to non-structural damage after the earthquake

Figure 7.25: General view of Armenia main hospital, showing retrofitting work in progress

Figure 7.26: Retrofit detail of Armenia main hospital, showing addition of external frame

Figure 7.27: School in Pijao: Shear cracks in columns at top of infill

Figure 7.28: Failure of columns at the top of the second storey of a Dosquebradas industrial facility