CHAPTER 5

SAND LIQUEFACTION IN THE CENTRAL VALLEY INDUCED BY THE 1990 EARTHQUAKE

5.1 The 1990 liquefaction and historical records

A major secondary effect of the July 16, 1990 Luzon earthquake was the liquefaction of sands in a large elongated zone of the Central Plain. The phenomenon had a devastating impact in Pangasinan and Tarlac provinces (Fig. 5.1), where surface soil conditions are conducive to liquefaction.

Cohesionless saturated fine sandy and silty sediments near the ground surface are liable to liquefy under the effect of intense cyclic ground shaking. The pore-water pressure build-up caused in these soils by powerful earthquakes often results in the loss of shear strength and the transformation of the material into a liquidlike mass. The consequences for buildings and other structures in such a case are devastating.

Reconnaissance studies made after the quake showed that liquefaction-related phenomena such as sand boils, fountains, lateral spreading, cracks, fissures and differential settlement had been induced in various areas and isolated spots in the Central Plain west of the major and minor ground ruptures (Fig. 5.1). In addition to the catastrophic damage caused in Dagupan City in the Gulf of Lingayen, liquefaction also affected San Fernando in La Union Province and severely damaged Agoo and Aringay.

The Central Plain in general and the zone around Dagupan in particular are thought to have undergone liquefaction at least twice in historical times. Records are available because the Spaniards built churches all over the country, and soon had to face the tremendous problem of earthquakes. Their solution for minimizing damage was a new architectural style, known as earthquake baroque, consisting basically of buttressed architecture on a massive body structure with squat bell towers. Historical records indicate that two major quakes jolted the zone along Lingayen Gulf, in 1792 and in 1896. In both cases the tremors were felt from Baguio to Manila. Damage was particularly heavy in Dagupan City and environs where eyewitnesses reported sand-boils, fountains and cracks with the emission of water and sand. Major structures, including churches, were badly damaged.

5.2 Liquefaction and related damage in the Central Plain

The 1,500 sq. km strip (Fig. 5.1) affected by liquefaction, the numerous scattered liquefaction-related phenomena in Central Plain and the coastal area between Agoo and Bauang testify to the regional extent of this secondary short-range effect of the July '90 quake. The mid-Luzon tectonic depression, known as the Central Plain (about 30,000 sq. km), was filled with clastic sediments during the Tertiary and Quaternary. The uppermost part of the sequence, consisting of loose to very loose fine sand, reacted to the ground-shaking with liquefaction on a regional scale. Sand boils, lateral spreading, fountains and fissures were reported throughout virtually the entire Plain, even outside the major liquefaction zone. As in the Japanese town of Niigata during the 1964 earthquake

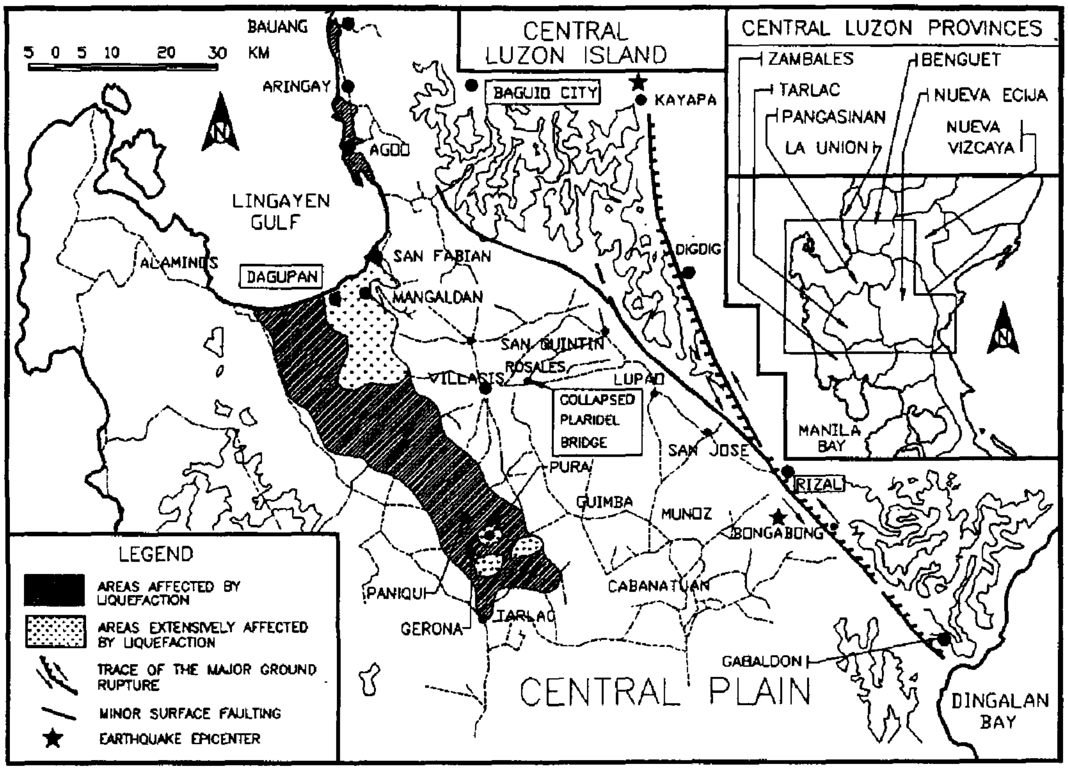

Fig. 5.1 – *Sand liquefaction in the Central Plain and the Agoo-Bauang area (adapted from Punongbayan and Umbal, 1990).*

(Seed et al., 1967), the uppermost sand layer in Dagupan City suffered severe liquefaction during the tremor. Many structures tilted and soon after the quake buildings looked as though they had been floating in a liquid.

According to eyewitness reports, fountains of gas and liquefied sand together with sand boils occurred soon after the beginning of the quake. The gas emissions can be attributed to the presence of decomposed organic matter at various depths within the sand layer, as it was confirmed by borings completed subsequently.

In the countryside near Dagupan City a number of Barangays (small villages) surrounded by water or located on river banks were reported to have subsided severely. Liquefaction in general occurred over a vast zone with an effect comparable to that recorded in Dagupan City.

Extensive liquefaction also explains the severe damage suffered by the road connecting Dagupan City to San Fabian through Mangaldan (Fig. 5.1). The rigid pavement of this road was deformed into an undulating strip several hundreds of meters in length with subsidence of the shoulder on the seaward side (both sides in some cases) ranging from 30 cm to 100 cm. Such behavior, which was also reported in Niigata, is attributable to the fact that the embankment under the rigid pavement acted as a floating shield preventing upward dissipation of the accumulated pore water pressure underneath. As a consequence of this local condition the pore pressure was dissipated along the foot-slopes of the shoulders on both sides of the road, thus resulting in the separation and sinking of the body of the shoulders. For a few months after the quake the cement concrete pavement exhibited marked waviness with a period of about 25 m.

The coastal road directly linking Dagupan City and San Fabian suffered the most severe damage. In some sections it was affected by multiple longitudinal cracks (10-30 m long and 50-90 cm wide) while in other zones the road embankment split into tilted blocks topped by portions of pavement still in place.

Intense liquefaction with sand boils, ground fissuring and subsidence occurred in Agoo, North of Dagupan. Similar phenomena were also reported near the cities of Tarlac, Gerona (collapse of the town hall due to sinking of foundations), Paniqui and Pura (Tarlac Province) where many houses tilted and subsided.

Along the MacArthur Highway, between Gerona and Tarlac, the central longitudinal joint of the concrete pavement separated 2 to 10 cm over a length of several kilometers, with a vertical difference of 5 to 10 cm due to faulting in some limited stretches. About 40 km SE of Dagupan the 650 m long truss of Plaridel Bridge in Carmen (Rosales) over the Agno River (Fig. 5.1) collapsed due to lateral spreading and loss of foundation bearing capacity. The occurrence of sand boils and long fissures was also reported by eyewitnesses along the riverbed which is mainly composed of saturated, loose to medium-dense, fine sediments). Liquefaction was also reported in Manila Port area (Wieczorek et al., 1990) and along the North Expressway leading to Angeles City.

5.2.1 Damage in Dagupan City

The most impressive liquefaction occurred in the commercial area of Dagupan City (Fig. 5.2), which is crossed by two major roads, Perez Blvd. and Fernandez Ave. Many buildings, bridges, road platforms and pavements, as well as electrical and sewerage systems suffered structural damage (top sketch).

In general the surroundings of Perez Blvd. and the zone to the south were hit catastrophically, while Fernandez Ave. was basically affected by severe sinking, the damage being significant in both locations.

The highest density of buildings is concentrated along and between these two roads (Dagupan City proper), the majority of constructions being two to three storeys high with a limited number of four to five storey buildings. In areas with scattered light one-storey concrete or wooden houses liquefaction was not so evident. There was also a significant bulging of the streets and numerous buildings sank and tilted in the most seriously affected part of the city, sand liquefaction being the major cause of foundation failures.

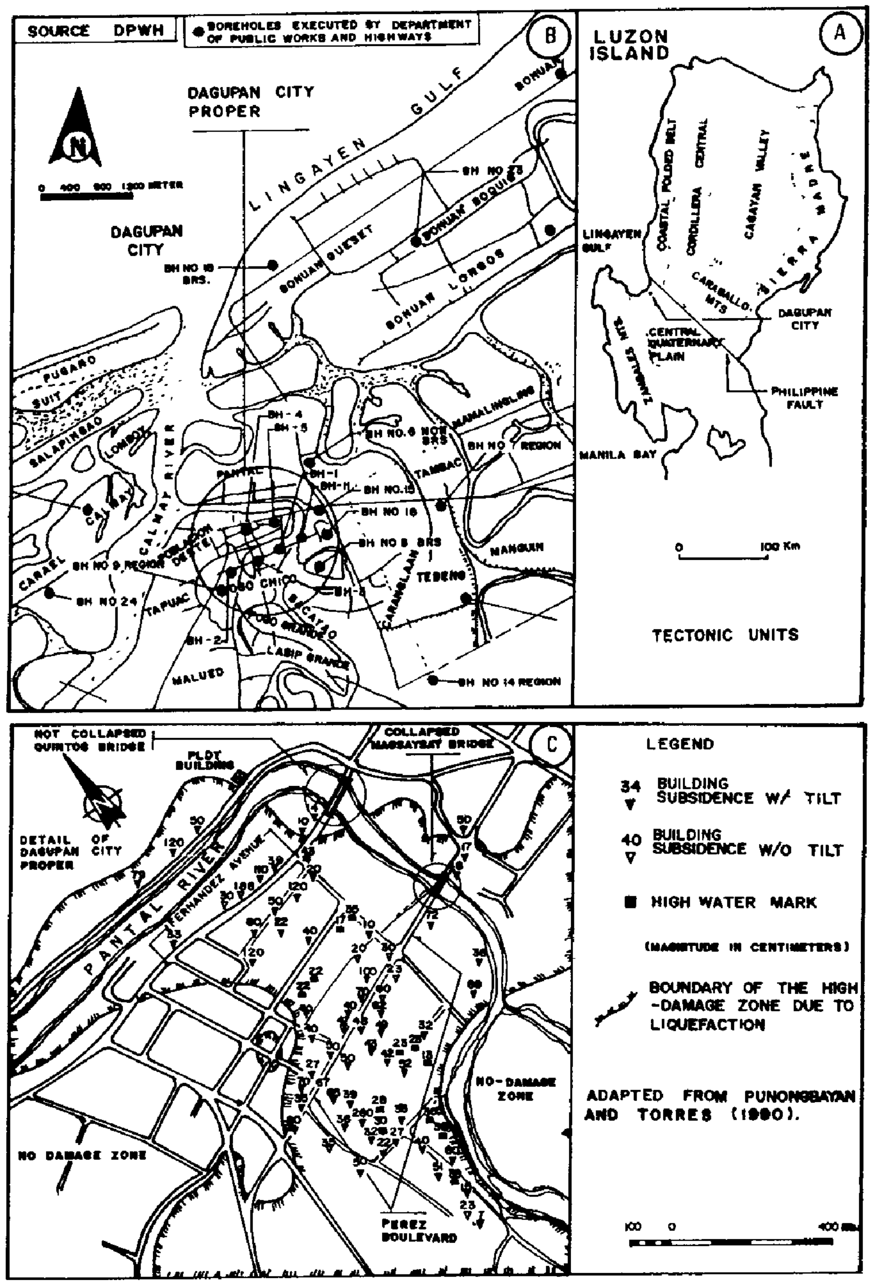

Fig. 5.2 – *Tectonic units in Luzon (A), overview of Dagupan City (B) and details of tilt and subsidence of major buildings in Dagupan City Proper (C). Adapted from Punongbayan and Torres, 1990.*

In Fernandez Ave. contiguous buildings underwent quasi-uniform sinking and moderate tilting for hundreds of meters on both sides of the road (Fig. 5.3, top). Figure 5.3, bottom, illustrates oblique and front views of new, well-kept buildings which suffered severe subsidence (140-180 cm) and tilting in Perez Blvd.

The lack of lateral support from adjacent structures was an essential factor for the severe tilting in Perez Blvd. of two isolated buildings (Fig. 5.4, top) in close sequence (non-uniform sinking 80-150 cm and tilting 12-14 degrees).

The most spectacular case, however, occurred in Perez Blvd. (Fig. 5.4 bottom, left), where tilting was estimated to amount to 15 degrees. The complete rotation and collapse of the structure was prevented by the next-door building. Heavy damage in general occurred in the area between the two major streets in Dagupan City proper, and some houses collapsed in Perez Blvd. Market.

Roads in Dagupan were catastrophically affected by sand liquefaction and the consequent bulging was the major cause of the destruction of the rigid pavement. The swelling of city streets was due to the light weight of the road structure compared with the heavier nature of the buildings. Figure 5.4, bottom right, shows a small truck which has sunk into the roadside due to road bulging and associated subsidence of the shoulders. Concrete pavements of houses and courtyards were disrupted almost everywhere.

Figure 5.5 shows the damaged pavement of the gasoline station on Perez Blvd. where the underground fuel tanks floated up.

Figure 5.6 illustrates Magsaysay Bridge on Perez Blvd., which collapsed during the quake. Four of the seven spans slid into the river, while the remaining three were significantly affected by the quake due to the tilting of the supporting piers. Lateral displacement of soils towards the center of the channel due to liquefaction was responsible for this tilting from the right and left banks towards the middle of the river. Figure 5.6 (bottom) shows the horizontal slip of concrete beams at the same site and the tilted sheet-piled cofferdam built before the quake with a view to widening the bridge.

In contrast, Quintos Bridge about 350 m downstream on Fernandez Ave. (Fig. 5.2) and structurally similar to Magsaysay Bridge suffered no damage. Besides the failure of building foundations and the bulging of roads, electricity poles were tilted and part of the power network in the city area was disrupted. Road bulging also affected the sewerage system.

Statistics for the City (Tokimatsu, Midorikawa and Tamura, 1991) as of July 31, 1990, indicate that 200 commercial and residential buildings were totally damaged and over 400 buildings partly damaged. More than 1,200 houses were destroyed beyond repair and about 6,000 houses partially collapsed. Figure 5.7 shows the damage statistics for about 120 reinforced concrete buildings in the area affected by the quake compared with the ones for Niigata as a result of the 1964 earthquake.

Over 90% of buildings were sampled between Fernandez Ave. and Perez Blvd. Only a few had piled foundations and about half of them tilted more than 1 degree in the liquefied zone. Figure 5.7 shows that both Dagupan City and Niigata were affected by similar damage. Differential settlement and lateral displacement of foundations in both cases were the major causes of failure.

Repeated visits to Dagupan City between 4 and 8 months after the earthquake showed that some buildings which first tilted during the July 1990 tremor continued to tilt for months finally being declared unsafe. This means that, under the unbalanced weight of already inclined structures, continuous uneven sinking persisted for a considerable period. A number of heavy structures affected by sinking and tilting were responsible for damage to nearby buildings. In some cases they leaned against them and in others they influenced the behavior of their foundations.

Adjoining buildings on both sides of the road were responsible for the bulging of streets and consequent damage to pavement and buried utilities After the quake large areas in Dagupan City and the surrounding countryside were inundated as a result of the dissipation of pore water pressure.

5.2.2 Damage in Pura City

The city of Pura in Tarlac Province, which is located east of the MacArthur Road about 4 km from Paniqui (Fig. 5.1), was also affected by the severe liquefaction of surficial sands. The damage to structures was not as spectacular as in Dagupan City, due to the smaller size of the city and the ab-

Fig. 5.3 – *Quasi-uniform sinking (150 cm) of contiguous buildings (top left) and uneven sinking and tilting (top right) on Fernandez Ave. Sunk and tilted buildings on Perez Blvd. (bottom), oblique and front views, with a differential settlement of 140-180 cm.*

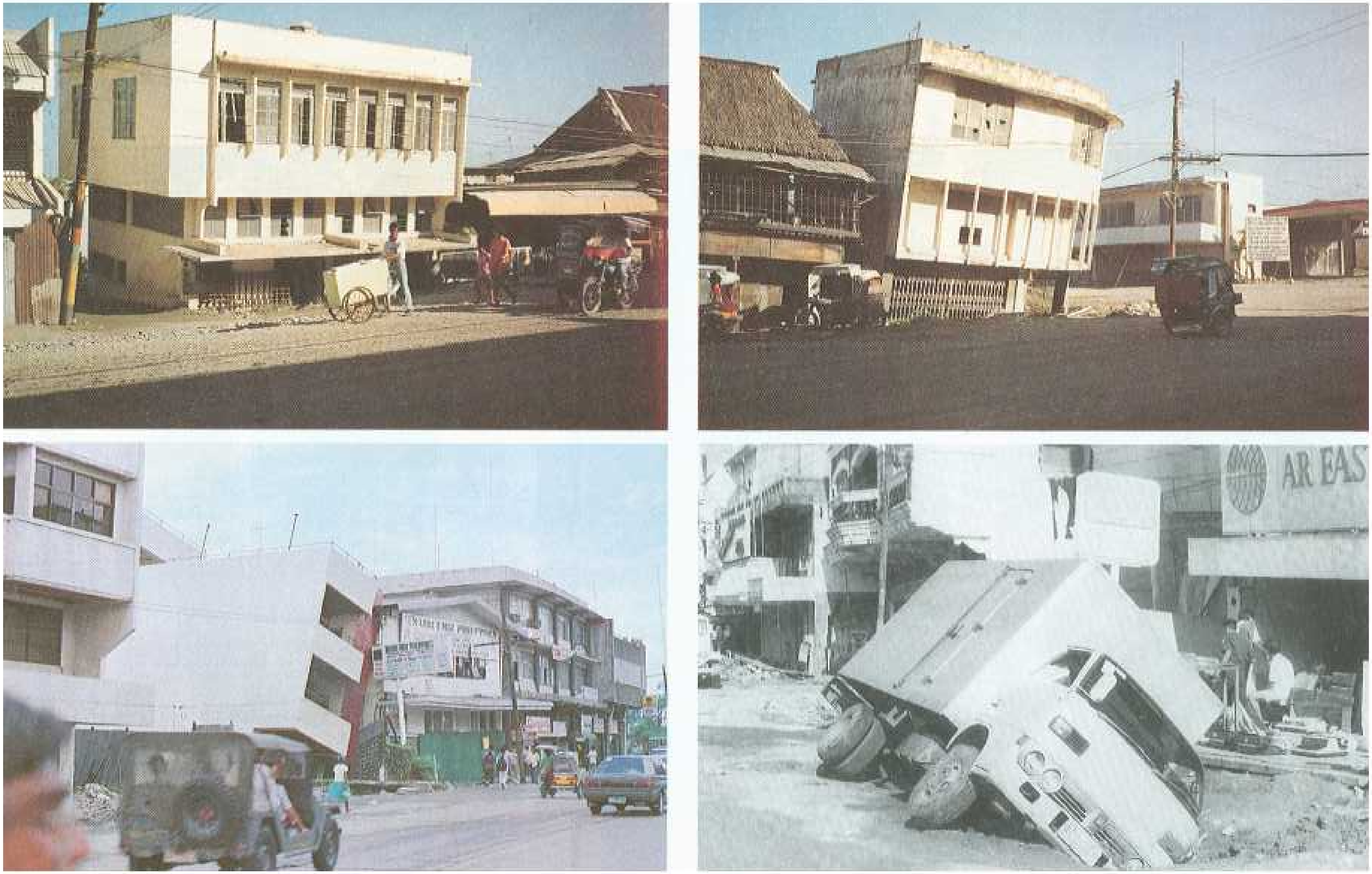

Fig. 5.4 – *Isolated consecutive buildings on Perez Blvd. which suffered 150 cm differential settlement towards the roadside (top). The tilting continued for months after the quake. Isolated tall building in Perez Blvd. (bottom left) with 15 degrees tilt due to severe foundation failure. Further rotation and collapse of the structure was prevented by the house next door. Truck sunk into the roadside (bottom right) due to road bulging and subsidence of the shoulder because of liquefaction (Courtesy of R. Punongbayan).*

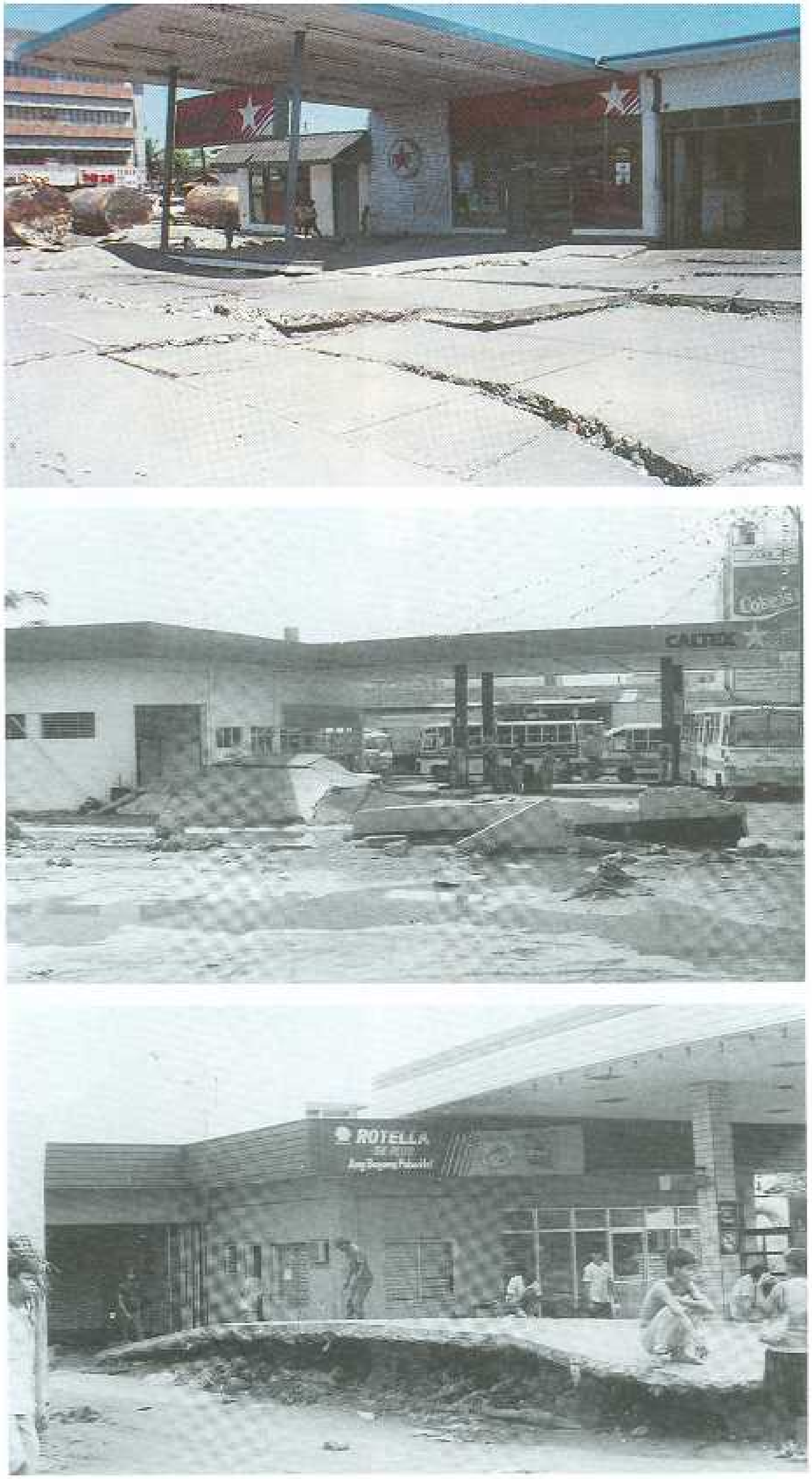

Fig. 5.5 – *View of the gasoline Station on Perez Blvd. (near the collapsed Magsaysay Bridge) where the cement concrete pavement was entirely disrupted by liquefaction and, locally, by the buried tanks floating up. Details of the upheaval of the pavement (center and bottom) due to the floating of tanks (Courtesy of R Punongbayan)*

Fig. 5.6 – *Collapsed Magsaysay Bridge seen from the left-hand river bank (top). Sunk and 12-degree tilted sheet-piled cofferdam (bottom). The horizontal displacement of concrete beams, due to lateral spreading and consequent tilting of the pier towards the center of the riverbed, exceeds 1 meter.*

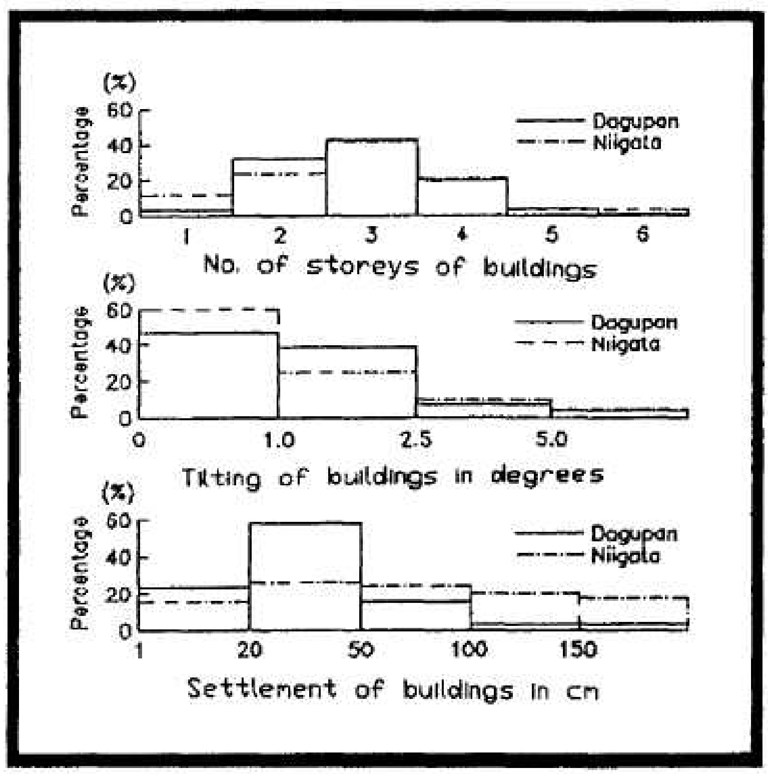

Fig. 5.7 – *Comparison of damage in Dagupan City during the 1990 quake with that in Niigata (Japan) as a result of the 1964 earthquake (Tokimatsu et al., 1991)*

Fig. 5.8 – Tilted houses in Pura City Proper (top). Isolated house outside Pura City with over 1.3 m of uneven settlement, and tilting and the bulging of the pavement inside the house (bottom).

sence of adjoining buildings over two storeys high. Eyewitnesses reported sandboils and fissures throughout the urban area.

The liquefaction of soils hinders the propagation of highly destructive shear waves. Thus, the damage to buildings and structures in general was mainly due to tilting and huge differential settlement, there being only a few signs of cracks, the concrete framework often remaining intact. Figure 5.8 shows some typical examples of tilting and differential settlement associated with the July 1990 earthquake. The road network was entirely disrupted, with long embankment undulations, longitudinal cracks and separation of shoulders.

5.3 Evaluation of the liquefaction potential in Dagupan City

Most of Dagupan City and the surrounding countryside facing the Gulf of Lingayen is a flat lagoon plain filled by loose sediments during the Quaternary (Fig. 5.1). Dagupan City, in particular, was built on a delta with some minor expansion zones created by land reclamation and construction of artificial cut-offs. Abandoned meanders of the Pantal River provide a useful indication of stream migration (Punongbayan et al., 1990; Torres et al., 1990) during the Quaternary (Fig. 5.9). The location of the old meanders coincides with the high-damage zone where severe liquefaction occurred. Loose deltaic deposits characterize the city area, the top sand layer (12-18 m) overlying more than 40 m of clay with silty sand intercalations The uppermost 4 m of sand may be locally replaced by clay including earthfill material. The water table is usually located at a depth of 1 to 1.5 m.

Figure 5.2 shows: sketch A) a map of the major tectonic units in Luzon, sketch B) the liquefied area in Dagupan City and the two most affected roads in the city proper, namely Perez Blvd. and Fernandez Avenue, sketch C) the detail of the area severely affected by liquefaction with data on building subsidence and tilt, and the location of the major city bridges (circled) on the Pantal River. The

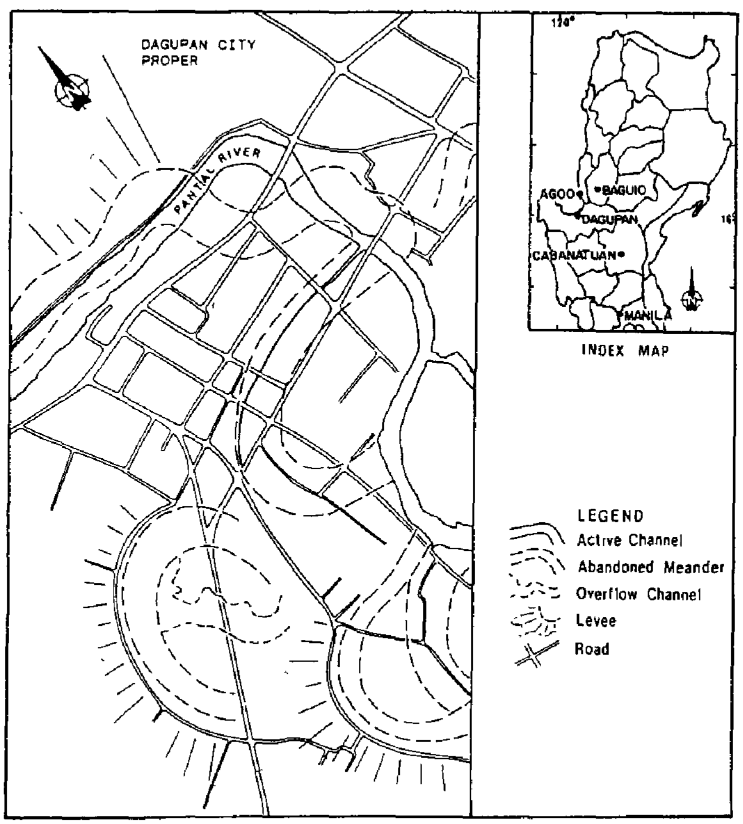

Fig. 5.9 – *Abandoned channels of Pantal River in Dagupan City Proper. The meandering of the river, during its Quaternary migrations, and the related deposition of fine sediments coincide quite well with the location of areas severely affected by liquefaction and high structural damage (Punongbayan and Torres, 1990).*

location of the PLDT building, which did not suffer any damage, is indicated northwest of the undamaged Quintos Bridge (sketch C).

Soil properties of the areas of the collapsed Magsaysay Bridge and the undamaged PLDT building were used for the calculation of the liquefaction potential. Figures 5.10 and 5.11 show the soil profiles, the damage zones and other relevant data along Perez Blvd. and Fernandez Ave.

In Perez Blvd., where the heaviest damage occurred, and in Fernandez Ave. which also heavily suffered the consequences of liquefaction, a number of boreholes and SPT were executed after the quake and laboratory tests were run on materials from various depths. Borehole data and laboratory test results relating to investigations conducted before the quake in the PLDT building area were also made available.

The simplified procedure proposed by Tokimatsu and Yoshimi (presented at the 1984 Eighth World Conference on Earthquake Engineering in San Francisco) was adopted for evaluating the liquefaction potential. This method basically follows the Seed and Idriss (1982) procedure, but has the advantage of introducing the effect of fines. Many investigators recognized the fact that soil vulnerability to earthquake-induced liquefaction is strongly influenced by the presence, quantity and type of fines (silt and clay). Based on field behavior and laboratory testing on undisturbed sand samples obtained by the freezing method, Tokimatsu and Yoshimi proposed an equation to compute the factor of safety F_l (liquefaction resistance factor). This is the ratio between the resistance of soil elements to dynamic loads and the dynamic loads induced by the earthquake motion. When F_l equals 1 or less the soil is likely to liquefy, above 1 liquefaction does not occur.

For a given earthquake the procedure is usually applied to close-by sites with extreme liquefaction and no-liquefaction conditions, high structural damage and no-damage at all, respectively. The

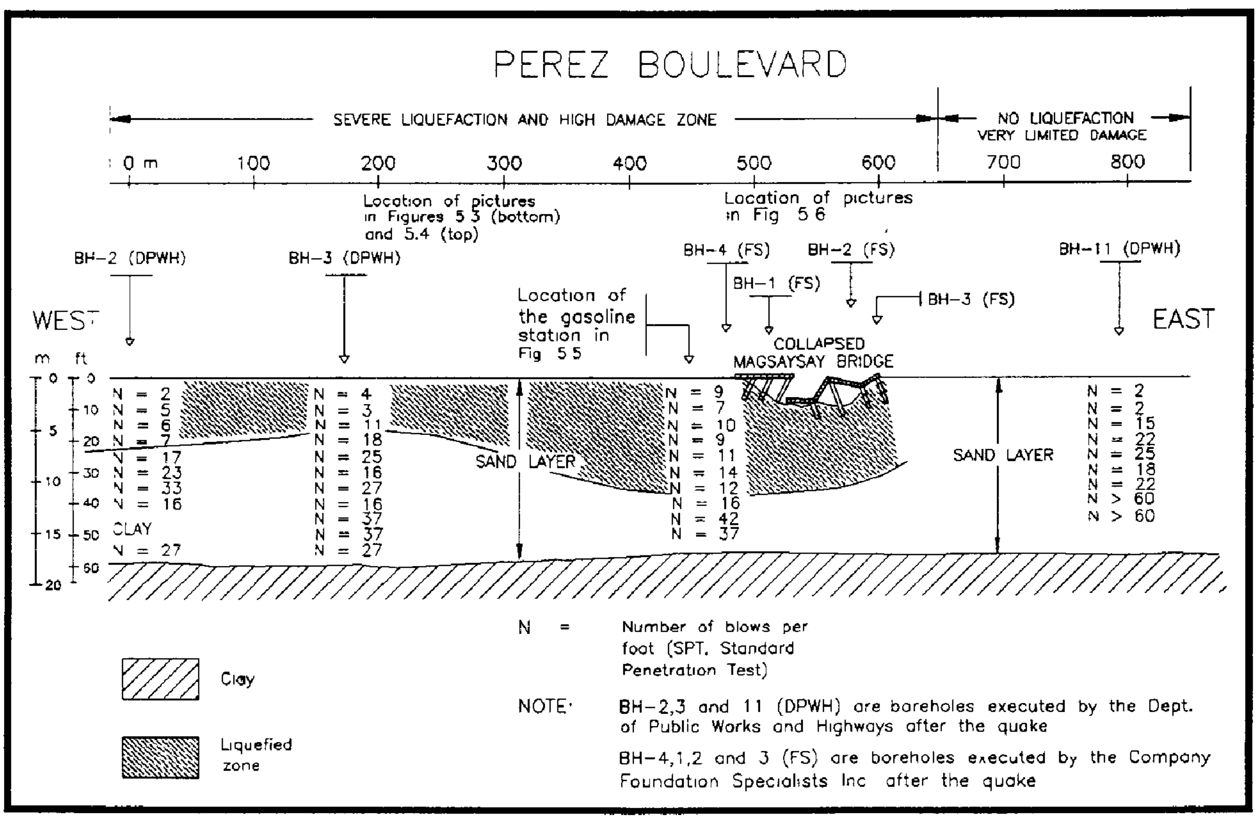

Fig. 5.10 – *Cross-section along Perez Blvd. where the major damage and the most impressive liquefaction effects occurred. Shown in the section are SPT (Standard Penetration Test) data and the layer which underwent liquefaction during the quake.*

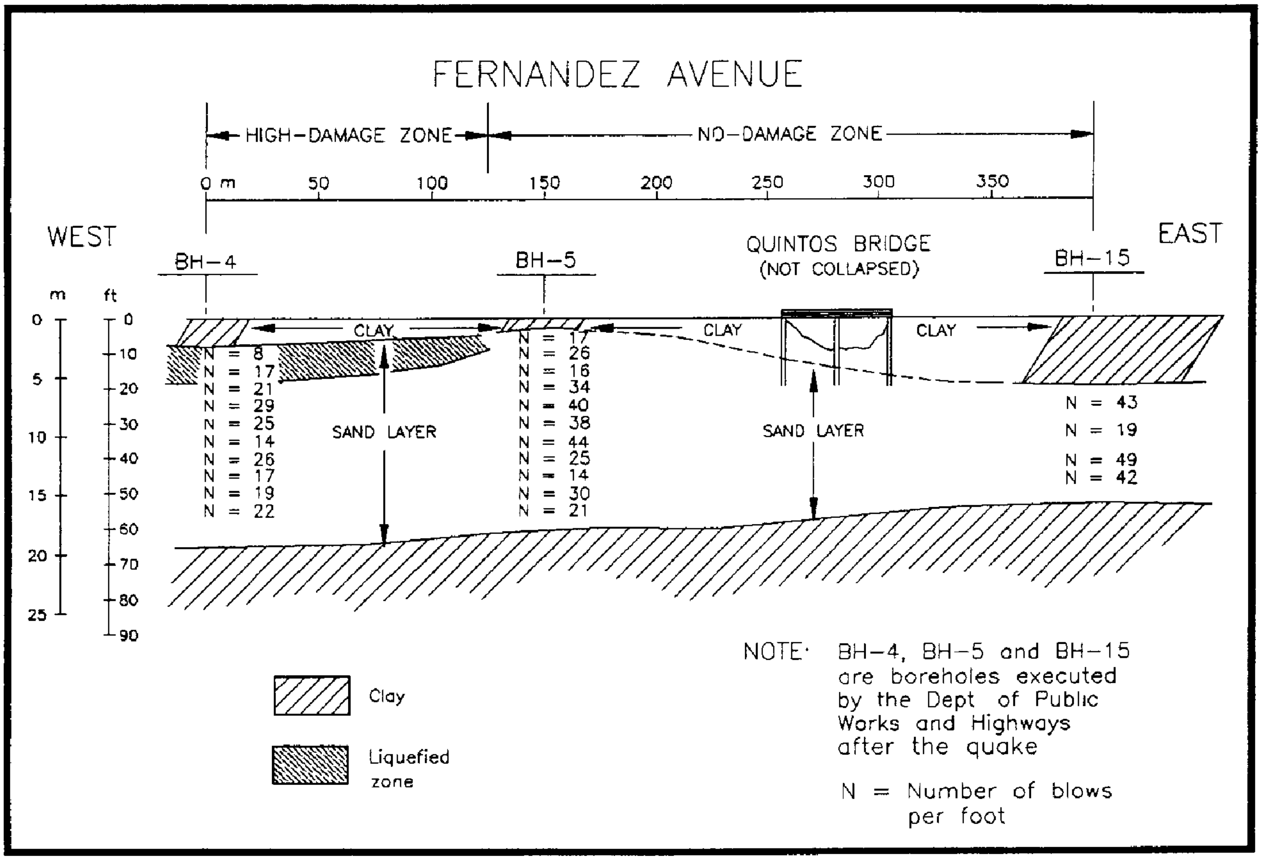

Fig. 5.11 – *Cross-section along Fernandez Avenue. Roadside buildings along the high damage zone were affected by quasi-uniform sinking. The section shows SPT data and the layer affected by the liquefaction.*

maximum ground acceleration, which satisfies in the Tokimatsu and Yoshimi equation both these extremes, is considered the value actually mobilized by the earthquake.

The outlined procedure was applied to the collapsed Magsaysay Bridge (Figs. 5.3C and 5.10) and to the undamaged PLDT building which is located near Quintos Bridge (Figs 5.3C and 5.11), both outside the liquefied area. The two bridges on the Pantal river and the building rested on piled foundations.

In terms of safety factors it was found that F_l was less than 1 for the top layer at the Magsaysay Bridge site and mainly greater than 1 for the same stratum at the PLDT Building.

In conclusion, the entire layer from ground surface down to a depth of 7 to 10 meters underwent liquefaction along a 600 m long cross-section in Perez Blvd. during the quake (Fig. 5.10). Severe damage involved most buildings in this area, several of them being affected by considerable uneven settlement and spectacular tilting. It is worthwhile to recall that the collapsed Magsaysay Bridge is located very near the gasoline Station where buried tanks floated up and the structural damage was most severe.

A thin liquefaction zone was identified along Fernandez Ave. (Fig. 5.11), where buildings mainly underwent a quasi-uniform settlement (90-120 cm).

In both commercial zones of Perez Blvd. and Fernandez Ave., and the area between them, however, 90% of the buildings were condemned, regardless the extent of subsidence due to liquefaction.