2.5 Liquefaction

Soil disasters occurred during the 1999 Chi-Chi earthquake, Taiwan, may be grouped into the following three; 1) large fault scarp on ground surface, 2) landslide, and 3) liquefaction of subsurface soils. The first one, fault scarp, was investigated in detail by Central Geological Survey, The Ministry of Economic Affairs, Taiwan, Republic of China, and the results of the investigations were reported elsewhere, for example, in their own web site (http://www.moeacgs.gov.tw/). In terms of structural and geotechnical engineering, the second one, landslide, might not damage heavily to buildings and structures on and in ground. In this chapter, therefore, the third one, liquefaction of subsurface soils and their damage to buildings and structures are reported considering mainly of relations between structural damage and soil conditions. One of the authors was a member of the Reconnaissance Team of AIJ (Architectural Institute of Japan) for this Taiwan earthquake, therefore, some of the ground surveys and their results shown in this chapter are also of those by the AIJ Team.

2.5.1 Outline of Surveys

Ground surveys were performed in the following three districts in Taiwan: 1) Taichung Harbor, 2) central part of Nantou city, and 3) Yuanlin district, from 16th to 18th, Oct. 1999. Ground failures and damage to foundations of structures were searched in each area, and their locations were marked on maps. Structural damage due to ground failures, for example, settlement and inclination of building, relative displacement between building and ground, etc., were measured, and some of them were recorded. The results of surveys in the three districts can be summarized as below.

2.5.2 Results of Surveys

Taichung Harbor

Figure 2.5.1 shows a schematic plan of Taichung Harbor. This harbor is located on the reclaimed land. In the harbor, remarkable ground failures were observed at North terminal only. Figure 2.5.2 shows a schematic map of North terminal in Taichung Harbor, and also shows the investigated area. North terminal has five wharfs (No. 1-4, and 4A), which had been built in 1973 and completed in 1976.

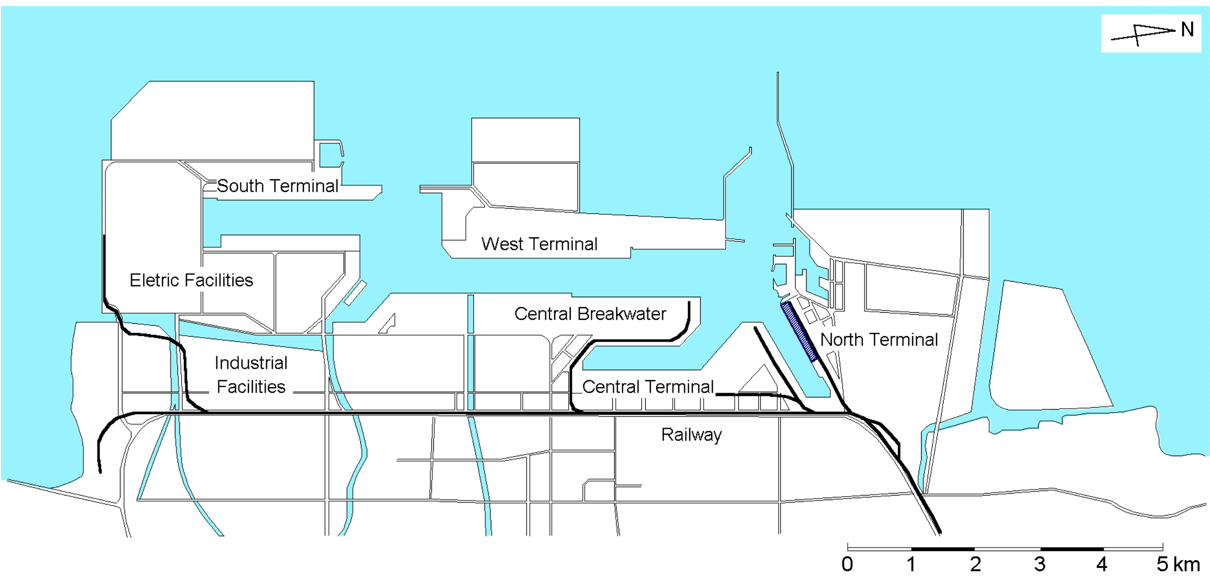


Figure 2.5.1. Schematic plan of Taichung Harbor.

Ground failures and structural damage observed in the investigated area are concluded in Figure 2.5.2. The backfills subsided due to seaward movements and inclinations of the caissons (Photo 2.5.1), and length and width of the subsided area were about 800m and 40m, respectively. Most of the caissons were damaged slightly or not. Figures 2.5.3 and 2.5.4 show horizontal seaward displacements of the caissons (Chen and Hwang, 2000) and settlements of backfills, respectively, which were measured at several spots in the wharfs after the earthquake. Maximum values of inclinations and horizontal displacements of the caissons were about 1-3 degree and 1.7m, respectively. Maximum settlement of backfills was about 1.4m. Comparing Figure 2.5.3 with Figure 2.5.4, it is indicated that the larger horizontal displacements of the caissons, the larger become settlements of backfills. Besides, many ground depressions were observed in the subsided area (Photo 2.5.2). Maximum length, width, and depth of the depressions could be 15m, 15m, and 2m, respectively. Soils observed in these ground depressions consisted mainly of fine sands and gravels with a diameter of 10-20cm. Due to the ground depressions, one belt conveyer facility and one reinforced concrete (R/C) framed warehouse were collapsed (Photos 2.5.3 and 2.5.4), and their locations are marked on Figure 2.5.2. Furthermore, remarks of sand boils were observed at several spots mainly around the ground depressions and the vertical gaps occurred between the caissons and backfills. Based on the above observations, it is indicated that these ground failures could be caused

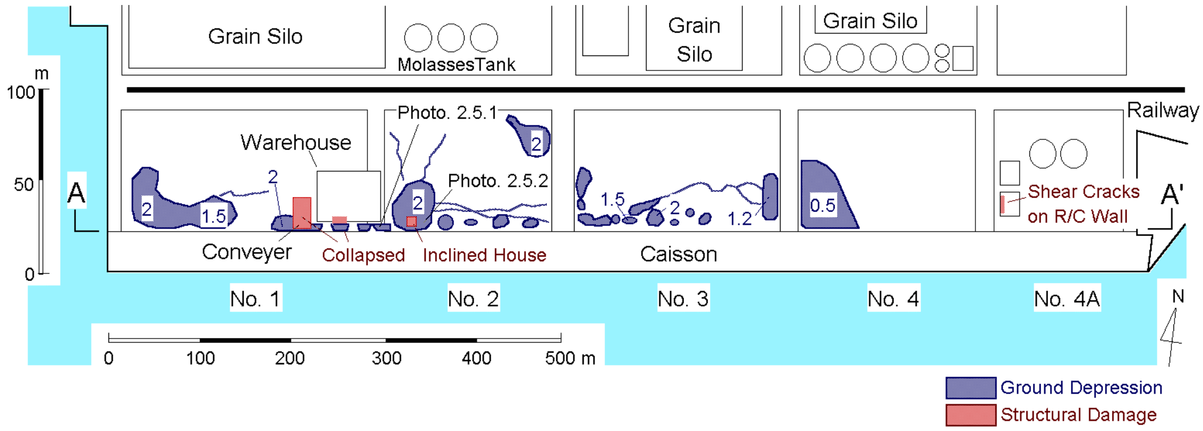


Figure 2.5.2. Schematic map showing damage to structures and soils at North terminal in Taichung Harbor. Numbers in the figure are maximum settlements of ground depressions (in m).

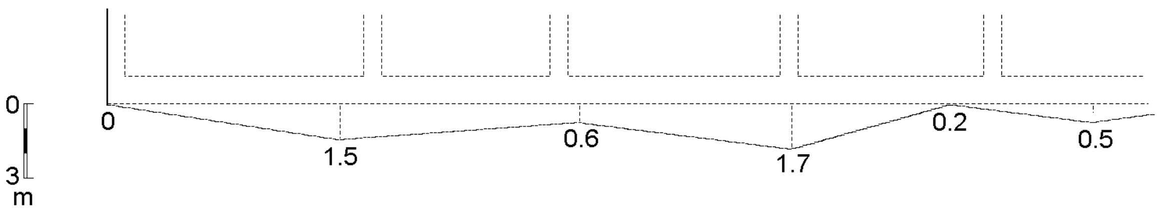


Figure 2.5.3. Rough sketch of horizontal seaward displacements of caissons (in m, Chen and Hwang, 2000).

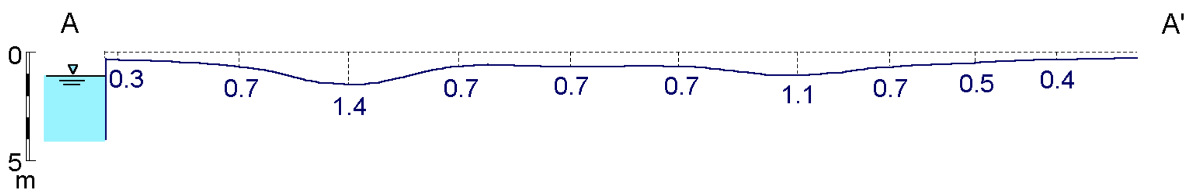


Figure 2.5.4. Rough sketch of maximum settlements of backfills along the line A-A' in Figure 2.5.2 (in m).

by liquefaction and/or lateral spreading of backfills.

Figure 2.5.5 shows a schematic section of subsurface soils and a caisson near the No.3 wharf in North terminal, which is based on the results of geological boring logs performed after the earthquake (Chen and Hwang, 2000). The original seabed consists mainly of sands with loose to medium dense, interbedded with several thin layers of clayey silt or silty clay. SPT-N values of the seabed range over about 20. Above the original seabed, sands dredged from the navigation channel and nearby areas are filled hydraulically to the present ground level. The hydraulic sand fills consist mainly of two layers, which are fine sands and silty sands, respectively. The both layers are quite loose, and their SPT-N values range from 5 to 14. The ground surface was paved with gravelly soils of thickness 30cm. Judging from these information, it is suggested that the fine sand layers up to a depth of 6m could be liquefied during the earthquake. Besides, it is also suggested that the gravels observed in the ground depressions stated above might be used for the pavement of ground surface.

In Taiwan, an intense strong motion array called TSMIP has been installed island-wide. Near Taichung Harbor, there are several seismograph stations in near distance. Among them, the closest one is the station located at the elementary school of Chingshui (Station Code: TCU059, on ground), where is about 4.7km southeast of the harbor. During the main shock, the accelerations of ground motions at the site were successfully recorded and are available tentatively (Lee *et al.*, 1999). Figures 2.5.6(a) and (b) show the acceleration time series of the two orthogonal horizontal motions (EW and NS components) recorded at TCU059. Peak ground accelerations (PGA) of the both motions are about 160cm/s^2, and their durations are about 30s long. Peak ground velocities and displacements (PGV and PGD) estimated by integrating the acceleration time series could

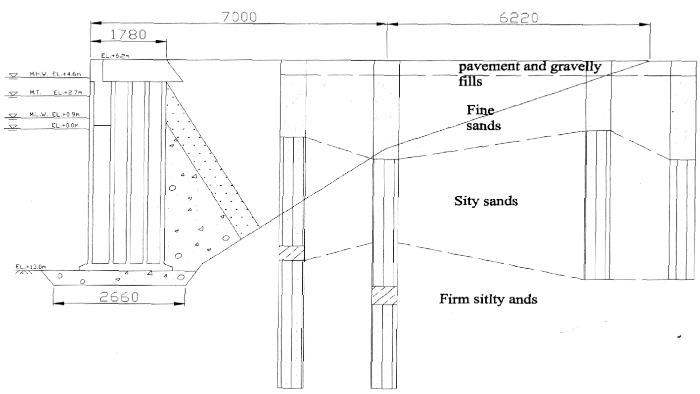


Figure 2.5.5. Schematic section of the No. 3 wharf in North terminal (Chen and Hwang, 2000).

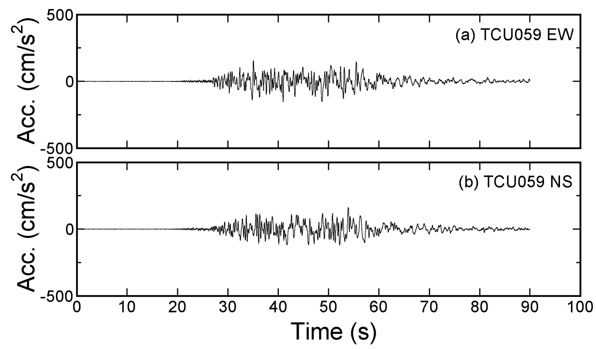


Figure 2.5.6. Acceleration time series recorded at TCU059 during the main shock (Lee *et al.*, 1999).

Photo 2.5.1. Settlement of backfills at North terminal in Taichung Harbor.

Photo 2.5.2. Ground depressions at North terminal in Taichung Harbor (Refer to color photo 18).

Photo 2.5.3. Collapsed belt conveyer facility at North terminal in Taichung Harbor.

Photo 2.5.4. Collapsed R/C warehouse at North terminal in Taichung Harbor.

be about 50cm/s and 40cm, respectively, for the both horizontal motions. In particular, the values of PGD are larger than those estimated from the acceleration records in Kobe, Japan, during the 1995 Hyogo-ken Nambu earthquake. From now, many studies on mechanism of damage to Taichung Harbor would be conducted using the damage information, soil profile data, and recorded ground motions. A study on this matter, for example, is performed in Chapter 5 of this report.

Central Part of Nantou City

Figure 2.5.7 shows a schematic map of central part of Nantou city. In this area, remarkable ground failures were observed at several local districts shown in the figure. For example, a five-storied R/C framed building (hereby called Building A shown in Figure 2.5.7) inclined 4 degree to the southern direction without any structural damage on the upper structure (Photo 2.5.5). In the park near the city hall shown in Figure 2.5.7, small vertical gaps between building and ground were observed. The embankments of Pinglin River settled by about 1m. Around Juingong Bridge on Pinglin River, a 16-storied R/C framed building (hereby called Building B shown in Figure 2.5.7) settled by about 70cm without any inclination. Some shear cracks were observed on the walls of Building B, and those might be due to differential settlements of the building. Except the above damage, however, any damage to the superstructure material of Building B could not be observed (Photo 2.5.6). On the basement floor of Building B, remarks of sand boils were observed (Photo 2.5.7), indicating that the subsurface soils under the building could be liquefied during the earthquake.

At the elementary school of Nantou (Station Code: TCU076, on ground), where is about 1km southwest of

Building B, the accelerations of ground motions during the main shock were successfully recorded and are available tentatively (Lee *et al*., 1999). Figures 2.5.8(a) and (b) show the acceleration time series of the two orthogonal horizontal motions (EW and NS components) recorded at TCU076. PGA values of EW and NS motions are about 340cm/s^2 and 420cm/s^2, respectively, and these values are about 2-3 times of those recorded at TCU059. However, PGV and PGD estimated from integration of the both horizontal acceleration records could be about 60cm/s and 35cm, respectively, and these values are almost same as those of TCU059.

Figure 2.5.9 shows a boring log at Site C shown in Figure 2.5.7 (Central Geological Survey, Taiwan, 1995), where is about 1km southeast of Building B. Any ground failures and remarks of soil liquefaction has not been reported at Site C. In Figure 2.5.9, SPT-N values up to a depth of 2m are about 10, and those at a depth over 2m range over 40, and the level of water table is about 5m depth. These information suggest that subsurface soils at Site C could not be liquefied during the earthquake, in which the values of PGA and PGV were 400cm/s^2 and 60cm/s at most, respectively. Based on the above suggestions, it is indicated that response characteristics of

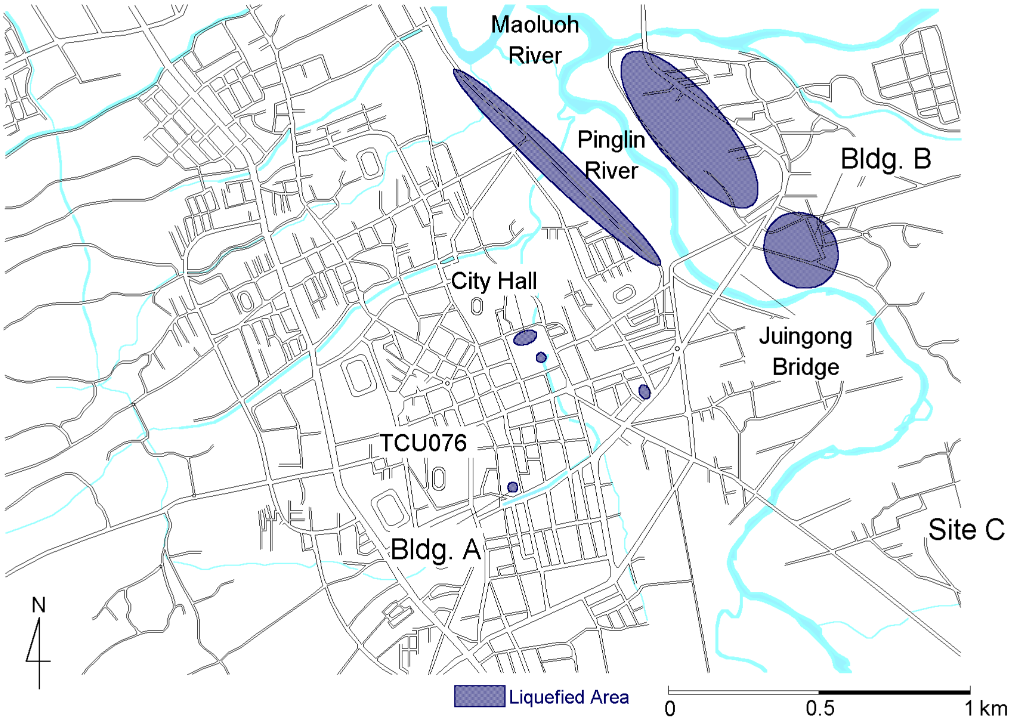


Figure 2.5.7. Schematic map showing liquefied areas in Nantou city.

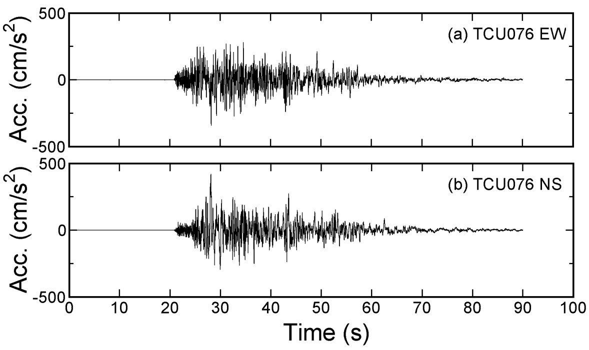
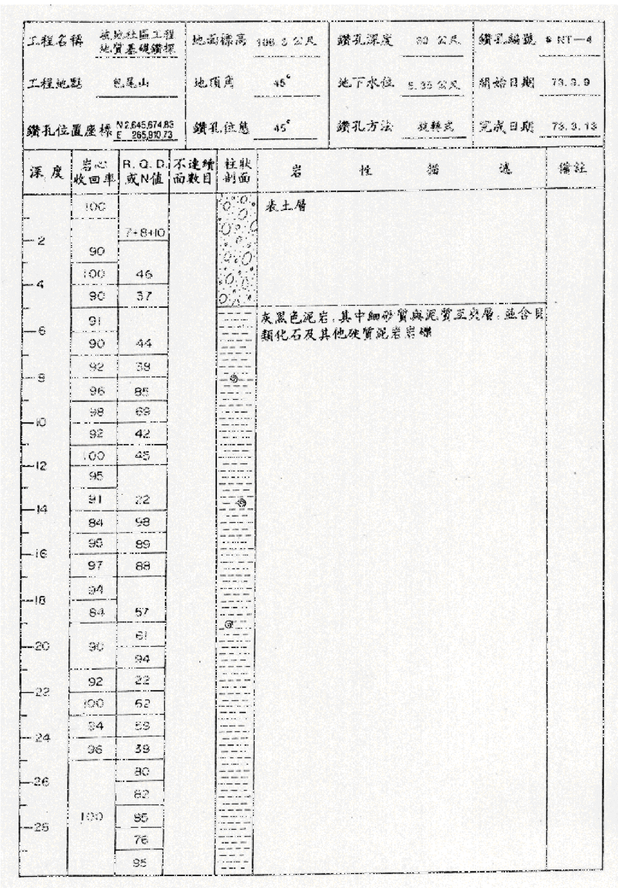


Figure 2.5.8. Acceleration time series recorded at TCU076 during the main shock (Lee *et al*., 1999).

subsurface soils during earthquakes could vary considerably among Sites A, B, and C.



工程名稱	坡地社區工程地質基礎鑽探	地面標高	106.5 公尺	鑽孔深度	30 公尺	鑽孔編號	# NT—4
工程地點	[illegible]山	地傾角	45°	地下水位	5.35 公尺	開始日期	73.3.9
鑽孔位置座標	N2,645,674.83 E 265,910.73	鑽孔傾態	45°	鑽孔方法	旋轉式	完成日期	73.3.13

深度	岩心收回率	R.Q.D.或N值	不連續面數目	柱狀剖面	岩性描述	備註
2, 4	100, 90, 100, 90	7+8+10, 46, 37			表土層	
6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28	91, 90, 92, 96, 98, 92, 100, 95, 91, 84, 95, 97, 94, 84, 90, 92, 100, 94, 96, 100	44, 38, 85, 69, 42, 45, 22, 98, 89, 88, 57, 61, 94, 22, 62, 59, 39, 80, 82, 85, 76, 95			灰黑色泥岩，其中細砂質與泥質互夾層，並含貝類化石及其他硬質泥岩岩礫	

Figure 2.5.9. Soil profile at Site C in Nantou city (Central Geological Survey, Taiwan, 1995).

Photo 2.5.5. Inclination of Building A in Nantou city.

Photo 2.5.6. Subsided Building B in Nantou city.

Photo 2.5.7. Remarks of sand boils at basement floor of Building B in Nantou city (Provided by Mr. Hitoshi Kumagai).

Yuanlin District

Figure 2.5.10 is a map showing liquefied areas in Yuanlin district, which have been reported elsewhere (According to comments of the district office). In the central area shaded in the figure, however, ground failures could be confirmed at several narrow sites only, in fact. For instance, Figure 2.5.11 shows a rough sketch of damage distribution in a small community, which is located in the shaded area shown in Figure 2.5.10. Several

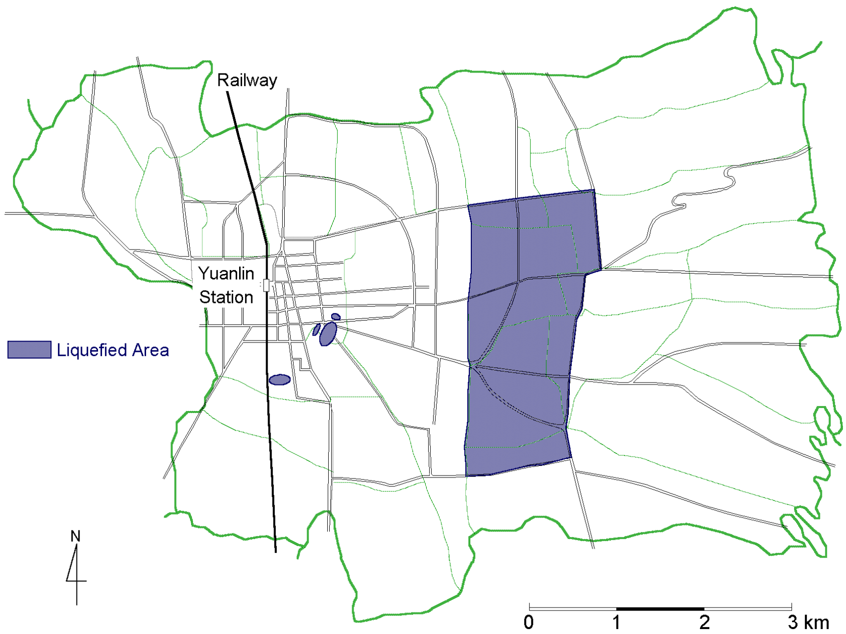


Figure 2.5.10. Schematic map showing liquefied areas in Yuanlin district.

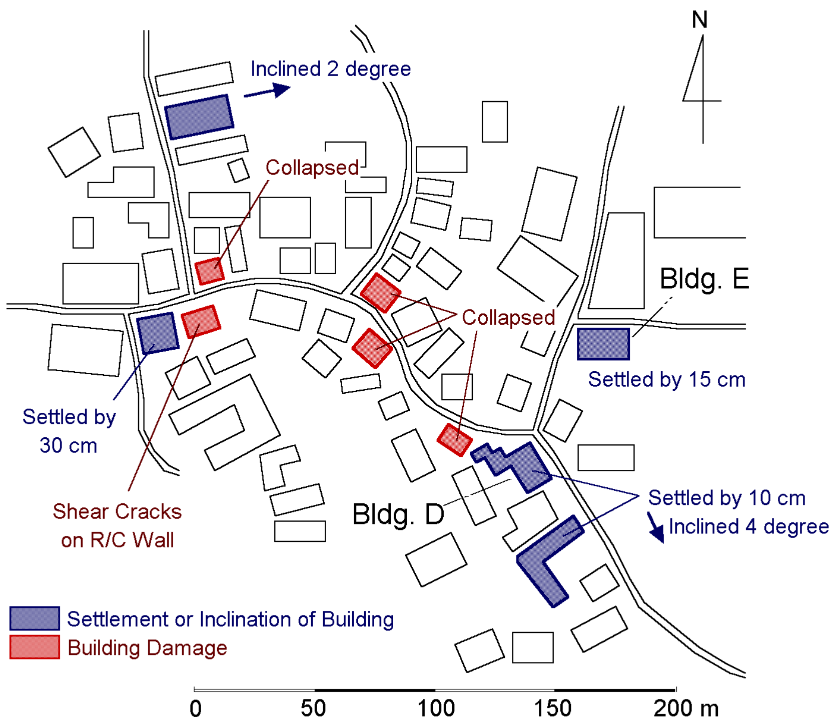


Figure 2.5.11. Schematic map showing damage to structures and soils in a small community, located in the shaded area in Figure 2.5.10.

R/C buildings, which were under four-storied, were collapsed in the area. On the other hand, several R/C buildings, which were over four-storied, settled and/or inclined without any damage to their upper structures. In Figure 2.5.11, it is suggested that these buildings and soil damage could occur at some limited local spots. Maximum values of settlements and inclinations of the buildings were about 30cm and 4 degree (Photo 2.5.8, Building D shown in Figure 2.5.11), respectively. Boiled sands (but they were silty) due to liquefaction were observed at several settled buildings (for example, Photo 2.5.9, Building E shown in Figure 2.5.11). Besides, several depressions of paddy fields were observed in this area, because there were in cultivated lands.

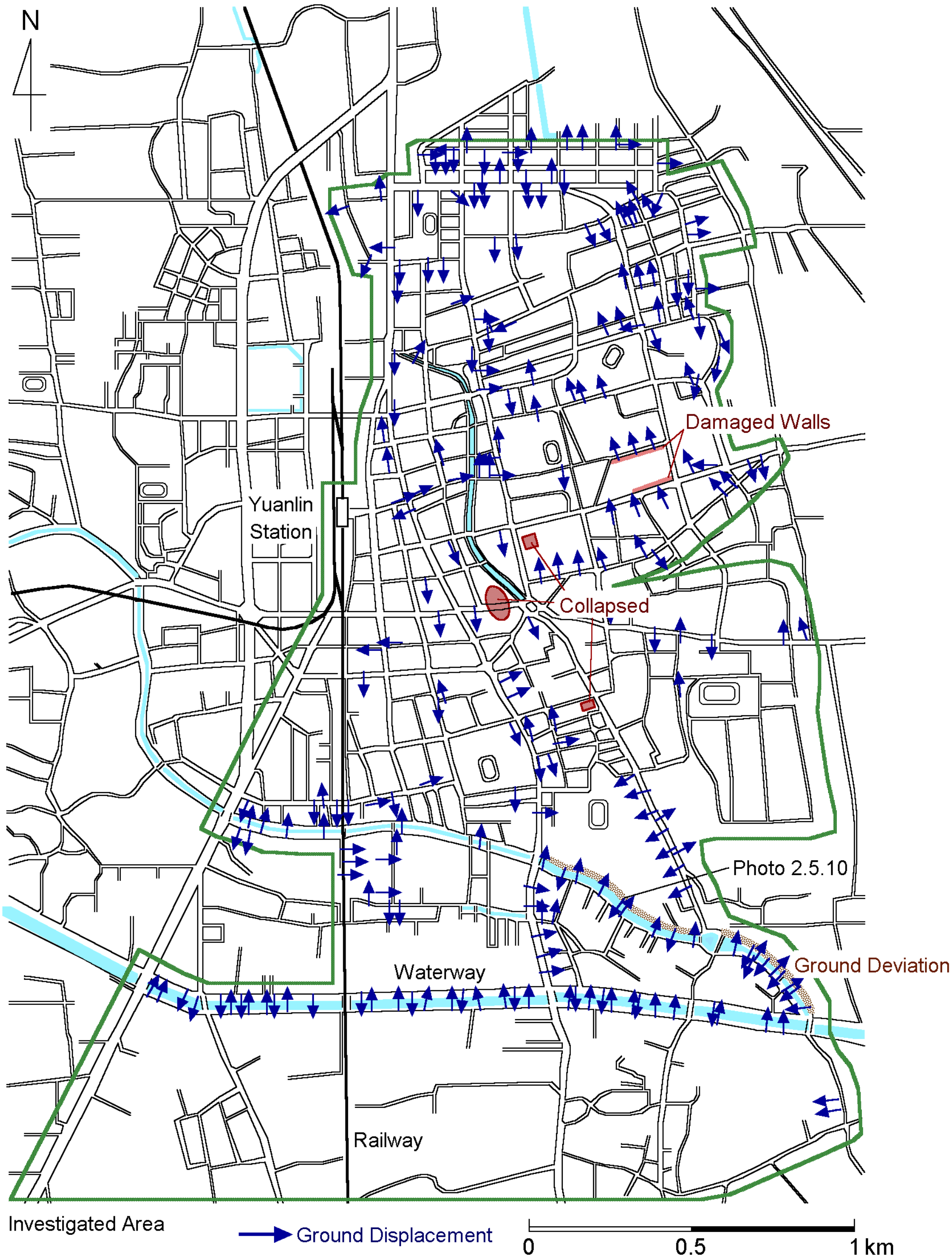


Figure 2.5.12. Schematic map showing structural damage and ground displacements around Yuanlin station.

Photo 2.5.8. Inclination of Building D in Yuanlin district (Refer to color photo 12).

Photo 2.5.9. Settlement of Building E in Yuanlin district.

Photo 2.5.10. Inclination of telegraph poles and ground deviations at waterway in Yuanlin district (Refer to color photo 13).

Around the station of Yuanlin, it was hard to find ground failures, but many inclined telegraph poles were found easily. The telegraph pole could incline to the opposite direction of ground displacement, when subsurface soils moved or flowed laterally during or after earthquakes. Therefore, the inclinations of telegraph poles in this area were recorded, and the opposite directions of the inclinations (maybe the directions of ground displacements) were marked on the map as shown in Figure 2.5.12. The investigated area is also shown in the figure. It is suggested that the embankments at the both side of the waterway could move or deviate to the waterway (Photo 2.5.10). Maximum horizontal displacements of ground to the waterway were about 1m. On the other hand, at the sites far from the waterway, the directions of ground displacements were various spatially, therefore, it was difficult to find out any rule nature. Based on the above observations, it is suggested that subsurface soils in the area could move or deviate to various directions during or after the earthquake.

2.5.3 Summary

Ground surveys were performed in Taichung Harbor, central part of Nantou city, and Yuanlin district, to investigate damage to buildings due to soil liquefaction during the 1999 Chi-Chi earthquake, Taiwan. The results of surveys in the three districts can be concluded as follows: 1) Taichung Harbor was damaged heavily due to liquefaction of subsurface soils. 2) In North terminal of Taichung Harbor, it is indicated that the larger horizontal displacements of caissons, the larger become settlements of backfills. 3) In North terminal, the fine sand layers up to a depth of 6m could be liquefied during the earthquake. 4) Settlements and inclinations of buildings due to soil liquefaction were remarkable at the sites where the level of water table might be shallow and the tall structures (over about four-storied) were built on. 5) Subsurface soils in Yuanlin district (near Yuanlin station) could move or deviate to various directions during or after the earthquake.

Acknowledgements

The authors are grateful to Prof. Akenori Shibata and Prof. Yoshiaki Nakano, the leader and the secretary of the AIJ Reconnaissance Team, respectively, and the other members of the Team, for their valuable assistance and co-operation in the ground surveys.

References

Central Geological Survey, The Ministry of Economic Affairs, Taiwan, Republic of China (1995). "Report on geological engineering survey and boring log, Nantou district."

Chen, H. C. and Hwang, G. S. (2000). "Preliminary analysis for quay wall movement in Taichung Harbor during the September 21, 1999, Chi-Chi earthquake," *Earthquake Engineering and Engineering Seismology, Special Issue for 921 Chi-Chi Earthquake*, Chinese Taiwan Society for Earthquake Engineering, Vol. 2, No. 1, pp. 43-54.

Lee, W. H. K., T. C. Shin, K. W. Kuo, and K. C. Chen (1999). "CWB free-field strong-motion data from the 921 Chi-Chi earthquake," Volume 1, *Digital Acceleration Files on CD-ROM, Pre-Publication Version (December 6, 1999)*, Seismology Center, Central Weather Bureau, Taipei, Taiwan.