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DAMAGES ON WATERFRONT GROUND DURING THE 1999 KOCAELI EARTHQUAKE IN TURKEY

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ABSTRACT

The 1999 Kocaeli earthquake of August 17, 1999 hit the western part of Turkey causing significant damage to buildings and civil engineering structures. This paper reports geotechnical aspects of damage mainly along the south coast of the Izmit Bay. Ground subsidence and loss were observed in the widespread area in the waterfront areas in the south of the Izmit Bay. It is supposed to have been caused by slope instability of the seabed and a fault dislocation. Significant ground subsidence was also observed along the southern coast of the Sapanca Lake. Site investigations of these areas were carried out by the reconnaissance teams from the Japanese Geotechnical Society. Ground survey and seabed depth measurement were carried out in order to clarify the cause of these damages. Three different factors were identified as possible causes for the damage. A fault which appeared on the ground surface caused direct damage to structures by the relative displacement between the two sides. A pull-apart dislocation by main and branch faults caused ground subsidence in a wide area. A submarine landslide caused land flows in a fill and an alluvial fan deposit flowed out. Soil liquefactions, though observed from place to place, did not seem to have caused significant geotechnical damage.

Key words: earthquake, fault, ground subsidence, site investigation, soil liquefaction, submarine landslide (**IGC**: C0)

INTRODUCTION

The Kocaeli earthquake of August 17, 1999 hit the western part of Turkey at 3:20 am, local time. It brought significant damage to various structures such as buildings and civil engineering structures in the Izmit Bay area and the Kocaeli prefecture (*see* Fig. 1 for affected area). Geotechnical damages were also observed in a widespread area. Many buildings were settled and tilted in the Adapazari city. Landslides were observed in a wide area around Izmit to the Black sea. Several pieces of shorelines flowed into the sea at several places in the south of the Izmit Bay, each of which was several hundred meters in width. Surface fault-induced damage was observed in the region from Yalova to Duzce. Ground subsidence occurred in the wide area from Golcuk to the eastern end of the Izmit Bay. Subsidence of ground was also observed in the southern coast of the Sapanca Lake.

The authors made site investigations as members of the reconnaissance team from Japanese Geotechnical Society

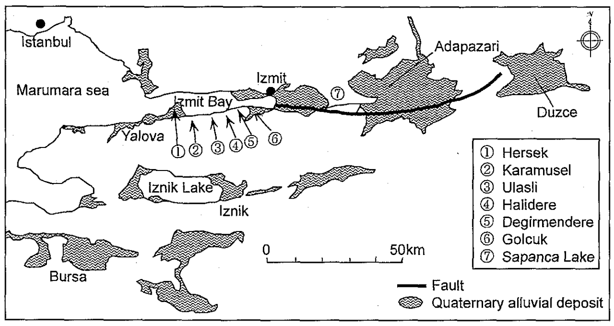

Fig. 1. Earthquake affected area with Quaternary deposit and sites of investigation

(JGS) between September 4 and 13, and between September 29 and October 5. Some of the damage seemed somewhat new, and in some places, it was difficult to recognize the mechanism immediately. Flowed out ground and ground subsidence in a wide area observed in the south of the Izmit Bay are examples of this kind. It is important to

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determine the mechanism in order to prevent future disasters. For this purpose, detailed ground surveys and seabed depth measurements were conducted in order to clarify the mechanism of these damages. This paper describes a general view of the geotechnical damage observed in the south of the Izmit Bay and the Sapanca Lake. Mechanisms of several kinds of damage are discussed.

GENERAL FEATURE OF INVESTIGATED SITE AND DAMAGE

The Kocaeli earthquake was caused by the dislocation of the North Anatolian Fault. This fault appeared on the ground surface from about 30 km west of Duzce city and ran to the west up to the Izmit Bay passing the Sapanca Lake, as shown in Fig. 1. The earthquake affected area is divided into two zones by the North Anatolian Fault: Istanbul zone in the north and Sakarya zone in the south. Areas reported in this paper, which are shown in Fig. 1, are located in the south of the fault, i.e., in the Sakarya Zone.

The Sakarya Zone is characterized by a variably metamorphosed and strongly deformed Triassic basement called the Karakaya Complex, which is overlain with a major unconformity by Liassic conglomerates and sandstones. Quaternary deposits appear in some places as fan deposits and basins, as shown in Fig. 1.

Various types of damage appeared in this area during the Kocaeli earthquake. Structural damage caused by inertia force was observed at many places, but will not be described in detail in this paper. Liquefaction was observed in the Hersek district and the Sapanca Lake. Land losses were observed in Karamusel, Ulasli, Halidere and Degirmendere, which were probably caused by a submarine landslide as will be discussed later. Fault-induced structural damage was observed in Degirmendere and Golcuk. Subsidence of the ground was observed in the widespread area from Golcuk to the eastern end of the Izmit Bay area and in the Sapanca Lake.

Three types of investigation were carried out. An aerial investigation by means of a helicopter gave a whole view of the damage. Information of the damages was obtained by a site investigation. Detailed investigations, including a seabed depth measurement, were then made to clarify the mechanism of the damage. Damages in these sites, shown in Fig. 1, will be described from west to east hereafter.

DAMAGE ALONG THE SOUTH COAST OF IZMIT BAY

Yalova

The Yalova city is a middle size city located in the western side of the Izmit Bay area. Many buildings were damaged by an inertia force. Figure 2 shows damage distribution of the city. Damage was in general low in the area along the shoreline, and it became severe as the distance from the sea increased. In this figure and subsequent figures, hollow arrow symbols are locations where photographs were taken and the number denotes the photograph number. Totally collapsed buildings were frequently seen in heavily damaged areas, a typical example is shown in Photo. 1. On the contrary, geotechnical damage was small even along the shorelines. The only exception was a differential settlement in the rockfill breakwater near the ferry terminal.

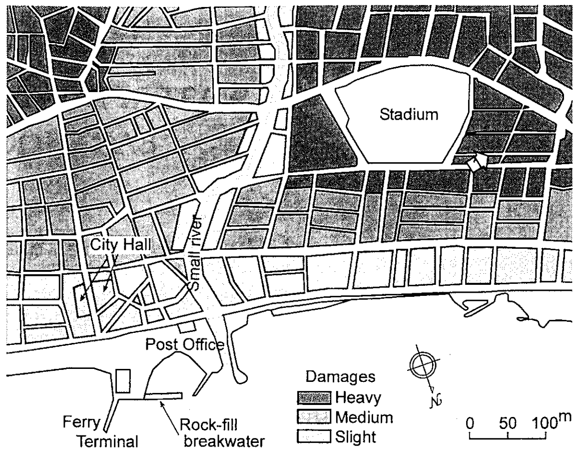


Fig. 2. Map of downtown Yalova city with damage distribution

Photo. 1. Damaged summer houses in Yalova

Altinova Peninsula

There was a lagoon in the east of the Helsek district, Altinova Peninsula, whose location is shown in Fig. 3. This lagoon waterlogged only in high tide before the earthquake, but became to waterlog all the time after the earthquake, as shown in Photo. 2. Subsidence occurred mainly in this lagoon. A maximum subsidence have been of the same order as the tidal range, i.e., several tens cm at maximum. Evidence of liquefaction such as a sand boil was not observed in this region. The reason of the subsidence is not clear at present.

On the contrary, liquefaction was observed in the west of the peninsula, as shown in Fig. 3. Figure 4 shows a detailed map of this region. A significant amount of sand boils was observed at the orchard.

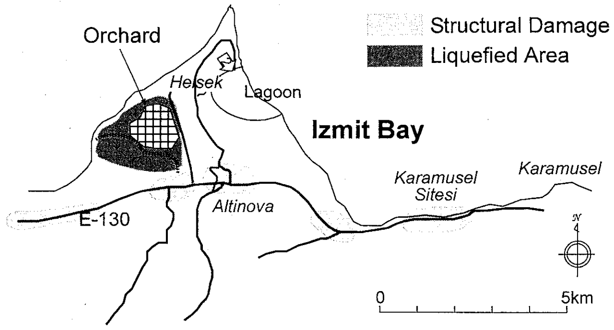


Fig. 3. Map showing the damaged area in the Altinova peninsula

Photo. 3. Cracks near the circular diaphragm wall

Photo. 2. Subsided lagoon in Hersek

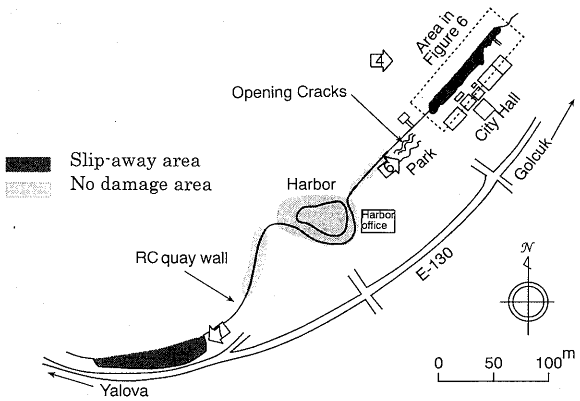


Fig. 5. Map in the vicinity of Karamursel

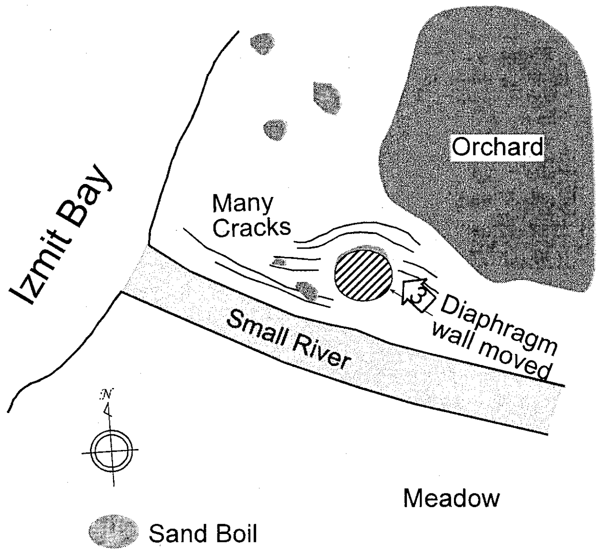


Fig. 4. Detailed map of the liquefied site in the Hersek district

A small river flowed into the Izmit Bay passing the orchard. Several cracks ran parallel to the river near the river-mouth as schematically shown in Fig. 4. Several sand boils were observed nearby. These observations suggest that a liquefaction-induced flow occurred.

There was a circular pit (diaphragm wall) with a 15 m diameter and 10 meter depth near the river. Cracks parallel to the river were also seen as shown in Fig. 4 and Photo. 3, and blue colored sand boils were observed on the side opposite to the river. The pit seemed to move toward the river probably because the ground had become loosened by soil liquefaction.

Karamusel

Karamusel city is the most western city among areas where significant ground failure was observed along the shoreline. Figure 5 shows a map in the vicinity of the Karamusel city with damage and no damaged area along the shoreline.

A fill area of about 200 m long and 25 m wide flowed out into the sea at the eastern end of this map. Details of this area are shown in Fig. 6 and Photo. 4. This fill was developed in 1968. Many cracks ran parallel to the shoreline on the rest of the fill and a little on the natural deposit. According to an interview with a resident, the seabed was about 100 m deep and the slope of the seabed was steep. The value of 100 m seems unlikely, so this report probably just indicates a deep and steep seabed. The section face of the remained part is shown in Photo. 5; the section is vertical. Considering the original deep and steep seabed and observation of damage, slope instability is supposed to have occurred here. Damage to buildings in the background was light.

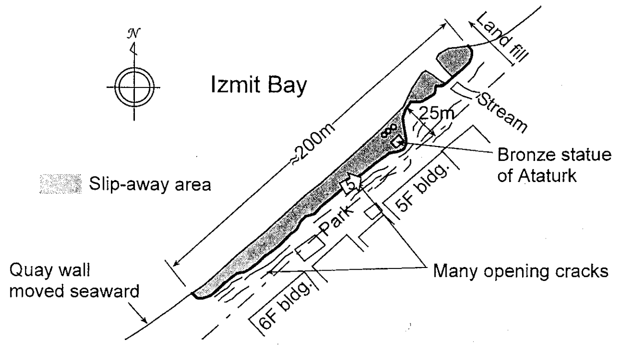


Fig. 6. Detailed map of lost shoreline at Karamursel

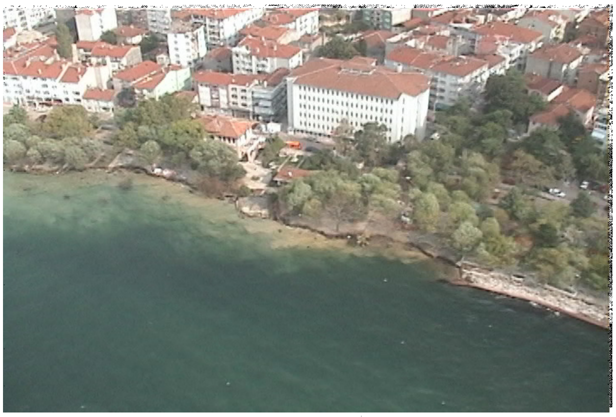


Photo. 4. Aerial view of flowed-out shoreline at Karamursel

Photo. 5. Face of the rest of flowed-out ground

Cracks parallel to the shoreline were also observed at the park just west of the above flowed out area. Subsidence of the ground was also observed here, as shown in Photo. 6, which indicates that this area was just going to flow out. According to the residents, these cracks appeared at the mainshock. Then, they enlarged and the ground movement occurred at the maximum aftershock.

Flowed out ground was also observed in the western part of Fig. 5, as shown in Photo. 7. Reinforced concrete quay wall tore off at the boundary to the remained portion. In addition, cracks parallel to the old shoreline were frequent in the backfill ground. Sand boils were also observed. They did not, however, seem to be a cause of the flow in the fill. According to a interview of fishermen,

Photo. 6. Subsidence of the ground with cracks parallel to the shoreline

Photo. 7. Flowed-out area on the west of Karamusel

the seabed was 2 m deep and the slope was gentle up to about 10 m from the shoreline before the earthquake, and then the slope became steep before the earthquake. The slope of the seabed became steep from 1–2 m from the seabed after the earthquake.

Ulasli

An area about 300 meters long and 40 m wide flowed out into the sea in the park in the Ulasli city, as shown in Fig. 7 and Photo. 8. Most of the park was fill with the crashed rock taken from nearby mountains. The stone masonry quay wall was developed in 1986. Several cracks were observed in the backfill ground, which ran parallel to the shoreline. Evidence of liquefaction was not observed.

There was a small river on the east side of the park. The riverbed was fairly steep and the river-mouth was a fan shape, which suggests that this area is an alluvial fan deposit. Gravel with fairly large diameter has deposited near the river-mouth, which is supposed to have been carried by a flood. Loss of the ground, therefore, occurred not only in the fill but also in the natural deposit.

There was a small football field just west of the lost

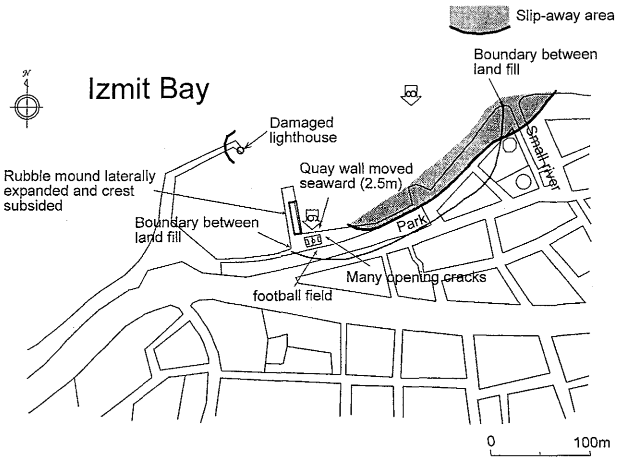


Fig. 7. Map in downtown of Ulasli

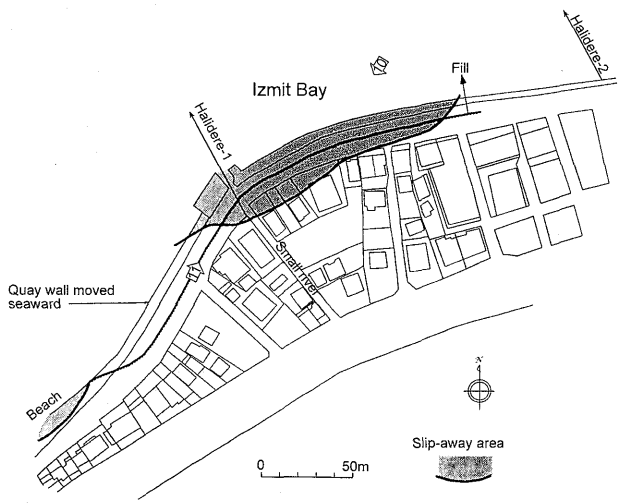


Fig. 8. Map of Halidere district with flowed out area

Photo. 8. Aerial view of flowed-out area in Ulasli

Photo. 10. Aerial view of flowed-out shoreline at Halidere district

Photo. 9. Crack parallel to shoreline on the football field

area. Large cracks opened and ran parallel to the coastal line, as shown in Photo. 9, but water or sand spouts were not found on the ground surface. A sum total of crack widths reached 2.5 m; therefore, the quay wall moved toward the sea more than 2.5 m, although it did not seem to be seriously damaged.

Damage was also observed at a small wharf on the west of the park. The crest of the rubble mounded foundation subsided because of the lateral expansion of the rubble foundation. A lighthouse was also damaged at the top of the breakwater, but it was not geotechnical damage.

Halidere

A piece of the north region about 200 m long and 20 m wide disappeared into the sea in the Halidere city, as shown in Fig. 8 and Photo. 10. The road broke as shown in Photo. 11, in which photographs taken before and after the earthquake are compared. A stream ran on the west of the damaged area, and the slope of the river is fairly steep at 6.5 degrees. This region is again supposed to be a fan deposit.

Depths of the seabed were measured by means of a simple ultrasonic device schematically shown in Fig. 9 along two lines shown in Fig. 8. Distances from the shore were identified by means of a Global Positioning system (GPS). The line Halidere-1 passes near the mouth of the river and the line Halidere-2 is located east of the city where the coastal land had not flowed out.

The result of measurements is shown in Fig. 10 together with the seabed depth prior to the earthquake read off from the marine chart with 5 m seabed depth

(a)

(b)

Photo. 11. Change of road before and after earthquake: (a) Before earthquake, (b) After earthquake

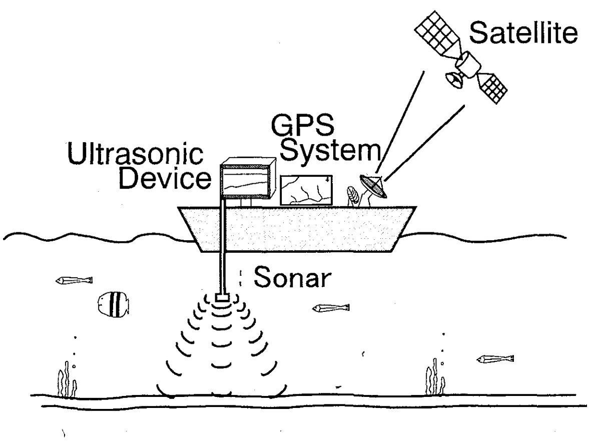
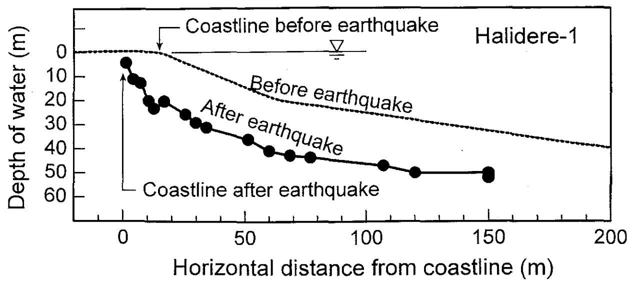
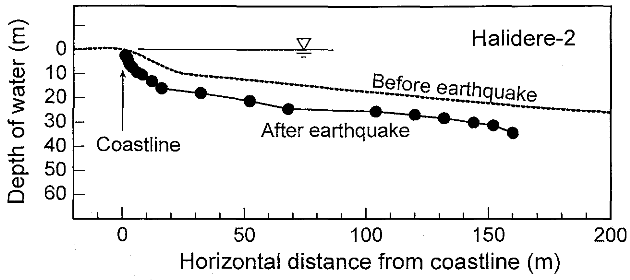


Fig. 9. Schematic figure of the device to measure water depth



(a)



(b)

Fig. 10. Depth of seabed before and after earthquake in Halidere: (a) Halidere-1 line, (b) Halidere-2 line

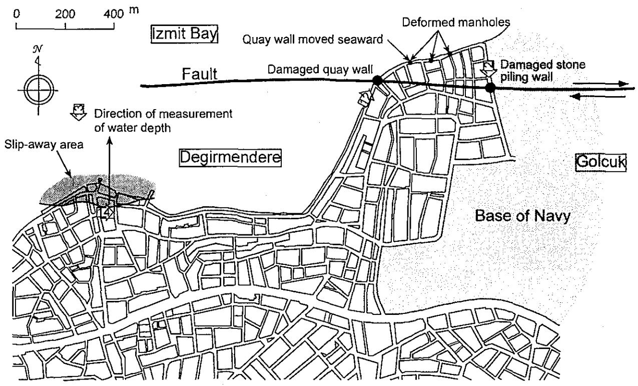


Fig. 11. Earthquake affected areas in Degirmendere

contour (Turkiye Marumara Denizi Izmit Limani, 1995), which was read off from the contour map of a seabed. Shapes of the seabed were changed drastically by the earthquake. A 20 m thickness of surface soil was lost along the line Halidere-1. It is also noted that the shape of the seabed is very steep, more than a 0.5 slope up to about 50 m from the shoreline. Surface soil was also lost by about 10 m thickness even along the line Halidere-2 where the ground was not lost. The slope is about 0.2 except close to the shore, which is also steep although it is a little gentler than the slope at the line Halidere-1. Change of seabed depth was also confirmed by a interviewing residents. A submarine landslide was supposed to have taken place in the wide area, and a huge mass of soil was taken away from the coastal region.

Change of the seabed depth continued more than 150 m from the shore, which suggests that the fault line is located more than 150 m offshore.

Degirmendere

The earthquake affected area in the Degirmendere city is shown in Fig. 11. Two types of geotechnical damages were observed in the city. One was damage induced by a fault in the east of the city; structures were damaged by a surface fault. The other was a loss of the ground in the west of the city, which was probably caused by a submarine landslide the same as before mentioned cities.

A stone masonry fence was damaged by a surface dislo-

(a)

(b)

Photo. 12. Fault dislocation-induced damage in Degirmendere: (a) Stone masonry fence, (b) Quay wall

Photo. 13. Loss of coastal land in Degirmendere

Photo. 14. View of flowed-out area. A thick-trunked tree indicates that this area is not a young fill; similar trees were frequently seen nearby.

cation with a relative horizontal displacement of 1.5 m in the east-west direction and 4.3 m in the north-south direction, as shown in Photo. 12(a), at the east end of the city, which is located at a boundary to the Golcuk Navy Base. This fault ran in the east-west direction and caused damage to buildings and houses along the line although the magnitude of the offset seemed smaller. A quay wall was damaged at the west end of the fault, as shown in Photo. 12(b). Then it vanishes into the Izmit Bay. This fault is supposed to be a main fault because its dislocation was in a right-lateral way, and it is on the line along the main fault in the Izmit city.

Several manholes changed in cross-sectional shape on the road along the shore in the north of the fault. Quay walls tilted toward the sea at the same place. These observations indicate that the ground moved toward the sea, but the mechanism is not known at present.

A coastal land about 100 m wide and 300 m long was lost into the sea in the west of the downtown, as shown in Fig. 11 and Photo. 13. There were a 4-story hotel and several buildings used for restaurants, etc. before the earthquake, but they flowed out into the sea with the land. Location of these buildings at present is still not known one year later, which suggests a huge mass movement into the sea. Buildings behind the lost area tilted and were damaged. This area was a fan deposit developed by the river flowing to the north in the middle of the lost area due to several factors. The slope of the riverbed was steep same as in previously described cities. The surface soil was sand including many gravel about 10 mm in diameter. Thick-trunked trees with diameters more than 50 cm were frequent, as shown in Photo. 14. Therefore, even if fill was made near the old shore, many parts of the lost area are supposed to have come from a natural deposit. Evidence of liquefaction could not be found at the ground surface of the background.

Sea depth was measured in the same way as Halidere in the direction shown in Fig. 11. The result was compared with the pre-earthquake seabed in Fig. 12. The original seabed was steep; the slope was about 0.16 in average up to 250 m from the original shoreline. The change of seabed depth reached about 20 m near the shore, and is about 10 m even 300 meters offshore from the current shore, which implies a huge submarine landslide in the sea. A simple extrapolation of the fault line at the east of the city suggests that the fault runs at 350 to 400 m off the coast. This distance is approximately the same as the distance where the seabed depth did not change after the earthquake. Fault dislocation, therefore, may affect the submarine landslide.

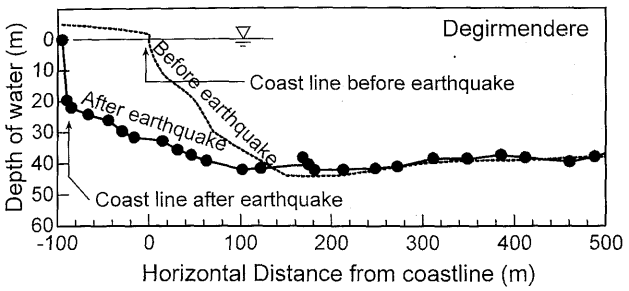


Fig. 12. Depth of seabed before and after the earthquake in Degirmendere

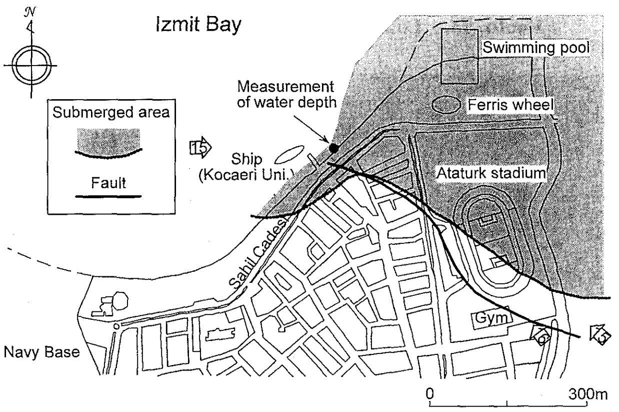


Fig. 13. Location of land subsidence and fault in Golcuk

(a)

(b)

Photo. 15. Aerial view of subsided area: (a) View to northwest direction, (b) View to northeast direction

Golcuk

A fault was found to run from the northwest to the southeast direction in the Kavakli district in the Golcuk city. This fault is assumed not to be a main fault but a branch fault because the main fault is assumed to run near the center of the Izmit Bay from the east end of the bay. The north part of the fault is shown in Fig. 13. There were many buildings significantly damaged by an inertia force in the south of this fault, but, they will not be described in this paper.

The main fault dislocated in a right-lateral way (Okamura and Matsuoka, 2000). There was, however, no horizontal offset; only a vertical offset was observed along this fault. The vertical offset was about 1.5 m at the east end of Fig. 13 and Photo. 15, and it gradually decreased to the west; it disappeared near the Sahil Cadesi (street).

Area northeast of the fault subsided, as shown in Photo. 15, which may be related to the vertical offset of the fault. The original flat land tilted slightly toward north; daubed terrain in Fig. 13 is a submerged area at high tide. A swimming pool and a Ferris wheel were submerged all the time, whereas the Ataturk stadium, which was located closed to the fault, waterlogged only at high tide, as shown in Photo. 15(a). Walls, street lamppost, and woods, etc. stood almost vertical as shown in Photo. 15(b), which suggests that subsidence occurred slowly keeping the level ground.

Photo. 16. Vertical dislocation of a branch fault

A seabed measurement was carried out by means of a plumb bob near the ship of the Kocaeli University at the west of the subsided area. A promenade along the shore subsided under the sea; a top of the quay wall was evaluated to settle about 2.8 m. One of the authors visited this site several times for several months after the earthquake and found that the waterlogged depths of the Ferris wheel increased gradually, which indicates that the subsidence of the ground gradually progressed.

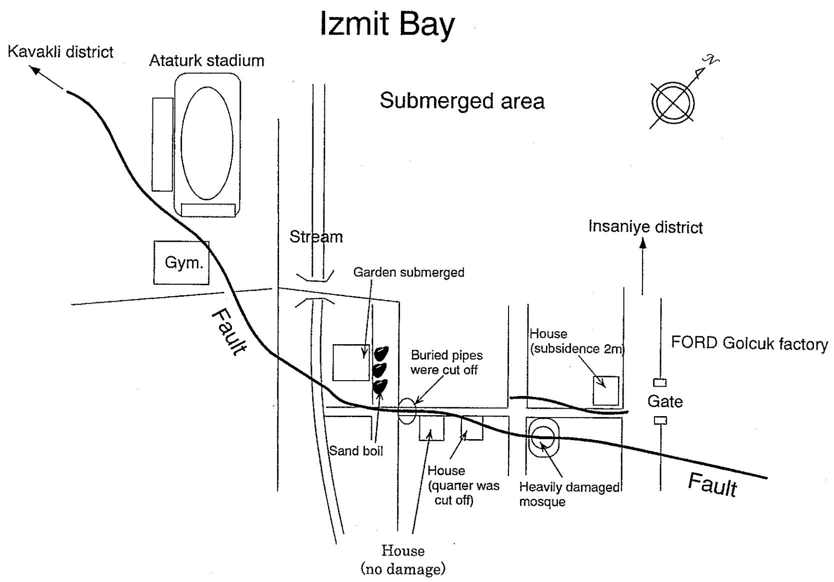


Fig. 14. Detailed map of fault and damage near the FORD Golcuk factory

Photo. 17. Subsided ground on the east of Golcuk

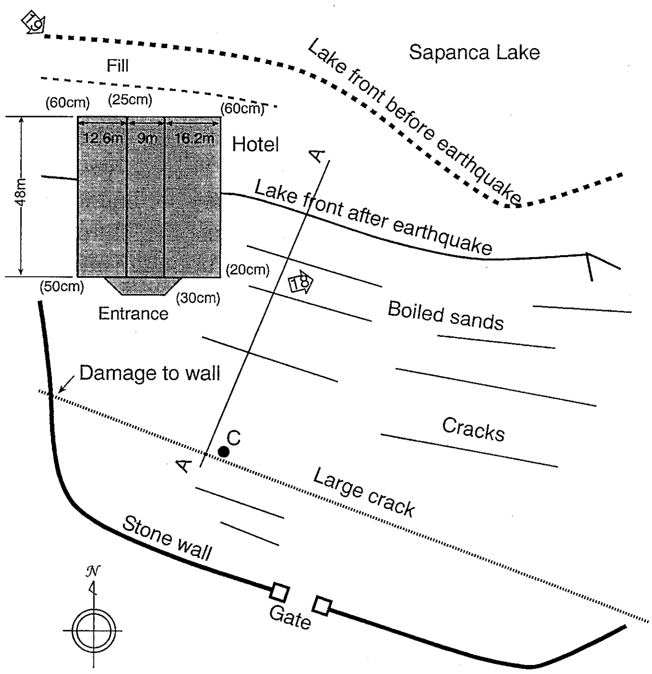


Fig. 15. Schematic figure showing damage at the Sapanca Hotel

Sand boils and cracks were found on the Sahil Cadesi and outside it in the submerged area. Therefore, a possibility that soil liquefaction played some role on the subsidence around the shoreline cannot be denied, but it is not supposed to be a major cause, considering the extent of the subsided area and purely vertical subsidence of the ground and surface structures.

The fault in Fig. 13 ran toward east or southeast outside the map, which is shown in Fig. 14. Structural damages were obtained along the fault due to vertical offset, as written in Fig. 14. The vertical offset of about 1.5 to 2 m continued inside the Ford Golcuk automotive factory located at the east end of Fig. 14 and continues more to the southeast direction.

Subsidence of the ground was continuously observed from Golcuk to the east along the shoreline for more than 10 km, as typically shown in Photo. 17.

DAMAGES AROUND SAPANCA LAKE

The Sapanca Hotel is located on the south coast of the Sapanca Lake. Figure 15 shows ground deformation around the Sapanca Lake. Here, locations of the lakeside may not be exact because there was no data on the old lakeside.

Traces associated with the liquefaction were widely found in the yard. There were many cracks running parallel to the lakeside and significant amount of sand boiled through Photo. 18 cracks. Photograph 17 shows the ground covered by boiled sand; almost all the ground is covered by boiled sand although it may be difficult to

Photo. 18. Sand boils in the yard of Sapanca Hotel

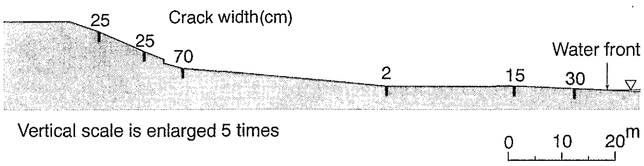


Fig. 16. Locations and width of cracks along A-A line

(a)

(b)

Photo. 19. Damage to Sapanca Hotel: (a) Aerial view. Settlement of the building and subsidence of fill and natural deposit occurrence, (b) Settlement of building

distinguish sand boils partly because of many fallen leafs that covered the ground surface. Figure 16 shows locations and widths of cracks along the A-A line with the elevation of the surface ground by means of a clinometer. A sum total of the crack width was about 1.7 m, which implies that lateral flow probably induced by soil liquefaction occurred.

The biggest crack ran in the N50°W to N60°W direction throughout the yard with a vertical offset of 10 to 20 cm. A stone masonry wall on the east of this crack was damaged. This crack was confirmed to continue on the road outside the yard in the southeast direction. Therefore, this crack may be caused not by soil liquefaction, but by a surface fault.

Ground subsidence in the north side of this large crack seems to become gradually large toward the lake. Subsidence was confirmed to continue towards east along the lakefront as partly seen in Photo. 19(a).

The Sapanca Hotel was set up in 1958 on the alluvial ground, which was the eastern wing of the current hotel. According to the hotel manager, the building settled during the earthquake of 1967 and was repaired after the earthquake. Then, a new building and an atrium, which connects two buildings, were built. The north of the hotel was filled for 20 m wide in 1983, which were also submerged, as shown in Photo. 19(a).

This building settled relative to the ground, and about a half of the hotel submerged, as shown in Photo. 19(b) and Fig. 15. Offset of about 20 to 30 cm was induced between each structural element, i.e., an old building, a new building, an atrium, and an entrance.

According to the hotel manager, the water level increased about 3 m just after the earthquake and guests on the second floor considered jumping into the lake in order to escape the sudden increase of water level. This implied that people thought a tsunami might hit the hotel. However, evidence of tsunami such as trance of water in the wall was not observed. Moreover, residents near the hotel did not feel a tsunami according to the interviews conducted. Therefore, people in the hotel might have felt the water flowing from the lake that was caused accompanying the settlement of the hotel. If this was so, then this suggests settlement occurred quickly.

A hotel employee who checked around the building at 7 AM the next morning after the earthquake found that the fill on the lake side had submerged a little, but the floor of the building did not submerged; settlement of the building and subsidence of the ground continued after the earthquake. He also reported that the huge sand boils and cracks in the yard were already there at that time.

The total amount of the settlement of the building can be evaluated roughly 1.5 m. On the other hand, settlement of the building relative to the ground surface is several tens cm, as shown in Fig. 15, in which relative settlement at the corner of the building is written in parentheses. Therefore, the ground itself is supposed to have subsided for about 1 m, as easily seen in

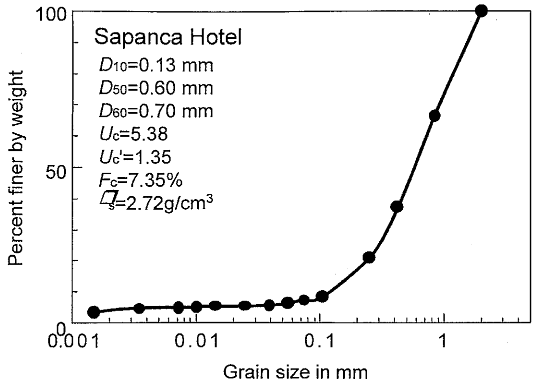


Fig. 17. Grain size distribution curve of the boiled sand

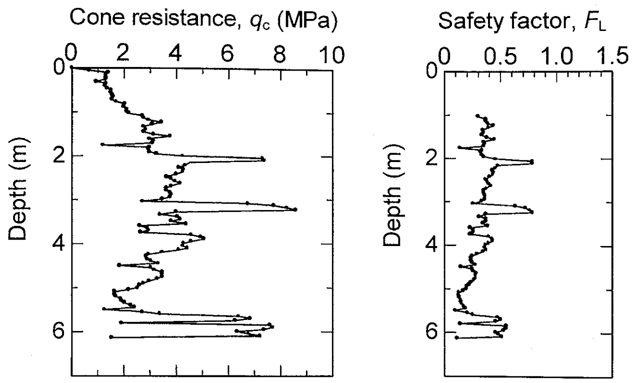


Fig. 18. CPT test result and evaluation of liquefaction potential: (a) CPT test result, (b) Safety factor against liquefaction

Photo. 19(a). Variety factors, such as a fault behavior, soil liquefaction and liquefaction-induced flow, may have affected the subsidence of the ground.

A soil test was carried out at point C in Fig. 15. A grain size distribution of the boiled sand in the yard is shown in Fig. 17. It is well-grained sand with fines contents less than 10% and a mean diameter of about 0.6 mm. Figure 18(a) shows the result of the cone penetration test. A thickness of the loose layer whose cone penetration resistance q_c is less than 4 MPa is about 6 m. A safety factor against soil liquefaction, F_L, is computed by a simplified method, i.e., to compute a ratio of liquefaction strength to the maximum shear strength during an earthquake. Liquefaction strength is evaluated based on Shibata et al. (1988), and a maximum shear stress caused by a ground shaking is evaluated by a method of Yoshimi and Tokimatsu (1983). The peak acceleration on the ground surface is assumed 400 cm/s^2, referring the peak acceleration of the observed record near the site. The result is shown in Fig. 18(b). The F_L value is smaller than unity in all layers, and less than 0.5 for almost all depths. This indicates that significant liquefaction occurred at this site.

SUMMARY AND DISCUSSION

Several kinds of geotechnical damage were observed during the 1999 Kocaeli earthquake. They can be summarized as follows:

Soil Liquefaction

Sand boils, which are a clear evidence of the onset of liquefaction, were found at several places. Liquefaction, however, did not seem to be a major cause of geotechnical damages because of the following several reasons.

There were several small fills in the earthquake affected area. Since all the fills that the authors found were lost because of submarine landslides or lateral and vertical movement of the ground, it is difficult to discuss the effect of soil liquefaction on the loss of the ground. According to interviews with residents, crashed rocks were used as a fill material in Ulasli and it was an ordinary fill material in this region. If other fills had been made with the same material, it would be difficult to have expected liquefaction in the fills.

As repeatedly described in the preceding, the slope of the river was steep. At Degirmendere, for example, a natural deposit was made of sand that includes many gravels. Therefore, it seems it would be difficult for liquefaction to occur.

Sand boils were not observed in the rest of the fill in the flowed out area although cracks were frequently observed. One should note, however, that this does not directly indicate that liquefaction did not occur. If lateral movement of the ground occurred earlier than sand spouting up to the ground surface, sand boils do not appear as excess porewater pressure decreases rapidly.

An example of this kind of damage are fills during the 1995 Hyogoken-Nambu earthquake where sand boils were not observed near the quay wall although liquefaction was supposed to have occurred. Lateral movement of the backfill ground was caused by the lateral movement of the quay wall under which the foundation ground was failed by shear but not by soil liquefaction (Iai, 1998). In other words, lateral movement of the quay wall whose cause was not soil liquefaction occurred earlier, and this caused lateral movement of the backfill ground. Therefore, if soil liquefaction of the backfill ground is the cause of the lateral movement of the quay wall, the ground would have been covered by boiled sand. Since sand boil was not observed at this site, soil liquefaction of the remained fill is supposed not to have been a main reason of the loss of the ground even if liquefaction occurred there.

Significant liquefaction was observed in the Sapanca Lake, too. The main cause of the ground subsidence was again supposed not to have been liquefaction. Volume change after the excess porewater pressure of the liquefied sand is an order of several percent (Nagase, 1988). Therefore, expected ground subsidence is an order of a few tens cm for the thickness of a liquefied layer of 6 m. This value looks too small to explain the subsidence of the ground. It seems sure, however, that relative settlement of the Sapanca Hotel was caused by soil liquefaction. Liquefaction seems also responsible of the lateral movement of about 2 m in the Hotel yard.

In summary, liquefaction caused several geotechnical damages such as lateral flow of ground and settlement of buildings, but this was not a major cause of the significant geotechnical damages widely observed in the investigated area.

Submarine Landslide

Loss of the ground was observed at several places such as Karamusel, Ulasli, Halidere and Degirmendere. A huge amount of soil moved in these places. According to the seabed movement, change of the seabed depth was of an order of 20 m, which is too large to consider that the vertical offset was caused by fault activities. Moreover, as can be seen from the case in Degirmendere where the location of the 4 story building is not known, not only vertical displacement but also a large amount of horizontal displacement occurred. Therefore, it is natural to consider that a submarine landslide occurred.

These flowed out areas have a common geotechnical feature in that they are alluvial fan deposit although in some cases only fill flowed out. Mountains are close by and the slope of the river is steep. In addition, as seen from Fig. 10 and Fig. 12, the slope of the seabed is also steep. Therefore, soils that had flowed from the mountain to the sea loosed a speed and deposited with its repose angle, i.e., in a fairly loose states. If so, it can be easily assumed that a submarine landslide occurred because of the failure of loose deposit. The slope of the new seabed is steep near the shore. Therefore, sedimentation as described above will be repeated. It is not certain that soil liquefaction became a trigger of the submarine landslide or if only an inertia force was sufficient to cause a slide. A surface fault may also be considered to have been a trigger for the slope instability.

It is noted that the masses are not balanced between the subsided part and lifted part in Figs. 10 and 12. The seabed map before the earthquake may not be sufficiently accurate because it had been developed for the traffic of ship; local irregularity and detailed configuration was not drawn. Another reason may be geological topology; mass movement might occur not only towards the direction normal to the shore but also parallel to the shore if the site juts out into the sea such as in Degirmendere.

Surface Fault

The surface fault seemed to cause two different types of damage. The one was a direct damage to the structures when offset of the ground took place. Structures on the surface fault were collapsed by shearing or tearing. The other was ground subsidence in a wide area. Since the former is easy to recognize, we will not discuss it.

Ground subsidence was observed in a widespread area along the shoreline from Golcuk to the eastern end of the Izmit Bay and the Sapanca Lake. As typically seen in Golcuk in Fig. 13, the subsided area was bounded by the surface fault in the land. Faults sometimes had vertical offset. In addition, subsidence occurred in a very wide area. It was supposed to have occurred slowly keeping the ground level, because surface structures such as trees and street lampposts stood vertical although they had submerged into the sea.

These areas are bounded by two faults. One is a main fault running in the north-east in the Izmit Bay as an extension of the main fault shown in Fig. 1 and the other is a branch fault running in the south-west as seen in Fig. 14. This situation suggests that this subsidence occurred because of the fault dislocation. In other words, areas bounded by two faults subsided due to the pull apart mechanism of the faults.

CONCLUDING REMARKS

Significant geotechnical damage was observed along the south shoreline of the Izmit Bay and south of the Sapanca Lake. These damages are supposed to have been caused by four factors. Submarine landslide occurred at the alluvial fan deposit where sand had deposited softly because the slope of the seabed was steep. Subsidence of the ground occurred in widespread area that is sandwiched by two faults. Surface fault also caused direct damage to the structures on the fault. Soil liquefaction was also observed at several places, but it was not supposed to be a main cause of significant geotechnical damage.

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