Impact of liquefaction on coastal structures in the 1999 Kocaeli, Turkey earthquake

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IMPACT OF LIQUEFACTION ON COASTAL STRUCTURES IN THE 1999 KOCAELI, TURKEY EARTHQUAKE

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ABSTRACT

An inventory is presented of the damage to marine structures caused by liquefaction in the 17.August, 1999 Kocaeli, Turkey earthquake. The inventory includes twenty-four coastal structures. The observations show that backfills behind quay walls and sheet-piled structures were almost invariably liquefied; quay walls and sheet-piled structures were displaced seaward; storage tanks near the shoreline were tilted; there were cases where the seabed settled, and structures settled and collapsed; the observations also show that the rubble-mound breakwaters survived the earthquake with very little or no damage.

KEY WORDS: Coastal structures; earthquake; Kocaeli (Turkey) earthquake liquefaction; pore pressure; quay walls; tsunami; waves.

INTRODUCTION

Liquefaction is a process in which shear strength of soil goes to zero due to developed excessive large pore pressures, and the soil behaves like viscous liquid producing excessive deformations or movements as a result of transit or repeated loads (NRC, 1985; Youd and Idriss, 2001).

The transit/repeated loads may be induced by effects such as earthquakes; shocks (the shock effects may be caused by a sudden failure of a slope, or blasting effects); surface waves; rocking motions that structures may execute under cyclic loadings (rocking motion of vertical-wall breakwaters under waves, for example) and so on.

Strength loss and large deformations of such soils can result in failures such as flow slides, slope instabilities, and increased bending forces on piles and other embedded structures (Chaney and Pamukcu, 1991, Hyodo, et al. 1999). With the soil liquefied, buried structures (such as pipelines) may float to the surface; large individual blocks (like those used for scour protection at

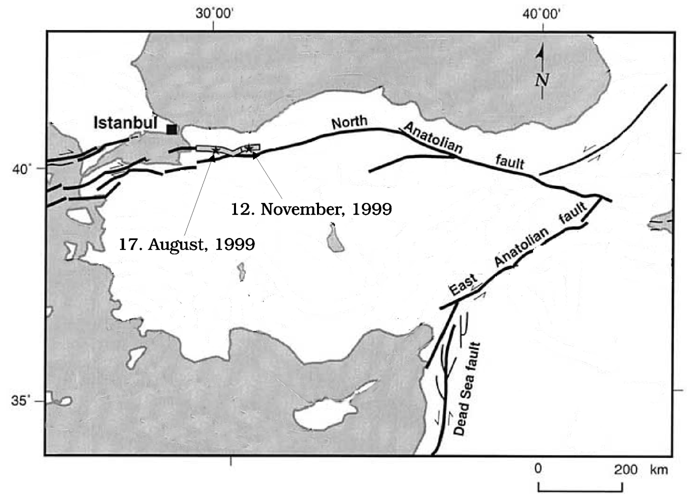

Fig. 1. The North Anatolian Fault. Adapted from Lettis et al. (2000 a).

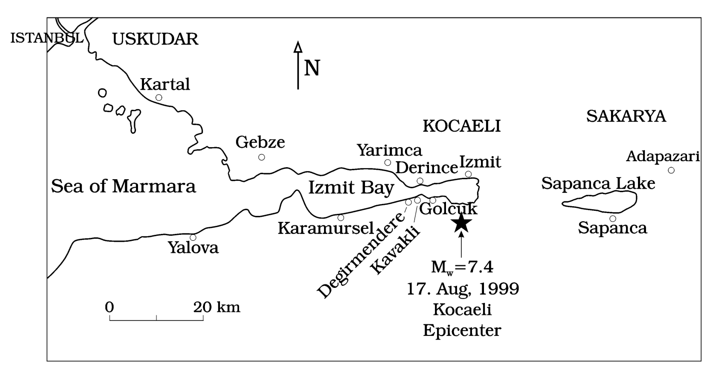

Fig. 2. Map of the area stricken by the 17. August, 1999 Kocaeli, Turkey earthquake.

marine structures) may sink in the seabed; sea mines may sink in the seabed and eventually disappear. Sand boils, ground fissures and/or lateral spreads are the field evidence of marine liquefaction (Youd and Idriss, 2001).

In 1999, Turkey experienced two earthquakes: (1) The 17.August, 1999 Kocaeli Earthquake, and (2) The 12.November, 1999 Duzce Earthquake. Both occurred on the North Anatolian Fault in the North Western Turkey (Fig. 1). The Kocaeli earthquake, which had a magnitude of M_w = 7.4 with its epicentre located rather close to the south east corner of the Izmit Bay (Figs. 2 and 3) and lasted 42 s with the largest horizontal acceleration of 0.407*g* (Safak et al., 2000), caused extensive damage to marine structures along the coast of the Izmit Bay.

Boulanger et al. (2000) discuss the damage to and the performance of the marine structures in the Kocaeli Earthquake in the special volume of the journal Earthquake Spectra (2000) dedicated to the this earthquake. Gunbak, Muyesser and Yuksel (2000) give an "inventory" of the damage inflicted over more than 20 marine structures while Yuksel et al. (2000, 2001) further elaborate on the effects of the Kocaeli Earthquake on the majority of the marine structures and coastal areas in the region.

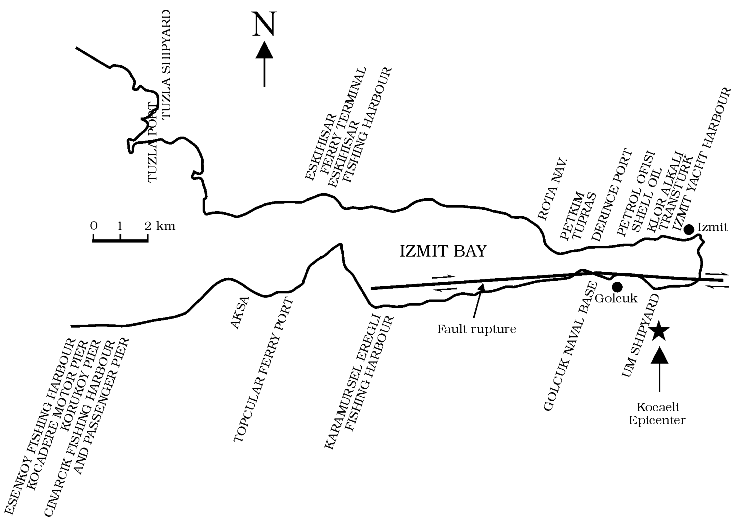

Fig. 3. Partial layout of coastal structures along the coastline of the Izmit Bay. Site of seabed settlements extend on the Northern coast from Rota Nav. to Izmit. Adapted from Gunbak et al. (2000), Yuksel et al. (2000, 2001).

The purpose of the present paper is to summarize the early results of a study where the focus is the impact of liquefaction on coastal structures in the 17.August, 1999 Kocaeli earthquake. The data compiled is mainly from Boulanger et al. (2000), Gunbak et al. (2000), Yuksel et al. (2000, 2001) and from a field visit of the authors, which took place 1-9.July, 2001.

INVENTORY OF THE DAMAGE CAUSED BY SEISMIC-INDUCED LIQUEFACTION, AND ANALYSIS

Table 1 lists an "inventory" of the damage to coastal structures along the coastline of the Izmit Bay (Table 1 is given at the end of the paper). The data has been compiled mainly from Boulanger et al. (2000), Gunbak et al. (2000), Yuksel et al. (2000, 2001) and during a visit by the present authors made on 1 thru 9.July, 2001, as mentioned previously. The names of the coastal facilities given in Column 2 in Table 1 are indicated in Fig. 3.

The following observations can be made from Table 1.

1. Almost invariably, backfill areas behind quay walls and sheet-piled structures failed due to liquefaction, as in Tuzla Port (Row 1, Table 1), Tuzla Shipyard (Row 2 C), Eskihisar Ferry Terminal (Row 3 A and B), Derince Port (Row 8 A and B), Shell Oil Facility (Row 11), Izmit Yacht Harbour (Row 14), UM Shipyard (Row 15), Golcuk Naval Base (Row 16 B), Karamursel Eregli Fishing Harbour (Row 17 B), Topcular Ferry Pier (Row 18), Cinarcik Fishing Harbour (Row 20) and Esenkoy Fishing Harbour (Row 24 B) although, in some cases, the failure in the backfill areas may have been influenced by other factors as well. From the table, the settlement in the backfill areas varies from O(10 cm) to O(1 m) in which the symbol O indicates the order of magnitude. The magnitude of the settlement generally decreases with the distance from the epicenter of the earthquake (Table 1 and Fig. 3), as anticipated. One of the implications of this kind of failure is that rail foundations for cranes present in the area settle unevenly, leading to tilting of (and eventually damage to) cranes, as revealed clearly in the case of Derince Port (see photographs in Boulanger et al., 2000, Yuksel et al., 2000).

2. Quay walls and sheet-piled structures were displaced seaward, as in Tuzla Port (Row 1 in Table 1), Tuzla Shipyard (Row 2 C), Derince Port (Row 8 A), Izmit Yacht Harbour (Row 14), Golcuk Naval base (Row 16 B), the displacements being in the range from O(10 cm) to O(1 m).

3. Storage tanks near the shoreline tilted due to liquefaction, as in Petrol Ofisi facilities (Row 10 C in Table 1), Klor Alkali facilities (Row 12) and Transturk facilities (Row 13).

4. There are cases where the seabed settled, as in Rota Navigation Trade Pier (Row 5 in Table 1), Tupras Refinery (Row 7), Petrol Ofisi facilities (Row 10 A) and Shell Oil Piers (Row 11), the settlement being in the range O(10 cm)-O(1 m). However, it is not clear if these settlements are caused by liquefaction (and therefore by the resulting consolidation) or by other processes such as slope instability, surface rupture, etc, or a combination of those processes.

5. There are also cases where structures settled, as in Petkim facilities (Row 6 in Table 1) and Petrol Ofisi facilities (Row

10 A), or they settled and eventually collapsed below water as in Shell Oil Piers (Row 11), Transturk facilities (Row 13), UM Shipyard (Row 15) and Aksa facilities (Row 19). Again, it is not quite clear if these settlements (and collapses) are caused by liquefaction or by other processes such as slope instability, surface rupture, etc, or a combination of those processes.

6. It is interesting to notice that although a large reclamation area settled in front of the 95.000-ton capacity silos in Derince Port TMO facilities (Row 9, Table 1), these silos survived the earthquake. Likewise, the 510-ton shipyard crane also survived the earthquake despite the large settlement of the area adjacent to this structure in UM Shipyard (Row 15). These structures survived the earthquake largely because of their foundations; both the TMO silos and the UM crane are supported on piles penetrating into the stiff soil, and therefore avoided any problem caused by liquefaction/weakening of the soil in the top layers due to pressure buildup. It is also interesting to note that the new pier in Petrol Ofisi facilities (Row 10 B in Table 1) has also survived the earthquake while the neighbouring old pier has not. This may also be attributed to the fact that the piles in this case, too, penetrated into the stiff soil.

7. The rubble-mound breakwaters survived the earthquake with practically no damage or very little damage, as in Tuzla Shipyard (Row 2 A in Table 1), Eskihisar Fishing Harbour (Row 4 A), Karamursel Eregli Fishing Harbour (Row 17 A), Cinarcik Fishing Harbour (Row 20) and Esenkoy Fishing Harbour (Row 24). However, it is not known if the seabed at these locations experienced liquefaction/weakening due to buildup of pore pressure.

DISCUSSION

Liquefaction of seabed

As mentioned previously, although the settlement of the seabed has been observed along the North coast of Izmit Bay at Rota Navigation Trade Pier, Tupras Refinery, Petrol Ofisi facilities and Shell Oil Piers (Fig. 3 and Rows 5, 7, 10 A, 11 in Table 1), it is not clear if these settlements are caused by liquefaction (and therefore by the resulting consolidation) or by other processes such as slope instability, surface rupture, etc., or a combination of those processes. This subsection discusses the possibility of liquefaction/weakening of the seabed by the shaking caused by the 17.August, 1999 earthquake.

Table 2 depicts a partial list of the earthquakes experienced in the vicinity of Sea of Marmara and North Anatolian Fault. Note the magnitudes of these past earthquakes (namely up to M_w = 7.1) before the 17.August, 1999 Kocaeli Earthquake occurred.

Now, given that the soil had been heavily shaken by the previous earthquakes (Table 2), we expect that there was not much "room" for the rearrangement of soil grains and therefore for buildup of pore pressure and hence for the resulting liquefaction/weakening of the seabed when the 17.August, 1999 earthquake occurred.

However, there is clear evidence that the soil has been liquefied in areas such as that marked "Liquefaction Zone" in the map in Fig. 2.6b of the paper by Lettis et al. (2000 b), the area to the East of Naval Base in Golcuk (see Fig. 3 for the location). Although

1. the locations where the seabed settlements were observed are not as close to the earthquake epicentre as the previously mentioned "Liquefaction Zone", and also
2. the soil in these locations is essentially different from that in this "Liquefaction Zone" area,

Table 2. A partial list of earthquakes that occurred in the vicinity of Sea of Marmara and North Anatolian Fault[1] (Taymaz, 1999).

Date	Latitude	Longtitude	Magnit.
20.06.1943	40.70	30.38	M = 6.3
13.08.1951	40.95	32.57	M_s = 6.7
26.05.1957	40.66	30.89	M_s = 7.0
18.09.1963	40.90	29.20	M_s = 6.4
09.10.1964	40.30	28.23	M_s = 6.9
22.07 1967	40.67	30.69	M_s = 7.1
30.07.1967	40.72	30.52	M_s = 5.6
03.09.1968	41.81	32.39	M_s = 6.6
05.10.1977	41.02	33.57	M_s = 5.8
05.07.1983	40.33	27.23	m_b = 5.5
21.10.1983	40.54	30.05	m_b = 5.1
24.04.1988	40.77	28.73	m_b = 5.0
17.08.1999	40.709 (Kocaeli)	29.998	M_w = 7.4
13.09.1999	40.765 (Marmara)	30.072	M_w = 5.9
11.11.1999	40.804 (Duzce)	30.260	M_w = 5.7
12.11.1999	40.790 (Duzce)	31.070	M_w = 7.1

[1] Note that M_s is the surface wave magnitude, M_w the moment magnitude and m_b the body wave magnitude. The relationships between these magnitudes are that M_w and M_s are rather close to each other for M_w smaller than about 8, while m_b becomes increasingly smaller than M_w when M_w becomes larger than about 6, Kramer (1996, p. 49).

the possibility of the seabed liquefaction (or weakening) may not be entirely ruled out. One reason why the seabed may be liquefied (or weakened) by the shaking of the 17.August, 1999 earthquake may be that this latest earthquake had a magnitude, which is significantly larger than the previous ones (the amplitude of the ground motion being at least a factor of 2 larger in the M_w = 7.4 earthquake than, for example, the M_w = 7.1 earthquake). It may also be noted that the duration of the earthquake is also an influencing factor. Unlike the liquefaction in on-land areas, the seabed is also subject to waves, another effect to cause liquefaction. (The seabed liquefaction under waves may occur in two forms, the residual liquefaction and the momentary liquefaction, see for example, Sumer and Fredsøe, 2002, Chapter 10). Since the seabed has a long history of wave exposure, it may be expected that the soil is well consolidated under the action of waves, and hence, again there was not much room for the accumulation of the pore pressure with the shaking of the 17.August, 1999 earthquake, similar to the effect of the long history of shaking due to the previous earthquakes. However, the wave statistics predicted from the wind data (with a 50-year significant wave height of O(1-2 m) and with a 50-year significant wave period of O(5 s) at Karamursel (Fig. 2) for water depths of O(20 m), Y. Yuksel, 2001, personal communication) implies that the waves will not induce any significant buildup of pore pressure or any significant effect of momentary liquefaction, and therefore the seabed may still have experienced liquefaction (or weakening) due to the shaking of the 17.August, 1999 earthquake.

Liquefaction of backfills

This subsection discusses two aspects of the backfill failure described in the preceding paragraphs:

1. the backfill material, and
2. the additional force exerted on the quay wall/sheet-piled structure.

As mentioned in the previous section, the backfills behind the quay walls and sheet-piled structures were almost invariably liquefied in the 17.August, 1999 earthquake. Although the backfill material varied from one case to another, it was typically hydraulically-placed sand from the seabed, as in the case of Derince Port.

A relevant question here is: Could the liquefaction failure have been avoided had the backfill material been replaced with a coarser material, a material which is sufficiently permeable so that all pore pressures developed in the backfill would dissipate as rapidly as they develop? Unfortunately, no data exists in conjunction with the 17.August, 1999 earthquake to reveal as to whether this is the case, and, if so, how coarse this material should be.

One of the implications of liquefaction (or a significant buildup of pore pressure) in the backfill is that the quay wall/sheet-piled structure undergoes an additional, seaward-directed horizontal (or almost horizontal) force caused by the accumulated pore pressure in the backfill behind the structure. This latter force contributes to the total horizontal force on the structure in the outward direction. In the liquefied state, the pressure acting on the wall is the hydrostatic pore pressure, $\gamma_w z$, plus the accumulated pore pressure, which is equal to the initial effective stress, the overburden-pressure value, $\sigma_0' = \gamma' z\ (1+2k_0)/3$ in which γ_w is the specific weight of water, z the depth measured downwards from the surface of the backfill, k_0 the coefficient of lateral earth pressure and γ' the submerged specific weight of the backfill material. (It may be noted that (1) the pressure on the wall in the "undisturbed" case is $\gamma_w z$ plus $k_0\gamma' z$; and (2) the initial effective stress has been taken as $\sigma_0' = \gamma' z\ (1+2k_0)/3$ rather than $\gamma' z$ in the above analysis on grounds that, this, when taken as $\sigma_0' = \gamma' z\ (1+2k_0)/3$, gives more realistic results for the liquefaction criterion, as observed in the works of McDougal et al., 1989, Jeng, 1997 and Sumer et al., 1999 in conjunction with liquefaction of soils under waves). From the preceding analysis, there is an additional force on the wall in the outward direction in the case of the liquefied backfill equal to $(1/2)\ \gamma' h^2\ (1-k_0)/3$ in which h is the height of the wall. This additional force obviously helps displace the structure seaward. As mentioned earlier, this kind of outward displacements of quay walls and sheet-piled structures have indeed been observed in the 17.August, 1999 earthquake, in Tuzla Port, Tuzla Shipyard, Derince Port, Izmit Yacht Harbour and Golcuk Naval Base (Rows 1, 2 C, 8 A, 14, 16 B in Table 1).

Remarks on the implication of tsunami for soil liquefaction

The 17.August, 1999 earthquake generated tsunami waves in the Izmit Bay. Yalciner et al. (2000), from their field surveys, concluded that a major tsunami was generated due to a large tectonic subsidence near and/or at the shoreline. This tsunami had a period shorter than 1 minute. It arrived at the Southern coasts one minute after the earthquake, and it arrived at the Northern coasts a few minutes after the earthquake. The sea receded first and subsequently rose and flooded the in-land areas with values of run-up heights of up to 2.5 m. Yalciner et al. also concluded that tsunami waves may have also been generated by sediment slumping in addition to tectonic subsidence.

Although no study is yet available, investigating the liquefaction of soil under tsunami waves near the shoreline, it may be expected that strong vertical (upward directed) pore-pressure gradients may be generated during a tsunami, particularly during the drawdown stage. This latter effect may help reduce the stiffness of the soil, eventually leading to liquefaction. However, how much this process has contributed to the observed settlements of the seabed and the observed settlements (and collapses) of the structures referred to in the preceding paragraphs (items 4 and 5 under Inventory of the Damage Caused by Seismic-Induced Liquefaction and Analysis) is unknown. Likewise, the contribution of the tsunamis to massive coast subsidences particularly at Kavakli and Degirmendere areas (reported in Bardet et al., 2000, see the map in Fig. 2 for these locations) is also unknown.

In the previous subsection, we have discussed the forces exerted on quay walls and sheet-piled structures by pore pressure, which tend to displace the structure in the seaward direction. Now, immediately after the earthquake, this force is equal to the undisturbed pore pressure force plus the accumulated pore pressure force, as described in the preceding subsection. With the water receded during the tsunami a few minutes after the earthquake, the hydrostatic pressure force on the wall at the sea side will decrease or completely vanish, and therefore the wall will undergo a relatively larger, seaward resultant pressure force. This effect may have played a significant role in the observed seaward displacements of quay walls and sheet-piled structures mentioned earlier.

CONCLUSIONS

1. Backfill areas behind quay walls and sheet-piled structures

failed due to liquefaction.

2. Quay walls and sheet-piled structures were displaced seaward. Liquefaction in backfill areas may have contributed to the seaward displacements of these structures.
3. Storage tanks near the shoreline were tilted due to liquefaction.
4. There are cases where the seabed settled, and there are also cases where structures settled and collapsed below water. It is not clear, however, whether these incidents are due to liquefaction, or due to other processes such as slope instability, surface rupture, etc, or due to a combination of these processes.
5. Two large structures (95.000-ton capacity silos and a 510-ton shipyard crane) and one newly constructed pier survived the earthquake despite the large settlement of the areas adjacent to these structures largely because of their foundations; namely these structures are supported on piles penetrating into the stiff soil.
6. The rubble-mound breakwaters survived the earthquake with practically no or very little damage.

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Table 1. "Inventory" of the damage to coastal structures caused by liquefaction in the 17. August, 1999 Kocaeli, Turkey earthquake.

No (1)	Name (2)	Structure (3)	Damage? (4)	Damage caused by liquefaction? (5)	Comments (6)	Reference (7)
1	Tuzla Port	Block-type quay wall with coarse limestone backfill	Yes	No?	• Quay wall was displaced seaward by O(40 cm). • Backfill settled by O(10 cm). No direct evidence of liquefaction (i.e., no sand boils)	Boulanger et al. (2000)
2	Tuzla Shipyard	A. Rubble-mound breakwater	No			Gunbak et al. (2000)
		B. Block-type breakwater	No			
		C. Block-type quay wall	Yes	Yes?	• The backfill area settled by O(20 cm). • Two rows of blocks between –1.7 m and –6 m depth moved seaward relative to neighboring blocks by O(20 cm).	
3	Eskihisar Ferry Terminal	A. Block-type quay wall	Yes	Yes?	• The backfill area settled by O(1-2 cm).	,,
		B. Sheet-piled structure	Yes	Yes?	• A sink hole of O(20 m^2) was observed behind the sheet piled structure	,,
4	Eskihisar Fishing Harbour	A. Rubble-mound breakwater	Very slight damage	No?		,,
		B. Block-type quay wall	,,	,,		
5	Rota Navigation Trade Pier	Pier supported on steel pipe piles	No		• Diver inspection showed O(70 cm) settlement of the seabed. No settlement of / damage to the piles.	,,
6	Petkim (Yarimca Petrochemical Complex)	Pier supported on reinforced-concrete piles, and two loading dolphins supported on reinforced concrete piles and two on steel-pipe piles	Yes	No?	• Reinforced concrete piles were damaged above the water surface. • The pier head experienced O(5-10 cm) sinking relative to the access trestle. Furthermore, lateral movements of O(40 cm) were also experienced.	Boulanger et al. (2000) and Visit by the present authors, 1-9. July, 2001
7	Tupras Refinery	Pier supported on steel pipe piles. The piles filled with concrete.	Yes	No	• Steel piles were buckled at/above the water surface. • Ground deformations and cracking along the shoreline were observed near the pier.	Boulanger et al. (2000) and Gunbak et al. (2000)
8	Derince Port	A. Block-type quay wall (Berths 6 through 8)	Yes	Yes	• The quay walls were displaced towards the sea by O(0.1-0.5m). • The backfill area settled by O(0.5-1 m). • There were very clear indications of liquefaction of the backfill area (and also in and around two warehouses located in this area), in the form of sand boils; Sand volcanoes the size O(30 cm) were observed very clearly.	Boulanger et al. (2000), Gunbak et al. (2000) and Visit by the present authors, 1-9. July, 2001
		B. Quay wall with steel-pile-supported deck and sheet-pile wall (Berths 3 through 5)	Yes	Yes?	• Minor damage at pile caps in some small number of piles. • The backfill area settled. No sand boils were observed, however.	
9	Derince Port, TMO Silos	Pile-supported, large, 95.000 ton capacity silos near the shoreline	Very minor	Yes?	• A large reclamation area in front of the silos settled (by O(1.5-3 m)). However, practically no damage occurred to the silos except there is a very minor damage at the top of the corner pile in the first row at the seaside.	Boulanger et al. (2000) and Visit by the present authors, 1-9. July, 2001

10	Petrol Ofisi	A. Old pier: Pier supported on reinforced concrete piles, the piles being almost entirely in the soft soil	Yes	No?	• The pier was tilted and displaced laterally (away from the new one), and one segment of the pier settled by O(7 cm). • The sea bottom settled. • Divers reportedly did not feel safe near the sea bottom because the sediment appeared unstable.	Boulanger et al. (2000) and Gunbak et al. (2000)
		B. New pier: Pier supported on reinforced concrete piles for the first 60 m, and on steel-pipe piles for the outer 100 m, constructed near the old pier and parallel to it, the piles penetrating into the stiff soil	Virtually none			
		C. Tanks near the shoreline	Yes	Yes?	• One of the two tanks, full at the time of the earthquake, tilted O(2-3%). • Ground cracking and deformations were visible in the fill between the tanks and the shoreline wall.	
11	Shell Oil Piers	Two piers supported on steel-pipe piles; 18 m by 12 m dolphin on steel piles; Fill area of 5 m by 57 m, encircled by reinforced concrete sheet piles	Yes	?	• The piers were extensively damaged and largely collapsed below water. • The fill area collapsed below water • The dolphin also collapsed below water. • A large rupture hole was observed in the seabed at the tip of the pier; this hole was later filled with sediment due to natural processes.	Boulanger et al. (2000), Gunbak et al. (2000) and Visit by the present authors, 1-9. July, 2001
12	Klor Alkali	Pier supported on reinforced concrete piles	Yes	Yes?	• The pier largely collapsed below water. • Storage tanks near the shoreline tilted.	Yuksel et al. (2000) and Kaya et al. (2001)
13	Transturk	Two piers supported on steel-pipe piles	Yes	?	• One of the piers largely collapsed below water. • The other pier remained intact. • One of the tanks closest to the shoreline was visibly tilted.	Boulanger et al. (2000)
14	Izmit Yacht Harbour (Public Marina)	Quay walls made up of 24 m long concrete segments supported on four row of piles, the inner three rows of piles being reinforced concrete and the outer row consisting of closely spaced concrete-infilled steel pipe piles	Yes	Yes?	• The backfill area adjacent to the shoreline section settled by as much as O(80 cm) due to liquefaction. • One segment of the wall was displaced towards the sea by O(10 to 30 cm). • Separation between neighboring segments of O(3 to 8 cm) was observed. • Piers extending perpendicular to the quay wall experienced a separation of O(3 cm) at the wall ends.	Boulanger et al. (2000), Gunbak et al. (2000) and Visit by the present authors, 1-9. July, 2001
15	UM Shipyard	Pier supported on steel pipe piles	Yes	Yes?	• The pier was completely damaged and collapsed below water. According to eyewitnesses, the collapse was gradual, implying that the failure was likely due to liquefaction, slope instability or both. • The fill area containing part of the ship yard on the shore settled over an area of O(50 m) and disappeared into the sea, the settlement being O(1 m) near the shoreline. • The 510-ton shipyard crane survived the earthquake with minor damage.	Boulanger et al. (2000), Gunbak et al. (2000) and Visit by the present authors, 1-9. July, 2001
16	Golcuk Naval Base	A. Seven piers supported on reinforced concrete piles	Yes	?	• Extensive damage due to surface rupture and ground failure, or a combination of both. Note that the fault rupture, involving as much as 5.5 m right-lateral slip and 2.5 m local vertical displacements (Earthquake Spectra, 2000, Chapter 2), ran through the Golcuk Naval Base, see Fig. 3.	Boulanger et al. (2000) and Gunbak et al. (2000)

		B. Sheet-piled quay wall	Yes	?	• Extensive seaward deformation of the sheet piling due to surface rupture and ground failure. • The backfill settled by O(1 m).	
		C. Dockyards	Yes	?	• Extensive damage due to surface rupture and ground failure, or a combination of both.	
17	Karamursel Eregli Fishing Harbour	A. Rubble-mound breakwater	Very slight damage	?	• A differential movement between the neighboring wave screens of O(10 cm).	Gunbak et al. (2000)
		B. Block-type quay wall	Yes	Yes?	• Crack between the crown wall and backfill of O(30 cm). • The backfill area settled by O(25 cm).	
18	Topcular Ferry Pier	Two piers supported on steel pipe piles	Yes	Yes?	• The fill area settled by O(15 cm).	,,
19	Aksa Piers and Dolphins	Two trestles supported on reinforced concrete piles and six dolphins supported on steel pipe piles	Yes	?	• One trestle was displaced laterally by O(25 cm). • The other trestle largely collapsed below water. • Four dolphins collapsed below water.	,,
20	Cinarcik Fishing Harbour	Rubble-mound breakwater		?	• Crack of width O(30 cm) along the breakwater crown wall near the backfill area. • Concrete slabs in the backfill area were separated (O(15 to 20 cm)) by swelling and sinking.	,,
21	Cinarcik Passenger Pier	Pier supported on steel piles	No			,,
22	Korukoy Pier	Pier supported on reinforced concrete piles	No			,,
23	Kocadere Motor Pier	?	No			,,
24	Esenkoy Fishing Harbour	A. Rubble-mound breakwater	Minor damage	?	• Cracks along the crown wall	,,
		B. Block-type quay walls	Yes	Yes?	• The backfill settled by O(3 cm)	