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PERFORMANCE OF INDUSTRIAL FACILITIES DURING THE 1999, KOCAELI, TURKEY EARTHQUAKE

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SUMMARY

Twenty-four facilities representing different industries in the epicentral region were surveyed in the days following the 1999 Kocaeli earthquake (M_w7.4). Approximately forty percent of heavy industry in Turkey was concentrated in the region affected by this earthquake. Information on typical industrial-facility construction practice in Turkey is presented. Since many of the industrial facilitates were designed according to U.S. and European standards, their performance is relevant to industrial facilities in other seismically active regions of the world. This paper summarizes reconnaissance observations from some of these industrial facilities including petrochemical facilities, automotive facilities, and power generation and transmission facilities.

INTRODUCTION

The 1999 Kocaeli earthquake occurred in northwestern Turkey, causing extensive damage to industrial facilities; see Figure 1. Many of these industrial facilities were located a short distance from that segment of the North Anatolian fault that ruptured during the earthquake. Twenty-four facilities representing different industries in the epicentral region were surveyed by an NSF-supported reconnaissance team shortly after the earthquake. Since many of the inspected facilities were designed in accordance with U.S. and European standards, their seismic performance is an indicator of the likely performance of industrial facilities in other seismically active regions of the world.

The widespread damage to industrial facilities had a substantial impact on the economy of the region in terms of both direct and indirect losses. Direct losses were a result of structural and nonstructural damage, including damage to equipment, mechanical, electrical, and plumbing systems. Indirect losses accrued from business interruption due to damage, loss of utilities, loss of transportation infrastructure, etc. To characterize damage and likely loss, a performance scale for structural and nonstructural components is defined. The performance scales for structural and nonstructural damage are reproduced from [1] in Tables 1 and 2 A list of the industrial facilities visited by the reconnaissance team, relevant construction information, and an approximate number of employees in each facility are presented in Table 3. The

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degree of damage (and thus loss) suffered by each facility is also listed in Table 3. Much additional information on the behavior of industrial facilities in the impacted region can be found in [1], [2] and [3]

Figure 2 shows 5%-damped elastic acceleration response spectra for 13 recorded acceleration histories in the epicentral region; the median spectrum is also shown. For reference, the figure also presents the elastic design spectra calculated using the provisions of the Turkish seismic code [4] and the 1997 Uniform Building Code (UBC) [5] for rock and soft soil sites. To construct the UBC spectra, a near-field spectral amplification factor of 1.0 was assumed; soil type S_E was assumed for the soft soil spectrum. The seismic demands of Figure 2 indicate that the industrial facilities in the epicentral region were subjected to levels of shaking not inconsistent with design-basis shaking for new building structures.

The following sections summarize the observations from the post-earthquake reconnaissance of some of the industrial facilities listed in Table 3, including petrochemical facilities, automotive facilities, and power generation and transmission facilities.

PETROCHEMICAL INDUSTRY

There is a heavy concentration of petrochemical facilities on the northern side of Izmit Bay (see Figure 1). Many of the badly damaged facilities were located within 15 km of the epicenter where the levels of earthquake shaking were moderate to high. Based on discussions with management staff at the facilities visited by the reconnaissance team, production at many of these facilities was highly dependent on an adequate supply of raw materials and product from other facilities in the region. The failure of or gross damage to some facilities in the epicentral region had a cascading effect on other businesses in the region. The Tupras refinery and the Petkim petrochemical plant were two such facilities.

Tupras Refinery

Significant damage occurred at this state-owned and state-managed oil refinery located approximately 19 km from the epicenter and within 2.5 km of the ruptured fault line. Prior to the earthquake, the Tupras refinery produced more than 200,000 barrels of oil-related product per day: approximately one-third of Turkey's total output. The Tupras product was primarily for domestic consumption, much of which was local to industry in the region affected by the earthquake. The Tupras refinery was designed and constructed in the early 1960s by U.S. contractors following U.S. standards of practice at that time. As such, the earthquake damage observed to the Tupras refinery would not be unexpected at refineries of a similar age that are located in other high seismic regions of the world. The plant was expanded in size and production in 1974 and 1983.

The damage to the Tupras refinery was widespread and included port facilities, storage tanks, cooling towers, stacks, and crude-oil processing units. Much of the damage was fire related: an indirect consequence of the earthquake shaking. The fire-fighting capability of the refinery was lost immediately following the earthquake because of multiple ruptures of the water pipeline from Lake Sapanca, 45 km east of the refinery. The refinery received all of its water from this lake. In the days immediately following the earthquake, the resulting fires were contained by aerial bombardment with foam. At the height of the conflagration, a 3-km region around the refinery was evacuated. The fires were extinguished by water drawn from Izmit Bay by using portable diesel pumps and flexible hose that didn't arrive at the refinery until three days after the earthquake. Had this fire-fighting equipment been stockpiled at the refinery in advance of the earthquake, the fires that took five days to extinguish would have been put out much sooner. For information, the Tupras refinery was visited two weeks after the earthquake and approximately ten days after the fires had been extinguished. Valuable lessons for refineries on the West Coast of the U.S. can be learned from the problems encountered by the fire-fighting and emergency-response at the Tupras refinery.

Figure 3 shows the main processing facility including part of the tank farm (in the foreground), and the loading and unloading jetty that serviced the refinery. Failure of this jetty prevented the loading and unloading of all fuel-oil products at the refinery. Ships tied up to the long arm of the T-shaped jetty (oriented north-west to south-east in the figure, where the top of the page is north). The jetty was composed of a reinforced concrete deck that was supported on steel piles. Modest ground failure was observed around the approach to the jetty. The support to the crude-oil pipeline that ran along the seawall near the jetty was lost (near Point A in Figure 3b). These pipes transferred fuel oil and other products between the refinery and ships tied to the jetty. The jetty was damaged due to failure of some of the piles near Point B in Figure 3b. The loading and unloading jetty was separated from the vertical leg of the jetty. Refinery staff reported that the heavy steel grating joining the two components of the jetty dropped into the water, indicating that the two components moved independently during the earthquake.

Tank farms and floating roof tanks

Many of the 100+ tanks in the Tupras refinery farm were constructed with floating roofs. Similar to observations from other earthquakes [6], sloshing of the fluid in many of these tanks damaged the perimeter seal, which permitted the fluid to escape from the containment. Substantial damage to a large number of tanks (30+) in the farm was reported. The inability of perimeter seals to retain the sloshing fluid in the tanks resulted in failure or sinking of these floating roofs. Each of these damaged floating roofs required repair or replacement before the tanks could be returned to service. Repair of the damaged or sunken roofs involved draining the tanks, decontamination of the roof, and replacement of the perimeter seals. Sloshing of fluid produced overtopping in several tanks and gross damage to the walls of other tanks (Figure 4b).

None of the tanks were anchored to their foundations, yet the reconnaissance team found no evidence of substantial sliding of the tanks. Although hard piping was attached at the base of each tank, there was no evidence of pipe failure in any of tanks not consumed by fire that were visited by the reconnaissance team. Approximately 20 tanks in the Tupras tank farm were severely damaged or destroyed by fire (Figure 4c). Gross expansion of a fixed-roof tank due to intense heating is shown in Figure 4d. This tank can be seen to the right of the middle of Figure 4c.

Main Processing Facility

The main processing facility is located between the tank farm and the loading jetty. An earthen berm and a road separate the facility from the tank farm. A total of four cooling towers, three made of wood and the fourth of reinforced concrete, were sited at the edge of the berm. One of the three wooden towers burned to the ground, another wooden tower was destroyed by earthquake shaking, and the third wooden tower suffered only slight damage. The reinforced concrete cooling tower appeared to be undamaged. The main processing facility is composed of three crude-oil processing units. Constructed in 1983, one of the three units was destroyed by the collapse of an approximately 115-m-tall reinforced concrete heater stack in the middle of the unit (Figure 4e). The upper two thirds of the one of the heater stacks collapsed while the other one (on the right in Figure 4e) survived. Both stacks were designed and detailed in 1978 following the requirements of ACI 307 [7]. The stacks had large penetrations for ductwork located approximately 30 m above the base. Kilic and Sozen [8] analyzed the two stacks and concluded that the collapse of the stack was not due to lack of strength caused by design or material deficiencies, but due to brittle failure of the reinforcing-bar splices in the region where flexural yielding occurred near the penetration. The other stack had two smaller penetrations at approximately same height above the base, and suffered no apparent damage. The calculated fundamental mode periods of the collapsed and undamaged stacks was calculated to be 2.0 and 1.6 seconds, respectively [8]. Some of the pipework was fractured by the collapsing heater stack, which ignited fires in the crude-oil unit; see Figure 4f. These fires buckled structural components that supported the furnace and the pipe runways.

Petkim Petrochemical Plant

The Petkim petrochemical facility is one of the largest state-owned facilities in Turkey. Similar to the Tupras refinery, the Petkim facility supplies many industrial facilities in the region, including a number of companies manufacturing components of tires. Parts of the Petkim facility were severely damaged. Maximum accelerations of approximately 0.32g were recorded at the YPT station (located in one of the buildings at Petkim), which was located within 200 m of the collapsed three-cell tower (Figure 5a). The figure shows the complete collapse of an older three-cell wooden cooling tower; but a newer four-cell tower adjacent to the collapsed tower suffered no damage. A reinforced concrete cooling tower approximately 400 m from the YPT station was badly damaged. Nonductile reinforced concrete columns in the cooling tower were severely damaged as shown in Figure 5b. The inset in Figure 5b shows typical damage and rebars details at the base of one column. The widely spaced and 90-degree hooked transverse ties failed, leading to dilation and failure of the core concrete in the plastic hinge zone. The Petkim petrochemical plant, similar to the Tupras refinery, had a dedicated port facility through which much of the plant's raw material and processed product passed. This port, like the Tupras port, was badly damaged and was not operational at the time of the earthquake reconnaissance.

AUTOMOTIVE INDUSTRY

Ford, Hyundai, and Toyota operate motor vehicle assembly plants in the epicentral region. Multinational industrial companies including Pirelli and Goodyear are located nearby. Sabanci, which is one of the biggest companies in Turkey, has several joint-venture facilities in the epicentral region, including BekSA (a joint venture with Bekaert of Belgium), BriSA (a joint venture with Bridgestone, Japan, to manufacture rubber goods and tires), DuSA (a joint venture with Du Pont, USA), EnerjiSA, and KordSA. All of these companies, with the exception of EnerjiSA, contribute in one form or another to the construction of motor vehicles.

Ford Assembly Plant

The body-shop building of a new Ford plant near Gölcük was under construction at the time of the earthquake. The single-story building was composed of 6-m-tall square reinforced concrete columns supporting one-way steel trusses and a lightweight space frame spanning between the trusses. The roof and walls were constructed of lightweight steel panels. This building was damaged during the earthquake by a combination of shaking and fault rupture and ground failure beneath the building. Damage included permanent deformations in the building frame, hinges in the cantilever columns, badly cracked and separated floor slabs, and collapse of some wall panels.

Hyundai Assembly Plant

The lateral force-resisting system in the Hyundai plant was composed of steel moment-resisting frames supported on a 0.6-m-deep raft foundation. The roof was constructed using a steel space frame and galvanized steel roof panels. Hyundai representatives reported that tensioned bolts in column-to-roof truss connections sheared. Nonstructural mechanical and electrical components in a utility penthouse, located approximately 9 m above ground level, suffered severe damage that included separation of elevated ducts from air handlers, movement of air handling units due to inadequate or no anchorage, and collapse of large-size ducts and cable trays due to inadequate attachments and anchorage.

Toyota Assembly Plant

The Toyota factory, which is located about 40 km west of Izmit in Adapazari, was constructed in 1994. The annual vehicle production capacity of the plant is 100,000 cars. The lateral force-resisting system in the main plant building was steel moment-resisting frames. Many of the columns in the building were jumbo shapes with flange thicknesses of up to 125 mm. Each column in the main building was supported on twelve 400-mm-diameter piles driven to rock at a depth of 14 m. Approximately 3,800 piles were

driven beneath the building. No structural damage was observed in this building but nonstructural damage was widespread, including the failure or collapse of skylights, light fixtures, storage racks, and one substation transformer. Ground movement damaged the parking lot that was sited approximately 100 m from the main plant.

Pirelli Tire Plant

The Pirelli tire plant in Izmit consists of approximately 20 interconnected buildings, with a total floor area of more than 200,000 m^2. Construction at the plant commenced in the 1960s One section of the oldest building in the plant, whose lateral force- resisting system was a non-ductile reinforced concrete moment frame, collapsed killing one person and injuring 20. Modest-to-severe structural damage was reported in other buildings in the facility, including hinging of reinforced concrete columns. Nonstructural damage was widespread and included fallen light fixtures and cable trays. The key pieces of equipment in the plant were extrusion machines, which processed all raw elastomeric materials. Although these machines were undamaged by the earthquake, Pirelli representatives noted that these machines could not be restarted because of the degree of structural and nonstructural damage in the buildings where the machines were located, and they could not be easily moved elsewhere in the plant and restarted due to their size.

Goodyear Tire Plant

Only modest nonstructural and contents damage was observed, including collapse of light fixtures and localized failures of the fire-protection system that doused building contents with water. No structural damage in the office buildings was observed.

BekSA

BekSA was established in 1987 and is reported to be the largest independent steel wire manufacturer in the world. Steel wire or cord is a key component in tires, bead wire, hose wire and spring wire. The 57,000 m^2 plant was partially operational ten days after the earthquake. The main plant building suffered no apparent structural damage, but some nonstructural damage, including breakage of windows at the top of the perimeter infill walls and cracking of infill masonry walls. One of the reinforced concrete framed office buildings collapsed completely. Many of the nonductile reinforced concrete columns in the main office building failed in shear but did not lose their ability to carry modest gravity loads.

DuSA

The DuSA plant near Izmit exports tire cord fabric and nylon yard, which are key components in the production of automotive tires and industrial fabrics. Heavy damage was reported in the main plant building: a precast reinforced concrete framed structure supported on a 1-m-thick raft foundation. The damage included unseating of precast beams from the corbels on the precast reinforced concrete columns. Substantial nonstructural damage was reported, including the failure of a continuous hot-process unit, equipment movement, overturning due to anchorage failures, and fracture of pipes due to relative movement of equipment. A new steel-frame building was under construction at the time of the earthquake. The structural frame suffered no damage.

KordSA

KordSA is a large producer of tire-cord fabric and industrial fabric. It was reported that the plant was 50% operational one week after the earthquake. The structural systems in the main plant building included braced steel frames in the tower and precast reinforced concrete framed construction elsewhere. Only minor structural damage was observed in the tower, with buckled steel braces and damaged bolted connections. The precast reinforced concrete framing in the main plant building suffered little-to-no structural damage. Some of the parapets atop the precast framing collapsed. Only modest nonstructural damage was observed in the interior areas. A product storage area was added to the main plant after the

original construction. The light steel-framed roof of this storage area collapsed, likely due to the differential movement of two supporting walls. A number of the *short* columns cast as part of the walls failed in shear. The masonry infill above these short columns fell through the roof of the storage area.

POWER GENERATION AND TRANSMISSION SYSTEMS

The seismic vulnerability of substation equipment is a subject of much interest to utilities in North America and is one focus of the research program at PEER. Because of this interest in substation equipment, the EnerjiSA power generation facility was visited by the reconnaissance team. The loss of the substation at Adapazari, one of the key substations in the epicentral region, substantially hampered recovery efforts days following the earthquake. Much effort was focused on restoring service as quickly as possible and the substation was on-line within 10 days of the earthquake.

Power Generation

EnerjiSA supplies electricity and processed steam for selected Sabanci companies, including BriSA, ToyotaSA, KordSA, DuSA and BekSA. EnerjiSA began production in 1997 as a 40-MW single-unit power plant. At the time of the earthquake, EnerjiSA was bringing online a 130-MW power unit and an additional 160 ton/hr of steam-generation capacity. Transformers in the EnerjiSA facility were mounted on rails to facilitate installation and maintenance. Simple braking mechanisms were used to prevent movement of the transformers and protect the electrical equipment that is attached to the transformer such as bushings. Movement along the rails of each transformer in the yard was observed. The typical movement, ranging between 50 and 100 mm, was most likely too small to endanger the interconnected equipment. However, one transformer, which was not in service at the time of the earthquake, rolled or slid more than 1 m, dropped off the ends of the two support rails, and overturned (Figure 6a). Two low-voltage bushings failed during the earthquake but had been replaced at the time of the reconnaissance visit. A heat-recovery steam boiler (Figure 6b) that had been installed but not brought online at the time of the earthquake slipped off its foundation during the earthquake. The fillet welds joining the boiler framing to the base plates atop the reinforced concrete foundation failed; these welds were small and of poor quality. The base plate connections of steel framing to components of both the existing and the new steam generation systems also failed.

Power Transmission

The 380 kV substation in Adapazari services the city of Adapazari and surrounding townships and industrial facilities. Ten days after the earthquake, much of the damaged electrical equipment had been replaced by components stockpiled at the substation and in Ankara. An aerial photograph of the substation is shown in Figure 7a. Much of the switching gear and two power transformers can be seen in the photograph. Numerous porcelain insulators failed during the earthquake; some of the fractured units can be seen in Figure 7b. Some of the circuit breakers in the substation were damaged and replaced after the after the earthquake. The failed circuit breakers typically had longer runs of interconnected equipment than those that survived the earthquake. The substation staff reported that no transformer bushings failed during the earthquake. The power transformers were not damaged. However, the brakes on the rail-mounted transformers failed to function during the earthquake; the maximum movement of these transformers was approximately 300 mm. Such movement appeared not to damage the transformers, the transformer bushings or the interconnected equipment.

OTHER HEAVY INDUSTRY

Bastas Plant

Bastas plant manufactures fluorescent light bulbs. Although the plant suffered no structural damage from the earthquake and power was available immediately after the earthquake using on-site emergency

generators, nonstructural damage to a glass furnace forced the shutdown of the plant. The furnace was mounted on an unanchored frame that moved approximately 35 mm. Compressed air to the furnace was lost when a valve was damaged on a temperature-control rack. The resulting change in the fuel-air mixture led to molten brass solidifying in the lines of the furnace and the destruction of a custom-made tube in the furnace. The lead-time to replace the custom-made tube was approximately two months, forcing the plant to close for this time because the tube was key to the function of the furnace and the plant.

Cap Plant

The Cap textile facility is located near Adapazari, on alluvium deposits between two rivers that are 500 m apart near the plant. The plant was composed of two 3-bay (transverse) by 15-bay (longitudinal) precast reinforced concrete buildings. The framing of the two buildings appeared to be most similar. One of the two precast buildings collapsed. The second building suffered severe damage. In this precast building, many of the columns hinged at the bases and wall and roof panels collapsed.

Habas Plant

The Habas plant in Izmit provides liquefied gases to commercial plants and medical facilities in the region. The major damage at Habas was the collapse of two of the three liquid gas storage tanks shown in Figure 8a. Each tank consisted of two concentric stainless steel shells, one with an outside diameter of 14.63 m and the other with an outside diameter of 12.80 m. The gap between the shells is filled with insulation. Both shells were supported on a 14.63-m-diameter, 1.07 -m-thick reinforced concrete slab that was in turn supported by sixteen 200-mm-diameter reinforced concrete columns. Each column was 2.5 m in height and reinforced with 16 No. 16-rnm-diameter longitudinal bars and 8-rnm-diameter ties at 100 mm on center. The two tanks containing liquid oxygen collapsed. The liquid nitrogen tank and its supporting structure was undamaged except for some hairline cracks in the columns. Habas representatives reported that at the time of the earthquake, the liquid oxygen tanks were 85% full and the liquid nitrogen tank was 25% full. The outer shells of the collapsed tanks buckled. Some of the failed columns beneath one of the liquid nitrogen tanks are shown in the photograph of Figure 8b.

Mannesmann Pipe Plant

The Mannesmann steel-pipe plant in Izmit was constructed in the mid-1950s. The plant is composed of two separate facilities for the fabrication of small and large diameter pipes. Each facility includes production buildings and warehouses. An administration building and storage yards are common to both facilities. Damage was observed in reinforced concrete and steel buildings. In two buildings, shear cracking was prevalent in nonductile columns with short shear spans due to the presence of infill masonry walls. In one of the large-pipe production buildings, the anchor bolts of a steel moment-resisting frame elongated and fractured. In the storage yard at the large-pipe area, two cranes that were constructed in the early 1970s suffered identical failures to the box sections supporting one leg of the crane. Mannesmann used the adjacent SEKA paper-mill port facility for handling raw materials and pipe product. As discussed in the following section, the SEKA port facility was badly damaged in the earthquake, forcing Mannesmann to use alternative and less efficient methods for moving raw materials and product.

SEKA Plant

SEKA is a state-owned paper mill that is located next to the Mannesmann plant. Paper and cardboard products are produced and processed in this plant, which includes five paper mills, each with two paper machines. Before the earthquake, SEKA moved raw materials and finished product through its port facility. Three reinforced concrete silos containing water collapsed. Figures 9a and 9b are photographs of undamaged and collapsed silos, respectively. The diameter of the silos was approximately 6 m. The collapsed silos were supported on six small square nonductile columns with minimal longitudinal reinforcement. The undamaged silos of Figure 9a were supported on larger (square) columns than those of the collapsed silos. The SEKA port facility is composed of two separate jetties, both of which failed

during the earthquake. Figure 10a shows one of the two jetties, constructed in the 1960s, which was supported on hammerhead reinforced concrete columns.

Liquid Gas Tanks

Cylindrical liquid gas tanks of the type shown in Figure 10b were common in the industrial parks in the regions affected by the earthquake. Most of the tanks of this type were not anchored and had hard-line pipe connections. These connections are most susceptible to damage due to movement and rotation of the tank with respect to the supporting saddle. Movement and rotation of the tank with respect to the pedestal are clearly evident in Figure 10b. Many spherical liquid petroleum gas (LPG) tanks were located in the epicentral region. These tanks were typically supported by braced steel frames or reinforced concrete frames. No damage to these tanks was observed.

SUMMARY

Approximately forty percent of the heavy industry in Turkey was located in the epicentral region of the August 17, 1999, Kocaeli earthquake. Observations from twenty-four facilities representing different industries in the region affected by the earthquake are presented. Structural and nonstructural damage are classified and the corresponding performance levels are identified for the industrial facilities visited by the reconnaissance team. Damage to petrochemical facilities, automotive facilities, and power generation and transmission facilities is summarized. The impact of nonstructural damage in some facilities was significant due to business interruption. Older facilities with nonductile reinforced concrete components were most vulnerable to damage and collapse. Some newer reinforced concrete and steel structures also suffered structural damage. One new steel-framed structure was located next to the ruptured fault line but had no structural damage. .

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Table 1 Structural damage classification

Level	*Damage*	*Function*	*Repair*	*Typical damage*
1	None	Fully operational	None	Negligible
2	Minor	Partially operational	Minor	Minor cracks in RC members; bolt failures in steel frames
3	Moderate	Out of operation for days or several weeks	Modest repair	Significant cracks in RC members; yielding in steel moment frames
4	Major	Out of operation for months	Major repair or replacement	Spalling and crushing of RC members; bar fracture in RC members; fracture of steel moment frames
5	Collapse	None	Not possible	Multiple component failures; part or full loss of floors or roofs; gross distortion of steel frames; large permanent drifts

Table 2 Nonstructural damage classification

Level	*Damage*	*Function*	*Repair*	*Typical damage*
1	None	Fully operational	None	Negligible
2	Minor	Partially operational	Clean up	Small movement of unanchored equipment; overturning of cabinets and shelved products
3	Moderate	Out of operation for days or several weeks	Engineered repair	Modest damage to architectural, mechanical, and plumbing systems; failure of equipment anchorage and movement of equipment
4	Major	Out of operation for months	Major repair or replacement	

Table 3 Industrial facilities visited

Facility	*Function/product*	*Construct. date*	*Construct. type*[1]	*Employees*	*Structural damage*[2]	*Nonstructural damage*[3]
Adapazari substation	Power distribution	-	RC	NA	1	4
Bastas	Fluorescent tubes	1960s	RC	NA	1	4
BekSA	Steel cord	1987	RC	240	4	3
BriSA	Tires	1974, 1989	RC	100	4	3
Camlica	Soft drinks	1999+	RC	NA	4	3
Cap Textile	Textiles	1997	RC	650	5	4
Citi	Glass vials	NA	RC	NA	3	3
DuSA	Chemicals	1987	Assorted	NA	4	4
DuSA	Chemicals	1999+	Steel	NA	1	NA
EnerjiSA	Power	1997	Steel	50	2	3
Ford	Automotive	1999+	RC	NA	3	NA
Goodyear	Tires	1963	Steel	500	2	3
Habas	Liquid gases	1995	Assorted	NA	5	4
Hyundai	Automotive	1997	Steel	850	4	4
KordSA	Tire cord	1973	Steel	1100	3	3
Mannesmann	Pipe	1955	Steel	200	3	3
Pakmaya	Food processing	1976	Steel	300	4	4
Petkim	Petrochemical	1967-1975	RC	2500	5	3
Pirelli	Tires	1962	RC	900	4	3
SEKA	Paper mill	1936-1960	RC	NA	4	4
Toprak Drug	Drugs	1990	RC	240	2	4
Toprak Clean	Cleaning supplies	1993	RC	250	3	4
Toyota	Automotive	1994	Steel	NA	1	2
Tupras	Refinery	1961	Assorted	1350	5	4

1. Assorted = steel and reinforced concrete; RC = reinforced concrete; NA = not available
2. see Table 1 for information on structural damage
3. see Table 2 for information on nonstructural damage

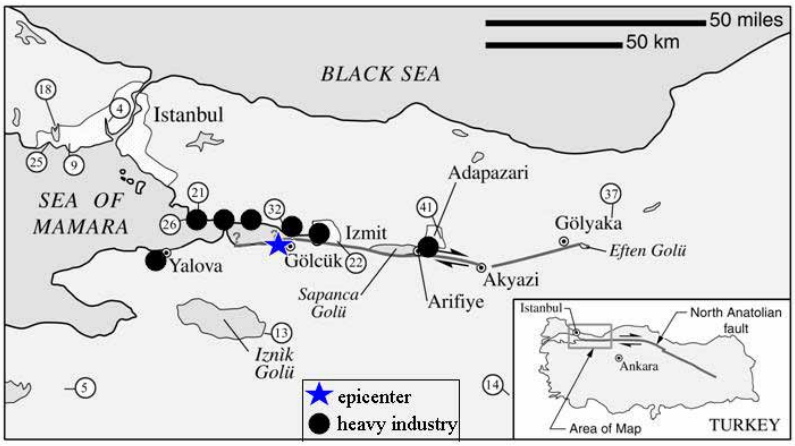

Figure 1 Map of affected region with industrial facilities relevant to epicenter (percentage of peak ground accelerations in terms of *g* are shown in circles)

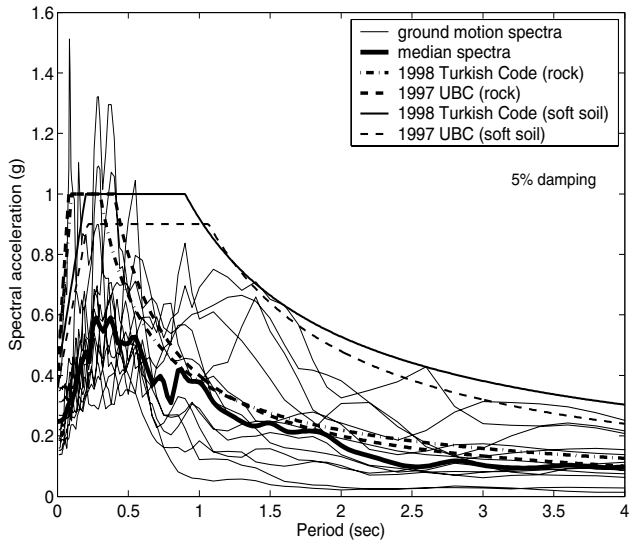

Figure 2 Elastic ground motion and response spectra for 5% damping

(a) (b)

Figure 3 Aerial photographs of Tupras refinery showing part of the tank farm and loading and unloading jetty

Figure 4 Damage to Tupras refinery: a) part view of tank farm, b) tank wall damage, c) tanks destroyed by fire, d) gross expansion of fixed roof tank, e) failed heater stack, and f) damage to heater unit caused by collapse of heater stack

(a) (b)

Figure 5 a) collapsed wooden cooling tower, and b) damage to nonductile columns in another cooling tower at the Petkim petrochemical facility

(a) (b)

Figure 6 a) toppled transformer, and b) damaged boiler in the EnerjiSA plant

(a) (b)

Figure 7 a) aerial photograph of Adapazari substation, and b) failed circuit breakers

(a) (b)

Figure 8 a) liquid gas tanks at Habas; and b) failed columns beneath the tank on the left

(a) (b)

Figure 9 Undamaged (a) and collapsed (b) silos at the SEKA paper mill

(a) (b)

Figure 10 a) failure of reinforced concrete jetty piers at SEKA, and b) typical damage to cylindrical liquid gas tanks