Pacific Earthquake Engineering Research Center

August 17, 1999, Kocaeli, Turkey Earthquake Field Investigation Report

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Summary

On August 17, 1999, at 3:01 AM, the industrial heart of the country of Turkey, the Izmit Bay area, was hard hit by a magnitude 7.4 earthquake, accompanied by severe ground shaking, extensive surface fault rupture of several meters, and shaking-induced ground failure in urbanized areas. In the days following the earthquake, as televised reports and information on the Internet flowed out of the densely urbanized Kocaeli Province and adjacent provinces in western Turkey, it became clear that there was significant information regarding the performance of the Turkish electric power system to be gained by studying this earthquake. This information would bring timely and relevant data to the earthquake research program funded by the California Energy Commission (CEC).

The Turkish Electric Generation and Transmission Company (TEAS) invited the Pacific Gas and Electric Company (PG&E) to send a team to Turkey to examine the damage and performance of the TEAS electric generation and transmission system after the earthquake. PG&E formed a joint CEC/PG&E reconnaissance team to gather critical, time-sensitive data and information regarding the earthquake and its effects on electric power reliability, electric utility customers, and the accuracy of earthquake loss prediction models.

Detailed briefings were held with TEAS in Ankara regarding the performance of the utility systems in the earthquake. Several field tours enabled the team to inspect many features of the surface fault rupture and its effect on structures and utility and transportation systems. Inspection of the surface fault features at selected locations illustrated many examples of poor and good performance of buildings, pipelines, and transportation corridors. It was noted by the field team that the site soil conditions and/or poor construction practices had played an important part in the amount of damaged or destroyed buildings in the area affected by the earthquake. The natural gas transmission and distribution systems performed quite well. The systems in the vicinity of the earthquake were well made and did not cross the fault rupture zone. The well-built trans-European motorway way also performed quite well. The only significant damage to the motorway was to an overcrossing that was built over the fault rupture zone, and to the toll collection stations in the vicinity of the earthquake.

The physical damage to electric generation, transmission, and distribution equipment was consistent with the experiences in past earthquakes in California, Japan, and elsewhere. In spite

of the severe earthquake conditions, the electric power transmission system was quickly restored on the day of the earthquake, thus promoting the timely restoration of customer service in all but the most severely damaged urban areas.

This investigation has had a large impact on the importance of the joint CEC-PG&E-PEER research program, and has reinforced the necessity of continuing to analyze the critical issues that affect safety and reliability of electric power in California. The detailed observations and data collected during and following the field investigation are being utilized in the planning of ongoing and future research activities covering all the topics of the program.

Introduction

West Coast electric utilities, such as PG&E, Southern California Edison, Los Angeles Department of Water and Power, Bonneville Power Authority, and British Columbia Hydro, have been assessing electric system performance after earthquakes for many years. In 1999, the CEC and PG&E were in the final stages of a research project regarding electric system seismic safety and reliability. Research on this topic was originally started by PG&E in 1996.

On August 17, 1999, a moment magnitude 7.4 earthquake struck near the cities of Izmit and Golcuk Turkey, in the Marmara Sea. The earthquake occurred on the North Anatolian fault, a fault that had been intensely studied by earthquake specialists from around the world for some time. The North Anatolian fault was recognized as sharing some highly significant similarities to the San Andreas fault in California (see figure 1). The similarity to the San Andreas fault and the similarities between TEAS and PG&E, combined with earthquake related effects in an urban setting, made Western Turkey an important case study area for assessing and refining the CEC/PG&E electric system seismic safety and reliability project.

In response to the Kocaeli earthquake, Lloyd Cluff, Manager of the PG&E Geosciences Department, contacted his associates in the Turkish geological community and established contact with TEAS to arrange for a field investigation. The purposes of the field investigation were:

1) to make observations and collect data that were time sensitive and would not be available after significant recovery efforts had taken place;
2) to interview TEAS representatives regarding their observations and actions taken to recover from the effects of the mainshock and aftershocks.
3) to make observations regarding the performance of the natural gas system in the area affected by the earthquake; and
4) to collect strong ground motion data related to the earthquake and aftershocks.

Funding for the field investigation came from three sources: 1) PG&E; 2) the CEC/PG&E contract; and 3) the Office of the Executive Director of the CEC. On September 2, 1999, the

CEC/PG&E team departed from San Francisco, California and flew to Istanbul, Turkey to conduct the field investigation..

The field team consisted of the following personnel:

Name	Primary Topics of Investigation	Organization
Lloyd Cluff, Team Leader	Seismic Geology, Damage Assessment and Structural Performance	PG&E Geosciences Dept.
Norman Abrahamson	Engineering Seismology	PG&E Geosciences Dept.
Robert Panero	Utility Risk Management	PG&E Insurance Dept.
William Savage	Seismology, Damage Assessment, and Electric and Natural Gas Utility Performance	PG&E Geosciences Dept.
Robert Anderson	Engineering Geology, Power Systems Performance	CEC Engineering Office
Aykut Barka	Geology, Seismology	Istanbul Technical University, Geology Dept.
Fakir Erdogan	Electric Power Systems	TEAS, Nuclear Engineering Dept.
Muzaffer Genc	Geology	TEAS, Nuclear Engineering Dept.

The field investigation performed by this team has provided input to the EERI reconnaissance report on the Kocaeli earthquake (Bardet and Bray, 2000).

Background

The country of Turkey is about 30% larger than the state of California. The population of Turkey is approximately 65 million. Istanbul, the largest city, is located on the east and west shores of the Bosphorus, approximately 40 kilometers northwest of Izmit. The industrial center of Turkey lies between Istanbul in the west and the valley east of the Bay of Izmit, where the August 17, 1999, Kocaeli earthquake took place.

The Turkish Electric Generation and Transmission Company (TEAS) owns and operates a modern electric power generation and transmission system. The total generation capacity in the country (1998 figures) is about 23,000 megawatts (MW), composed of hydroelectric plants (44%), and thermal plants fueled by coal (28%), natural gas (19%), liquid fuels (7%), and other (3%). TEAS produces 70% of the energy generated in Turkey, with the rest produced primarily by private thermal plants. TEAS operates almost 13,000 km of transmission lines at 380,000 volts (380 kV), and more than 27,000 km lines at 154 kV. The first 154 kV line was built in 1952, and the first 380 kV line in 1979. The Turkish electrical network is connected to Bulgaria, Georgia, Iran, Armenia, Azerbaijan, Iraq, and Syria; energy is currently imported from the first three.

In 1993, the Turkish Electricity Authority was separated into two state-owned entities, TEAS and the Turkish Electricity Distribution Company (TEDAS). TEDAS divided the distribution system into provincial or regional units, which operate either as affiliated partnerships or as subunits of TEDAS. The distribution substations primarily operate at 34.5 kV (including 30 kV and 31.5 kV), 15 kV, and 0.4 kV. Power is distributed with overhead lines installed on metal towers or concrete poles, and with underground direct-burial cables.

There are several independent power producers in this area as well as several small dams. The Turkish electric system is about the size of the PG&E system in California. At the time of the Kocaeli earthquake the electric system in Turkey was undergoing a major expansion, so new equipment and materials were readily available in country which greatly facilitated the restoration effort. The National Transmission Grid Project is financed by the World Bank and is intended to be completed in 2004. This project will establish among other elements the independent operation of the transmission grid system.

The total lengths of the North Anatolian and the San Andreas fault zones are approximately 1,500 kilometers and 1,200 kilometers respectively. The North Anatolian fault zone, like the San Andreas fault zone, is segmented and has numerous related faults. The western end of the North Anatolian fault extends off shore from Yalova and goes west under the Marmara Sea towards Europe and the Aegean Sea. Prior to the Kocaeli earthquake, the North Anatolian fault system had experienced ten major earthquakes since 1939. The total of the aggregate rupture length for the ten earthquakes is approximately 1,000 kilometers (Stein and others, 1997). They had estimated that the North Anatolian fault zone segment south of Izmit had a 12% chance of having a magnitude 6.7 or greater earthquake by 2026.

Findings

The surface rupture associated with the Kocaeli earthquake occurred in four segments. The total length was approximately 120 kilometers along the North Anatolian fault. The rupture propagated in a bi-directional (east and west) manner with the epicenter of the earthquake occurring approximately 11 kilometers southeast of Izmit, Turkey. The type of faulting was primarily right lateral strike slip, the same style of faulting that occurs on the San Andreas fault. The maximum total horizontal displacement at any one site was 5 meters. The total vertical displacement did not exceed 3 meters at any one site. The amount of horizontal displacement was less than that observed at some locations after the 1992 Landers, California earthquake (6 meters) or the 1999 Hector Mine earthquake (5.2 meters). The duration of strong ground shaking from the earthquake wasr 45 seconds. The recorded peak horizontal ground acceleration was 0.42g. However, none of the power plants, substations, or switchyards in the area affected by the earthquake had strong motion recorders. There have not been any aftershocks over magnitude 6, out of more than 2,400 aftershocks.

Site-specific conditions and the quality of construction had significant impacts on the performance of buildings and infrastructure elements such as transmission and distribution of electricity, natural gas, and water. Facilities located on semiconsolidated to unconsolidated alluvium or fluvial or lacustrine deposits generally performed relatively poorly. In general, facilities located on limestone, sandstone, and other well-indurated materials performed better than their counterparts built on softer geologic materials.

The August 17, 1999, Kocaeli earthquake caused an immediate, countrywide blackout of the transmission system due to high-voltage substation damage and power plants tripping off. Major distribution system damage occurred in five provinces: Sakarya (Adapazari), Kocaeli (Izmit), Yalova, Istanbul, and Bolu. Additional affected provinces were Bursa and Eskisehir. These seven provinces consume more that 40 per cent of all the power used in the country. In the following sections, the generation and transmission system damage is summarized, and the process of transmission system restoration is described. Then the electric distribution system damage is summarized, the performance of the natural gas system is discussed, and conclusions from the earthquake are drawn.

ELECTRIC POWER SYSTEM PERFORMANCE

Damage to Power Generation

None of the TEAS generating stations were damaged by the earthquake. The closest thermal power plants to the earthquake are the fuel-oil and natural gas plants at Ambarli, on the west side of Istanbul. Two small hydroelectric plants located north and south of the eastern segment of the fault rupture had no damage reported. No geothermal, solar, or wind farm power generating facilities were located in the area affected by the earthquake. Currently there are no nuclear power plants operating or under construction in Turkey.

Enerji SA Autoproducer (Cogeneration) Plant, Kosekoy, Kocaeli Province. A 40 MW natural gas fired cogeneration plant, the Enerji SA plant (see figure 2), is part of an industrial park several kilometers west of the Kosekoy substation southeast of Izmit and within about three kilometers of the fault rupture. The estimated peak horizontal ground acceleration at the site was 0.4 g. The plant consists of a frame 6 combustion turbine generator (CTG) and Heat Recovery Steam Generation (HRSG) unit and was put into service in March 1998. Two additional units were under construction at the time of the earthquake. The CTG was built on piles due to the soft soil conditions, but the HRSG was not, even though both units were built on semiconsolidated alluvium.

At the time of the earthquake, the CTG's lubrication oil high/low alarm signaled, and the plant tripped. The emergency diesel generator started in two minutes. The turbine was cooled down, turning slowly for two days. The immediate post-earthquake inspection revealed only minor damage: the CTG foundation settled differentially by 0.5 cm; nuts on the foundation connection bolts partially loosened; nuts on the anchorage for the water treatment plant also loosened; the HRSG displaced sufficiently to pull a base plate off its threaded anchors; there was some concrete spalling on the west side of the HRSG foundation; and unanchored parts storage shelves and other inadequately restrained objects were damaged. This amount of differential settlement is within the preliminary design tolerance for some modern US built natural gas-fired plants. The facility manager said that were no procedures and experience to base what to do for a frame 6 CTG power plant that had just had experienced a magnitude 7.4 earthquake. The fact that a frame 6 CTG withstood this amount of settlement and was able to resume operation after minor repairs and an inspection lends credence that 0.5 cm of settlement was not overly excessive for the Enerji SA plant. There was no damage to the plant's natural gas supply connections.

There was some damage to the two units under construction, including twisted I-beams, the input flue colliding with other parts in the HRSG, and an 80-tonne package boiler jumping off its foundation because it was not yet attached. The plant manager said that the inlet flue of the partially built HRSG had been damaged by colliding with other parts of the HRSG.

The plant office building had cracks and one broken column. The building was not built on piles, but had a continuous perimeter footing and a concrete slab on grade. The stairway dilated and there were large cracks in the shear walls. In addition bookcases overturned in the offices..

Although the transformers at the generator were mounted on wheels that rolled in steel channels, they did not move enough to cause damage. In the 154 kV switchyard adjacent to the power plant, a bus bar was damaged and high-voltage bushings on the two 154/34.5 kV transformers were broken at their bases. Connections to the bushings were by flexible conductors, so the plant personnel concluded that the bushings failed due to strong shaking. The transformers were rail mounted with brakes on the wheels, but it is not known if they moved significantly during the earthquake.

The insurance carrier for Enerji SA asked for a detailed inspection before the plant could be restarted, which took about 3 1/2 weeks following the earthquake to reach the final testing stage. All the pressure switches had to be re-calibrated. This was an unforeseen delay and if there had been a customer available to receive power this could have been a significant financial loss to Enerji SA. During that period, the substation was repaired using spares on hand for the new construction, and was reconnected to the TEAS grid at 34.5 kV in 40 hours and at 154 kV in 60 hours. As the Enerji SA customers recovered their operations, they could be supplied by the grid until the plant restarted.

Damage to Electric Power Transmission

Turkey has interconnections with Azerbaijan, Georgia, Armenia, Bulgaria, Iran, Iraq, and Syria. After the earthquake Turkey was importing power from Bulgaria. There are two main electric transmission systems in Turkey, one at 380kV and the other at 154kV. The 380 kV lines were out of service after the mainshock. The 154kV electric transmission system remained operational after the mainshock and aftershock of the morning of August 17, 1999.

There were no transmission towers that were taken out of service due to earthquake damage. The most severely threatened tower was a 154 kV electric transmission tower on a short connection to a substation that is part of a large Ford automotive manufacturing facility under construction near the city of Golcuk (see figure 3). Surface strike-slip faulting with a large normal component crossed the foundation of the tower, and twisted and elevated one leg and its concrete footing about two meters out of the ground. The tower did not tilt. It was supported by the remaining three legs, and remained in service.

Nine transmission substations suffered damage or disruption to transformers, switching equipment, and buildings. All of the damage was associated with strong ground shaking. Tang (2000) provides additional descriptions of substation damage. Figure 4 shows the locations of the substations. Estimates of the peak ground acceleration at each substation have been provided by Dr. Ellen Rathje (personal communication, August 2000)

1. Adapazari 380 kV Substation

The Adapazari substation is located in the southern part of the city of Adapazari, at a cut-and-fill site on the south flank of a low hill. The 380 kV facilities were installed in 1983. The site is about 3 km from the nearest fault rupture segment. The peak horizontal ground acceleration estimated for the site is 0.4 g.

- Six Asea minimum-oil-type circuit breaker sets failed (three individual breakers in each set) due to oil leakage and porcelain breakage. The connecting equipment was also broken and fell, including six horizontal and seven vertical disconnecting switches, their rigid aluminum connectors, and two post insulators. A marshaling kiosk that housed signaling cables and equipment for one circuit breaker was also damaged. The damaged Asea circuit breakers were located on what appeared to be the fill part of the site, with undamaged Asea breakers still standing on the cut side. Three 1986-vintage Hitachi minimum-oil-type breakers also were located on the fill, but were not damaged.

- The rigid pipe connections between the reserve oil tanks and main tanks for two 380/154 kV power transformers were damaged due to displacement of the transformers on their rails. The transformer displacements also appeared to cause breakage (with oil leaks) of two tertiary bushings due to insufficient slack in the flexible connectors.

- Two other 380/154 kV rail-mounted power transformers also were displaced about 30 cm, and two neutral bushings, two tertiary bushings, and six 154 kV arresters were broken. One 380 kV bushing with a rigid connector was also broken.

- One post insulator of a 154 kV circuit breaker feeder was broken.

- The three-story, concrete-frame and masonry-infill building housing the Regional Load Dispatching Center for northwest Turkey was damaged to the point that staff did not enter the building for several days, and some critical control equipment was moved into an adjacent portable building. Unanchored battery racks for an emergency power supply toppled, and some SCADA computer equipment was damaged internally (circuit cards and a hard disk drive) due to strong shaking.

- The operation management facility at the substation, also a three-story, concrete-frame and masonry-infill building, was moderately damaged. Activities were relocated to four temporary buildings and tents erected nearby.

As a result of the circuit-breaker damage at the Adapazari substation, four 380 kV transmission lines were out of operation after the earthquake. However, two 380 kV transmission lines bypassed this substation, linking undamaged substations to the northwest and southeast. These two lines were critical to power restoration, as will be discussed later. TEAS planned these two lines to afford reliability protection in the event of fire affecting the Adapazari facility.

A small substation located next to the north side of the Adapazari Substation and been out of service for several years when the earthquake hit. No damage was apparent to the substation; however it did not have its components hooked up to the local power grid. The small substation had been in operation during the 1957 Turkish earthquake and was partially damaged. The Adapazari substation personnel told us that shortly after the substation had been repaired in 1957, an aftershock knocked it right back down and out of service.

2. Osmanca 380 kV Substation

The Osmancha substation is located near the Black Sea coast just south of Akcakoca, about 40 km north of the eastern end of the earthquake fault rupture. Similar circuit-breaker damage to that at the Adapazari Substation occurred, taking the two 380 kV lines passing through the station out of service. Six sets of Asea 380 kV minimum-oil-type current breakers fell over, along with four post insulators and 10 vertical and seven horizontal disconnect switches. Also, one marshaling kiosk was damaged due to broken anchor bolts. The peak horizontal ground acceleration estimated for the site is 0.2g.

3. Eregli 380 kV Substation

The Eregli substation is located on the Black Sea coast about 65 km from the eastern end of the earthquake rupture. A small oil leakage occurred on a 380 kV bushing of a 380/154/15.8 kV transformer. The cause of the leakage is unknown, and may have been due to cracked porcelain or gasket slippage. The peak horizontal ground acceleration estimated for the site is 0.1g.

4. Bursa Sanayi 380 kV Substation

This substation, located 80 km southwest of the fault rupture, contains nine transformers. The two largest ones, 250 MVA 380/154 kV units, moved 16 cm and 11 cm respectively on their rails with clamps, but no damage occurred. The peak horizontal ground acceleration estimated for the site is 0.1g.

5. Kosekoy 154 kV Substation

This substation is located southeast of Izmit close to the fault rupture. Of two 154/33 kV transformers, the unit in service had no damage, but the spare fell off the end of its rail mount. The peak horizontal ground acceleration estimated for the site is 0.4g.

6. Yalova 154 kV Substation

The Yalova substation is located at the city of Yalova. The 154/33 kV transformer in service went off its rails and fell over. The spare transformer slid off its platform and nearly fell over; an oil leak on one of the 154 kV bushings was noted. Electrical contacts of the 154 kV disconnect switches were damaged due to pounding, but were either repaired or used as is. Post insulators on the 154 kV wave trap were broken. The 34.5 kV switchyard building had some concrete damage but continued to be used, and a residential building on the site had cracked walls and a collapsed roof. The peak horizontal ground acceleration estimated for the site is 0.3g.

7. Yarimca-1 154 kV Substation

This substation is located on the north side of the Bay of Izmit, northwest of Golcuk near the refinery and petrochemical plant, and about 4 km from the fault rupture. Three 154/34/5 kV transformers went off their rails, but were still operable. The peak horizontal ground acceleration estimated for the site is 0.3g.

8. Sultanmurat 154 kV Substation

This substation on the west side of Istanbul is a gas insulated (GIS) facility. At the time of the earthquake, a Buscholz warning and disconnect signals were received from two transformers, causing the fire protection systems to engage and take the transformers out of service. No damage occurred. The peak horizontal ground acceleration estimated for the site is 0.1g.

9. Ikitelli 380 kV Substation

This substation is also located on the west side of Istanbul. Cracks were observed in residential buildings at the substation, but the damage did not interfere with operation of the substation. The peak horizontal ground acceleration estimated for the site is 0.1g.

A small substation was under construction at the Ford Motor Company car manufacturing plant in Golcuk. The substation had not yet been connected to the 154 kV electric transmission system located just to the south of the facility. Surface rupture was observed in the substation, but the substation was otherwise undamaged. The amount of surface rupture was not measured but appeared to be less than a vertical offset of 4 cm. This amount of vertical offset may not have adversely affected the substation had it been on-line at the time of the earthquake.

Recovery of the National Electric Transmission System

The following time line summarizes the process of power transmission restoration and other recovery actions taken by TEAS personnel in response to the Kocaeli earthquake.

3:02 AM, August 17

The TEAS national electric system was de-energized during the earthquake shaking, principally due to substation damage. Only isolated regions that were fed from Bulgaria, Georgia, and Iran, and areas in the far western part of the country that could be maintained by local power plants were able to stay in service. All the hydroelectric plants and the thermal plants outside of the Aegean region tripped off. All staff responsible for load dispatching were called in to begin working.

3:30 AM

The appropriate staff under the chairmanship of the General Manager assembled in the National Load Dispatching Center near Ankara to supervise the recovery actions and to organize necessary activities using all the resources of the company. Buses began to be energized.

4:00 AM

The Hamitabat thermal plant 140 km west of Istanbul was energized from the Bulgarian connection and put back in service so that Istanbul could be energized. Similarly, plants to the east and south of the earthquake-affected area were brought back in service, and lines in the 380 kV and 154 kV grids began to be energized.

6:30 AM

The connection between the Istanbul region and the Central Anatolian region was established using the two 380 kV lines that crossed the Izmit-Adapazari area but bypassed the damaged Adapazari and Osmanca substations (Figure 4). The step-by-step restoration of generation plants and transmission lines proceeded outside of the strongly damaged area. Inspection of substation damage continued.

7:30 AM

The determination of damage to the 380 kV portions of the Adapazari and Osmanca substations prevented their being energized. The 154 kV sides of these substations were being checked.

8:00 AM

Although it was determined that the 154 kV buses could be energized in the damaged substations in the strongly shaken areas, the local governors requested that the local distribution system not be energized because of the serious risks associated with introducing power into damaged areas and potentially damaged customer equipment.

8:30 AM

With the exception of the specific damaged substations and areas mentioned above, the 380 kV and 154 kV system returned to normal operation. An expert commission composed of technical staff and assistance teams was established by TEAS headquarters, and was assigned the responsibility for determining the earthquake-related damages for recovery planning purposes. They departed shortly to the earthquake affected areas.

8:54 AM

A strong aftershock in the Duzce area caused the 380 kV connection between Ankara and Istanbul to relay off, thus causing the entire grid to de-energize again. The line-by-line and plant-by-plant restoration process began again.

11:30 AM

The grid was restored once again, except for the 380 kV sides of the Adapazari, Osmanca, and Eregli substations.

1:30 PM

The 154 kV side of the Adapazari substation was checked and verified as safe, so the local grid was energized and electricity was made available at 34.5 kV whenever it would be needed.

2:00 PM

The 154/34.5 kV transformers at the other damaged substations in the strongly shaken area were energized so that distribution circuits could be energized as needed. At this time, the transmission system was brought back to normal operation except for the damaged parts. Distribution system components were subsequently brought back online as soon as circuits could be tested and damaged areas disconnected. Most distribution service was restored by the evening of August 17, except for areas with damaged circuits.

August 30

By this date after the main shock, all substation equipment damages were repaired. These repairs were made possible in part by the fortunate availability of new circuit breakers and other equipment that had been received by TEAS in preparation for extensive new construction. Efficient and effective TEAS teams were formed to carry out repairs with assistance from personnel from equipment manufacturers. In particular, a team of 130 engineers and maintenance specialists rebuilt the 380 kV side of the Adapazari substation, and a similar team of 100 repaired the 380 kV side of the Osmanca substation. As noted previously, the redundant configuration of the 380 kV system enabled these substations to be bypassed while repairs were made, without delaying grid restoration and distribution circuit restoration.

The cost for damaged equipment that TEAS replaced immediately following the earthquake was US$1,483,000. This included 9 circuit breaker sets, 11 disconnect switches, three transformer bushings, and six lighting arresters. TEAS estimates that they will spend an additional US$10.5 million to replace weak or damaged but operational equipment.

Damage and Restoration of Electric Distribution

In the affected provinces, the distribution systems experienced heavy damage that was closely associated with the intense building damage and the associated strong shaking and ground failure. The distribution systems include KORFEZ (Izmit), SEDAS (Sakarya and Bolu), TEDAS (Yalova), and BEDAS and AKTAS (Istanbul).

A common type of damage to tower mounted electric transformers in Adapazari and Golcuk was falling out of their box frame attachments to the towers due to a lack of adequate restraints on the transformers. There were two main types of damage to the underground portion of the electric distribution system in Turkey. First the connections to the buildings and other lines were broken, and second, emergency crews would dig up portions of underground power lines. The need for power distribution service was reduced by several hundred thousand customers due to the large number of buildings that were either destroyed or so heavily damaged that they may not be saved.

The distribution systems generally contain the following elements, with the typical damage indicated:

- Medium voltage (MV) lines operating typically at 34.5 kV or 15.8 kV; damaged by failure of towers, building collapse knocking down lines, line burndown.

- Low voltage (LV) lines operating at below 15.8 kV down to 400 volts; damaged by failure of towers, building collapse knocking down or pulling down lines.

- MV-MV transformers typically housed in small substations: damaged by bushing breakage or oil leaks caused by strong shaking, building debris falling on transformers, cables pulling on insulators, large displacement or toppling of transformers due to inadequate anchorage.

- MV-LV transformers typically pole-mounted; damaged by falling of transformer due to inadequate anchorage, pole failure causing transformer to fall, building collapse pulling on overhead lines breaking insulators.

- MV and LV direct burial cables used primarily in urban areas; damaged by ground failure, foundation failure of buildings, and cables being pulled during post-earthquake building rescue and demolition activities.

Damage statistics for the five primary provinces are shown in Table 1.

Table 1. Distribution System Damage in the Kocaeli Earthquake. The upper number refers to the pre-earthquake totals within the province, and the lower number refers to the amount damaged due to the earthquake. Note that the length of cables and overhead lines represents the entire length of the circuits that were damaged or destroyed.

Province	**MV-MV Transfmr**	**MV-LV Transfmr**	**MV Lines (km)**	**MV Towers**	**MV Cables (km)**	**LV lines (km)**	**LV Towers**	**LV cables (km)**	**Service Trucks**
Kocaeli	39 13	2,267 233	2,620 130	28,833 1,210	95 19	6,597 270	80,718 3,449	225 61	53 23
Sakarya	9 4	2,299 248	1,805 165	29,913 750	120 65	5,159 215	114,301 550	580 135	127 11
Istanbul	157 4	8,372 750	6,826 72	38,802 2175	2,613 900	124,662 2,665	208,000 20,700	4,998 2,400	108 32
Yalova	3 0	369 101	289 100	5,798 200	45 0	787 125	14,828 850	75 35	11 5
Bolu	4 0	2,477 101	3,239 200	34,297 0	28 5	4,482 25	106,885 500	125 35	65 0
Total Damage Cost USD	$960K	$9,609K	$19,029K	(incl. w/ Lines)	$6,238K	$11,790K	(incl. w/ Lines)	$15,934K	$648K

Restoration of distribution service was closely controlled by local officials and distribution company personnel to assure that power was restored only when circuits had been disconnected from damaged structures and properly tested. The TEDAS maintenance personnel had the transformers operational by noon on the 17th; however, the crisis control center delayed authorizing the engerizing of the transformers until the threat of electrically ignited fires was past. Electric power was restored locally by two p.m. Electric power was first restored to hospitals and municipal water wells. Most distribution areas in the affected provinces were restored in a matter of days. Emergency response and recovery facilities, such as hospitals and water pumps, received high priority for restoration. A shortage of emergency power generators and rescue equipment was a problem.

Because of the extensive damage to underground cables, it is planned to collocate replacement cables with other utilities. The existing damaged cables are being abandoned in place.

The total cost of distribution system damage is estimated to be US$69.6 million. This includes the damage cost of $64.2 million shown in Table 1, plus an additional $5.4 million that includes new equipment used to replace damaged equipment and new construction of poles and lines to serve the tent encampments and other temporary housing established for people who lost their housing. The actual total cost will not be determined until all the repairs have been completed.

Lessons Learned

The electric power system in Turkey was hit by extreme earthquake effects due to the Kocaeli earthquake: severe ground shaking, more than 100 km of surface fault rupture of several meters, and shaking-induced ground failure in urbanized areas. The earthquake-affection region contained the heart of Turkey's industrial facilities, and was densely urbanized. In spite of these conditions, the transmission system was restored quickly, thus promoting the timely restoration of customer service in all but the most severely damaged urban areas. There are several important observations:

- The extensive damage to several 380 kV substations was not a major factor in transmission power restoration due to the existence of 380 kV transmission lines that bypassed the damaged stations (see Figure 4). Power could then be rerouted to the distribution system via the 154 kV transmission system, whose substations were much less damaged. The redundant system design used by TEAS performed successfully in this earthquake, even though explicit planning for such earthquakes had not been done. Also, the electric power feed from Bulgaria to Istanbul provided important redundancy from the west.

- The power generation and transmission personnel were responsive and organized in their efforts to stabilize the post-earthquake situation, rapidly assess critical damage, and restore system operations. In general, the crisis management actions taken by TEAS were effective. The distribution company actions were also responsive and effective. Of particular importance was the coordination between local government representatives and the local distribution companies to safely restore power. Thus the dangers of restoring power into damaged or collapsed buildings could be avoided.

- The physical damage to generation, transmission, and distribution equipment was consistent with the experiences in past earthquakes in California, Japan, and elsewhere, and included the following typical observations:
    - ◊ Generating plants may not have experienced high ground accelerations (0.4+ g) and did not suffer significant damage.
    - ◊ Transmission towers and lines are highly resistant to earthquake damage, even when displaced by surface fault rupture.

◊ Porcelain insulators used in high-voltage substation equipment are generally vulnerable to strong earthquake shaking and loading caused by interconnection with other equipment, unless high-strength insulators and appropriate seismic designs are used.
◊ Unanchored equipment is seismically vulnerable, particularly transformers sitting on rails or inadequately attached pole-mounted transformers. Transformer damage can significantly delay customer service restoration.
◊ Distribution power poles and towers are vulnerable to damage due to liquefaction and other ground failures, particularly in urban areas where buildings are likely to be damaged as well and can fail into the poles and towers.
◊ Pole-mounted transformers fail if shaking causes the poles to break, or if they are not adequately anchored to the poles.
◊ Underground cables are prone to damage where they connect to surface electrical supplies or buildings, and due to subsequent degradation in cable insulation due to physical or electrical effects. Such damage can lead to long delays in power restoration because of the relative difficulty in repairing underground cables compared to overhead lines.

It is interesting to note that the TEAS and TEDAS staff did not report any distribution transformer explosions or fires. Some pole mounted transformers in both the Northridge and Hector Mine, California earthquake areas exploded. It is thought that the electric transmission and distribution lines did not arc and transformers did not blow up in the Kocaeli earthquake since the loss of the high-voltage power supply was initiated by the earthquake damage to the Adapazari substation so that the distribution lines were not energized. This prevented the arcing of power lines or the exploding of transformers. One important element of the effect of the loss of power was the loss of power to the water distribution and treatment systems. The loss of power caused pumps to shut down until emergency generators could be located and brought into service. The water systems had to be carefully checked before water service could be restored to those customers able to receive water through the restored elements of the water supply system.

NATURAL GAS SYSTEM PERFORMANCE

Background

Turkey does not produce any significant quantities of natural gas. Most of the gas used in Turkey is bottled propane. Natural gas distribution lines are being developed but are not nearly as prevalent as in California. The natural gas transmission system in the vicinity of the earthquake was limited to the BOTAS main natural gas transmission lines, and the IZGAS natural gas distribution system in the vicinity of Izmit.

The natural gas transmission system serving Turkey is operated by BOTAS, and is comprised of modern high-pressure steel pipelines. In the region of the earthquake, the BOTAS pipeline crosses the Bay of Izmit between Muallim on the north and the western side of the Hersek

Peninsula on the south. The pipeline thus crosses the North Anatolian fault essentially at the western end of the observed surface fault rupture. Following the earthquake, BOTAS personnel inspected the system, and found no damage. A single gas leak was found near the north side of the Bay of Izmit crossing, west of Izmit, at a flange connection that was repaired by tightening the bolts.

The field team visited the local natural gas distribution company in Izmit called IZGAS. IZGAS was the fifth largest natural distribution company in Turkey when the earthquake struck. At the time of the earthquake IZGAS had 26,000 customers and 380 kilometers of newly built (1995) steel and polyethylene pipes. Natural gas is supplied to the IZGAS system by two connections with the BOTAS natural gas transmission lines. The IZGAS system was located to the north of the North Anatolian fault. IZGAS reported that their system did not cross any fault ruptures associated with the Kocaeli earthquake. The IZGAS system was built in the mid-to late 1990s and was made of steel and polyethylene pipe. The main loss to the IZGAS company due to the earthquake was the loss of customers, damage to the gas meters, and the loss of revenue due to the loss of demand for natural gas. IZGAS reported that 860 gas meters were damaged due to collapsed buildings, and that they had lost 8,000 customers during the earthquake. What was clear is that the IZGAS system performed well but buildings that the gas was fed into were destroyed or heavily damaged. None of the gas pipelines were seriously damaged by the earthquake. Fortunately, there were no fires associated with gas leaks. The SCADA system survived the earthquake, but the SCADA operator fled from his station. Locally, the electric system was not re-energized until the potential for electrically ignited gas fires was mitigated.

Dr. Aykut Barka mentioned that a Turkish television crew had video taped some lights over the area of the epicenter and the shorelines near Izmit and Golcuk. He referred to the lights as possibly being earthquake lights. The engineer for the Minister of State had mentioned that some lights were observed close to a major chemical plant near Izmit, and was concerned about the possibility of gas being released during an earthquake and setting the plant on fire. He also mentioned that a methane pocket was released and had exploded along the Marmara Sea coast during the earthquake. Earthquake lights may be a potential fire or explosive hazard, especially in areas that may have methane, hydrogen sulfide, or natural gas deposits near ground surface.

Lessons Learned

The IZGAS distribution pipelines did not cross the surface fault rupture segments of the North Anatolian fault. The BOTAS natural gas transmission line crossed the North Anatolian fault near Yalova, in the Marmara Sea. Nevertheless, the gas lines were exposed to ground accelerations estimated to be in the range of approximately 0.2 to 0.35 g. The gas system performed similarly to the newer gas systems installed (polyethylene and steel) in the Northridge and Loma Prieta earthquakes. Standard practice for natural gas system siting, design and construction appears to be effective in coping with moderate to strong levels of earthquake shaking (0.2 to 0.35+g) in the Kocaeli earthquake, or much higher levels up to about 1.0 g as experienced in the Northridge earthquake. For pipelines sited crossing active faults or other locations of large permanent ground displacement, detailed seismic analysis and associated design adjustments should be carried out.

CONCLUDING REMARKS

Californians have benefited from the observations made and interviews conducted after the Kocaeli earthquake, since the Turkish electric generation, transmission, and distribution systems are similar to those in California. Major benefits from this earthquake were the collection of strong ground motion records, the first-hand field observations of substation equipment design and damage, and the interviews with engineers, managers and technicians of both TEAS and TEDAS, all without actually having suffered a major urban earthquake in California. It is important to note that the Kocaeli earthquake was similar in size to the moment magnitude 7.4 Landers, California earthquake of June 1992. A major difference between the Kocaeli and the Landers earthquakes is that the Kocaeli earthquake occurred in an area that was locally highly urbanized, while the Landers earthquake occurred in a sparsely populated (desert rural) region of California. Personnel from PG&E and the CEC, working with TEAS, TEDAS, and the Istanbul Technical University Geology Department, reaffirmed the importance and applicability of the electric system seismic safety and reliability research carried out under the Public Interest Energy Research program by PG&E and the Pacific Earthquake Engineering Research Center (PG&E's subcontractor). It is noted that PG&E has continued to investigate the earthquake and the North Anatolian fault on their own.

Turkey has been experiencing rapid industrial and population growth, which has led to a significant expansion in the number of water supply, natural gas distribution, and electric power facilities. As this development continues, and as the full recovery from the Kocaeli earthquake occurs, more attention is needed to address the threats from future earthquakes, particularly those occurring to the west along the North Anatolian fault, and thus closer to Istanbul. To improve future performance of lifeline systems in Turkey, an assessment of equipment and system performance vulnerabilities to earthquake activity would serve to identify potential damage conditions that the current level of system resiliency could not adequately handle. Then appropriate mitigation plans could be developed and implemented. These actions would enable the gas delivery and electric power systems in Turkey to continue to provide responsive service restoration after future earthquakes.

California is also experiencing significant population and industrial growth which has led to a need to expand our infrastructure base of electric power generation, transmission distribution, natural gas transmission and distribution and water collection, transmission and distribution systems. By applying lessons learned from the Kocaeli and other large earthquakes, we are able to help prudently develop our infrastructure so that it is more resistant to significant damage from earthquakes. This is a major goal for electric system safety and reliability improvement within California.