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THE BEHAVIOUR OF STRUCTURES BUILT ON ACTIVE FAULT ZONES : EXAMPLES FROM THE RECENT EARTHQUAKES OF TURKEY

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The 1999 Kocaeli and Düzce earthquakes of Turkey caused loss of many people and severe structural damage to structures. In addition to poor quality construction and inappropriate construction materials, the damage was caused partly by the permanent displacement of the ground due to faulting and partly by the liquefaction and lateral spread of the ground. The aim of this paper is to make an attempt to describe the general features of the surface ruptures and related ground failures and damage to structures, and to discuss several important examples from both earthquakes which may be precursory for the earthquake engineering community to develop seismic codes for structures in active fault zones.

Key Words : *active fault, earthquake, ground failure, lateral spreading, North Anatolian Fault, seismic code, submarine landslide, subsidence, structure, surface rupture*

1. INTRODUCTION

The Kocaeli earthquake of August 17, 1999 and the Düzce earthquake of November 12, 1999 occurred in Turkey are the inland earthquakes involving surface rupturing of the ground for great lengths. These two earthquakes caused ground-surface failures across a broad area of the northwestern part of Turkey. These failures included zones of ground fissures and extensional cracking, lateral displacements, settlements with vertical-displacements, compressive deformations and submarine landslides. Furthermore, the fault breaks occurred right beneath various structures. Ground cracks displaced the foundations of houses and bridges, broke apart sidewalls and streets, deformed railways, ruptured utility lines and destroyed some buildings within a belt. There is no doubt that this phenomenon is of great concern to the earthquake engineering community all over the world as it may be observed in any country having active fault zones.

The seismic design of engineering structures is generally carried out by considering the possible shaking characteristics of the ground during earthquakes in the region. It is a fact that the permanent relative displacement of the ground is not considered in any seismic code all over the world, except for very long linear structures such as pipelines. This problem is currently considered to be beyond the capability of seismic design concept for structures in the earthquake engineering, although it must be dealt with somewhat.

After earthquakes, some scientists from various disciplines say that "it was told before not to build the structures in this area since a fault or faults passed through it". This statement is always encountered by the engineering community all over the world. If this advice is just followed any structure should not be built in seismically very active countries such as Turkey, Japan, Taiwan and the Western part of USA while the societies of these countries demand better living environments. Therefore, the engineering community must find the ways to be able to deal with the designing and building structures in active fault zones rather than just turning their heads other way. The examples observed in these two great earthquakes occurred in Turkey in 1999 taught the authors some important lessons and also provided some direct answers to those people who hesitate to suggest constructions near fault zones. In this paper, an attempt is made to describe and discuss several important examples which may be precursory for the earthquake engineering community to develop seismic design codes for structures in active fault zones together with responsible scientists for better living environment of their societies who have just to live on the top of the seismically active belts of the earth.

2. DEFINITION OF FAULTS AND FAULTING TYPES

The fault is geologically defined as a discontinuity in geological medium along which a relative displacement took place. Faults may range in length from a few microns to many kilometers. A fault is geologically defined as active if a relative movement took place in a period less than two millions years or if slip has occurred, variously in historical or Holocene or Quaternary time or earthquake foci are located. On the other hand, the service life of engineering structures could not generally be greater than 100–150 years. Taking this fact into consideration, there were new attempts to define active faults for engineering purposes by various US government agencies defined the active faults as given below[1] :

(1) It moved in the last 10 000 years (Holocene),
(2) It moved in the last 35 000 years (in nuclear power plant site selection)
(3) It moved in the last 150 000 years,
(4) It moved twice in the last 500 000 years.

However, these diverse definitions, based on the agency's perception of risk, also lead to confusion. Since the definitions of active faults are still quite broad and diverse, the engineering community expect more specific and quantitative definitions concerning active faults from the earth scientists in order to be able to develop seismic design codes in active fault zones.

It is well known that the earth's crust is ruptured and contain numerous faults and various kinds of discontinuities, and it is almost impossible to find a piece of land without faults. During the construction of various structures in most cases, it is almost impossible not to cross a fault or faults. Therefore, one of the most important items is how to identify which fault segments observed on ground surface will move or rupture during an earthquake. It is well known that a fault zone may involve various kinds of fractures and it is a zone having a finite volume[2]. In other words, it is not a single plane. Furthermore, the faults may have a negative or positive flower structure, which consists of more or less symmetrical splays into subfaults near the intersection of the main fault with the ground surface, as a result of their trans-tensional or trans-pressional nature and the reduction of vertical stress near the earth surface as shown in **Fig.1**. For example, even a fault having a narrow thickness at depth may cause a quite broad rupture zones and numerous fractures on the ground surface during earthquakes. In addition to that, it is impossible to say the same ground breaks will re-rupture during a future earthquake in regions with thick alluvial deposits. Furthermore, the movements of a fault zone may be diluted if a thick alluvial deposit is found on the top of the fault as it happened in Erzincan and elsewhere in Turkey[3]. The ground ruptures observed in the Kocaeli earthquake of August 17, 1999 could not probably correspond to those of 1719 in engineering sense while it may broadly correspond to the same fault in a geological sense. Therefore, the size and location concepts in earth sciences must have the same sense in structural design concerning the fault zone in quantitative terms for developing seismic codes for structures built and/or to be built in active fault zones.

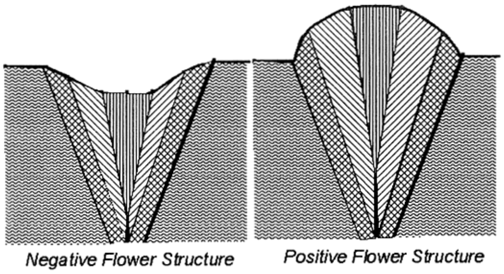


Fig.1 Negative and positive flower structures due to trans-tension or trans-pression faulting.

3. THE SURFACE RUPTURES OF THE 1999 KOCAELI AND DÜZCE EARTHQUAKES

(1) Kocaeli earthquake and surface fault rupture

The August 17, 1999 Kocaeli earthquake (M_s = 7.4) occurred at 03.02 on local time and struck the eastern Marmara region. Records of the maximum ground acceleration were measured as 0.45 g. The earthquake lasted 45 seconds and consisted of several subevents. The earthquake was felt over a large area, as far as in east of Ankara that is about 300 km away. Official estimates place the death tolls about 18 000 and injuries more than 25 000, and collapse or heavy damage of more than 40 000 buildings. Gölcük, Izmit, Yalova and Adapazari are the cities which suffered severe structural damages during the earthquake. The earthquake also caused considerable damage in the suburbs of Istanbul, approximately 70 km away from the earthquake's epicentre. In addition to poor quality construction and inappropriate construction materials, the damage was caused partly by the permanent displacement of ground due to faulting, and partly by liquefaction and lateral spreading of the ground towards lakes, rivers and sea.

The earthquake originated at a depth of 15 kilometers and occurred on the northern strand of the North Anatolian Fault Zone (NAFZ) with a right-lateral strike slip movement. The Kocaeli earthquake

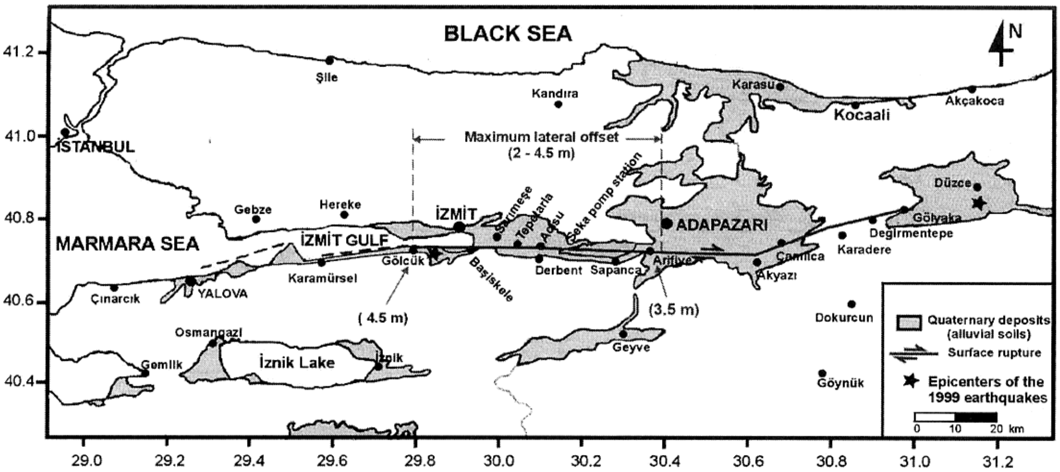


Fig.2 Rupture path of the fault during 1999 Kocaeli earthquake.

produced a surface rupture over a distance of 120 km between Gölyaka in the east and Hersek in the west as shown in **Fig.2**. Between Gölcük and Degirmendere the surface rupture disappeared and extended towards west (Hersek delta) as a near-shore strike-slip fault.

From the surveys of offset fence lines, roads and tree lines, the maximum offset along the surface rupture was measured about 4.5-5 m (**Fig.3**). General trend of the surface rupture has an orientation of NE-SW in the east between Gölyaka and Akyazi and then it appears with a general trend of E-W in the western part of the earthquake region. Width of the primary surface rupture traces varied from 5 to 20 m with little or no secondary deformation. However, broad zones of primary and secondary deformation up to 200 m wide were evident. The fault rupture produced typical examples of strike-slip offset, including well-formed moletracks, left-stepping en-echelon fault traces in various scales, uplift of pressure ridges and subsidence (**Fig.4**). Furthermore, the observations of striations on the existing fault rupture near Arifiye (Adapazari) and Tepetarla (between Adapazari and Kocaeli) imply that the vertical component of the fault motion has a normal fault sense with vertical offsets of 10–20 cm in these parts of the fault segment. This may be a further evidence of trans-tensional nature of the western part of the North Anatolian Fault.

In the western part of the earthquake-affected region, between Kavakli (Gölcük) and Hisareyn, a normal fault striking N45-60W/75-80NE with a significant vertical offset was observed. It produced a scarp of 3.5 km in total length and a vertical movement or a drop up to 2 m and some lateral movement (**Fig.5**). The fault initiates somewhere at the sea shore in Kavakli and terminates near the D-80 highway in Hisareyn village without apparent connection with any other earthquake break. This fault caused rotation of a pylon of a power line (**Fig.6**) near the Ford automobile factory construction site about 10 degrees and global subsidence of the basin with local submergence of the coastline and inundation of the

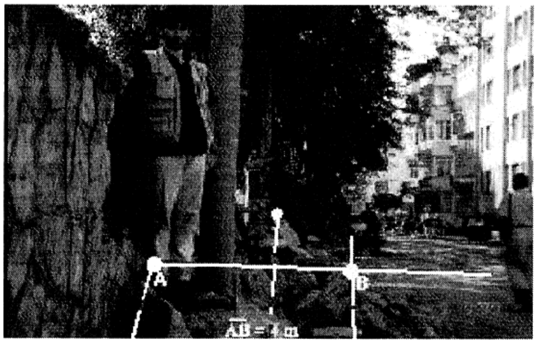


Fig.3 A typical view from the right lateral offset during Kocaeli earthquake (western wall of the Naval Command Center in Gölcük / slip: 4–5 m)

Fig.4 Moletrack between Gölyaka and Akyazi in Aksudere valley (Kocaeli Earthquake).

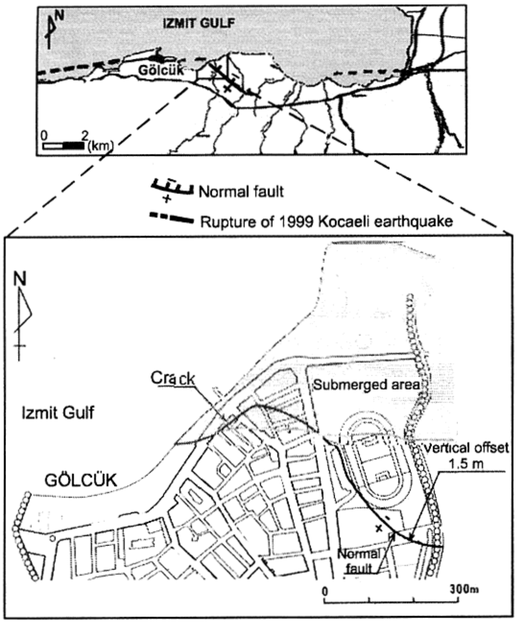


Fig.5 (a) Location and orientation of the normal fault at the east of Gölcük, and (b) a part of submerged land in Gölcük town (rearranged from Ishihara et al. 2000[4]).

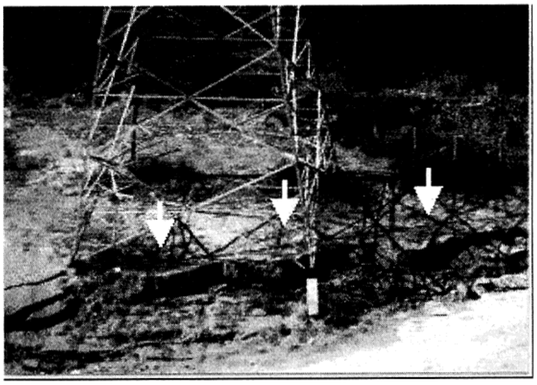
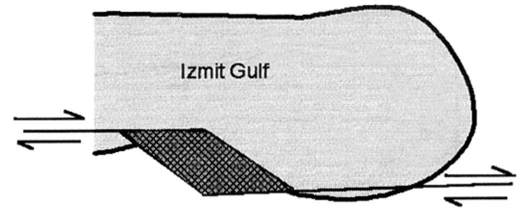
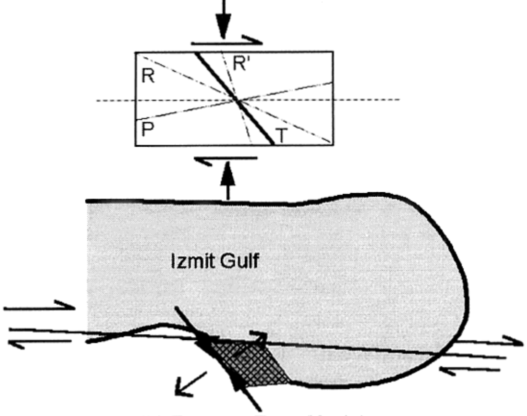


Fig.6 The fault with a normal component which caused rotation of a pylon of power line at the south of Ford automobile factory construction site.



(a) Pull-apart Model



(b) Fracture Zone Model

Fig.7 Models for explaining the cause of normal faulting between Kavakli and Hisareyn (P : P′ - fractures, T : T′ fractures, R-R′ : Reidel fractures).

northeastern part of Gölcük town (see **Fig.5**). Several models are suggested for explaining the cause of the normal faulting. These models may be broadly divided into the pull-apart model and the fracture zone model as illustrated in **Fig.7**. To validate the pull-apart model one need to find one more lateral strike-slip fault segment at the Hisareyn terminus of the normal fault. Since such a fault could not be found during both aerial and land surveying of this normal fault, this model must be declined.

Surface rupture of the 1999 Kocaeli earthquake, which traversed both rural and urban areas, generally occurred across the floors or edges of alluvial basins, and locally followed the prominent mountain range front to the south of the rupture zone. The direction of fault scarps coincides almost with that from the fault plane solutions. The fault seems to follow the centre of the depression of the region rather than the fault segments depicted on the previous geological maps, due to flowering phenomenon.

(2) Düzce earthquake and surface fault rupture

An earthquake of magnitude 7.2 on the Richter scale occurred at 18.45 on local time on November 12, 1999 in Bolu province of Turkey, which was subjected to big earthquakes in the past, three months after the devastating Kocaeli earthquake. The epicenter of this earthquake was about 110 km east of that of the Kocaeli earthquake (see **Fig.2**) and it occurred on Düzce fault. Official estimates placed the death tolls more than 850 and injuries about 4 950. This earthquake caused severe structural damages in Düzce and Bolu cities, and Kaynasli town. It is estimated that about 1 350 buildings collapsed and 7 000 residential and industrial buildings suffered heavy damage. Records of the maximum ground accelerations were 0.513 g and 0.805 g at Düzce and Bolu, respectively. On the contrary to the Kocaeli earthquake, liquefaction was not widely distributed throughout the Düzce earthquake region. Liquefaction fissures and sand boils were limited on or near the surface fault rupture.

The North Anatolian Fault between Erzincan in the far east and Bolu splays into two strands west-

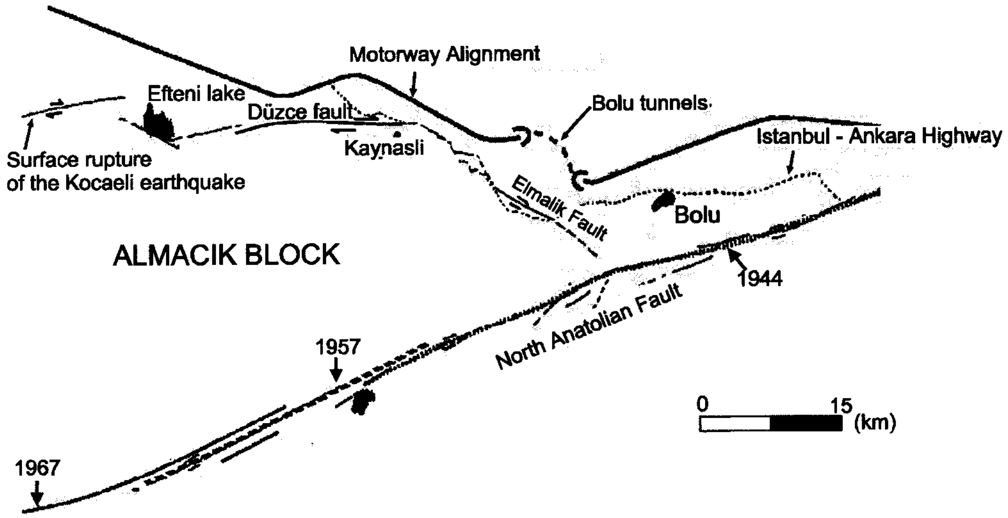


Fig.8 Active faults and previous earthquakes between Bolu and Düzce, and the position of the Ankara-Istanbul motorway project.

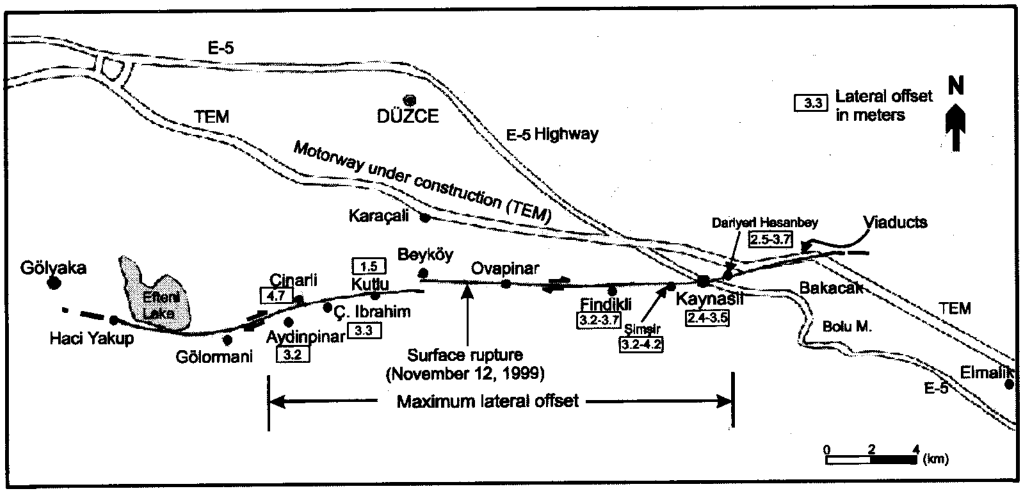


Fig.9 Rupture path of the fault during Düzce earthquake and amount of lateral offsets measured at certain locations.

wards Bolu (**Fig.8**). The southern strand goes into the Mudurnu valley and the Düzce-Hendek fault in the north surrounding a crustal block called Almacik block. The Düzce earthquake originated at a depth of 14 kilometers and caused a right-lateral strike slip movement on the Düzce fault with a slight normal faulting component. The surface rupture was 40 km long. There is an approximately 5 km step over at the eastern tip of the surface rupture resulted from the Kocaeli earthquake near Efteni Lake. The surface rupture, with a general trend of E-W, appeared at the south of Gölyaka town and terminated at a location about 2 km far from the west portal of the Bolu Tunnels (**Fig.9**).

The maximum lateral offset is about 5 m. As seen from **Fig.9**, the amount of right-lateral offsets, clearly observed on roads, fences and tree lines (**Fig.10**), increase in the central part of the rupture zone. The average lateral offset is about 3 m. Vertical offsets observed at some locations in the southern block are between 0.1 to 1.5 m and indicate that although the earthquake fault exhibits the characteristics of a strike-slip fault, it also has a normal component. The striations with inclinations between 25° and 30° on the surface rupture confirm the presence of normal component. Towards west, the surface rupture follows the southern shore of Efteni Lake. The nearly vertical displacements reaching up to 3 m observed at this locality are probably due to sliding of loose and weathered material forming the steep slopes rather than by faulting.

The width of the fault zone varied from 1 m to 50 m. Faulting seems to occur in the form of a series of planes parallel to each other with a general trend of

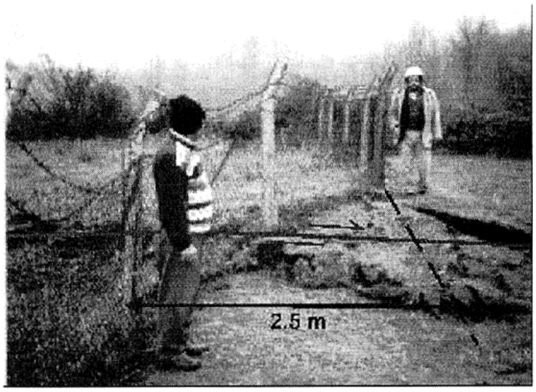


Fig.10 A typical right lateral offsets from the surface fault rupture resulted from the 1999 Düzce earthquake.

Fig.11 A typical view from the surface rupture and pressure ridges at the eastern part of Cinarli village (view from east to west).

E-W. Due to left stepping observed at some locations, pressure ridges were evident (**Fig.11**). In this zone, in addition to Riedel fractures crossing the main rupture surface with angles between 25° and 60°, en-echelon fractures were also well developed. The direction of fault scarps coincides almost with those obtained from the fault plane solutions. The surface rupture seems not to follow the depicted fault segment that passes through the boundary between the alluvial sequence and rock units at the southern edge of Düzce Plain. It should be remembered that such traces of rupture observed along the south of the Düzce plain are just the products of flowering phenomenon during the motion of strike-slip faults as a result of reduction of vertical stress near the ground surface.

4. EFFECTS OF FAULT BREAKS ON STRUCTURES

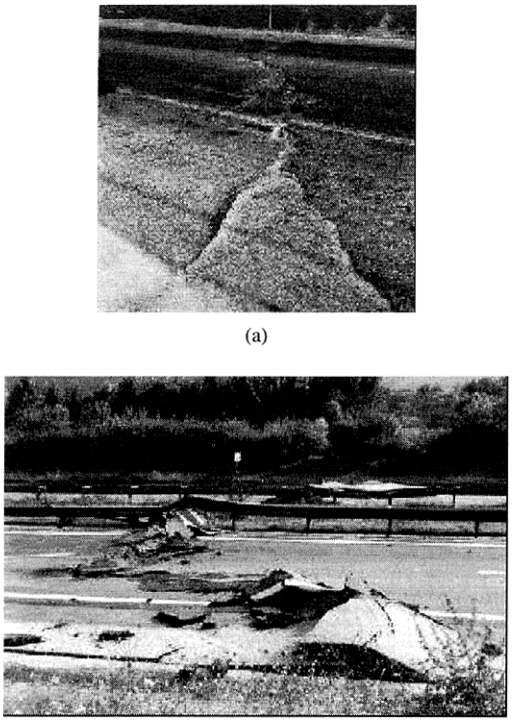
Although the mechanisms that cause ground failure near fault zones can vary, faults appear to be important in localizing ground failure. This section is included to demonstrate what fault breaks have direct impacts on the structures which may be some help to earthquake engineering community to develop seismic design codes for structures in active fault zones together with responsible scientists for better living environment of their societies who have just to live on the top of the seismically active belts of the earth. For the purpose, several important examples from both devastating earthquakes occurred in Turkey in 1999[5),6)] are selected and discussed.

(1) Roadways

Roadways are line-like structures and they may be built directly on the existing ground surface, elevated through viaducts and/or embankments or a mixture of the both. The fault zones in many parts of Turkey have generally alluvial deposits on the rock basement. The D-100 and D-130 highways passing through the earthquake affected region in the 1999 Kocaeli earthquake were directly built on existing ground surface. The D-130 highway was damaged near Basiskele region at the southeast corner of the Izmit Gulf where the fault has a relative horizontal displacement of 230 cm without any remarkable vertical component. The damaged part of the roadway was re-surfaced on the same day of the earthquake and the roadway was in service in such a short period of time. Damage to the D-100 highway took place at several points near the Kocaeli-Sakarya provincial boundary as a result of secondary normal faulting associated with the main lateral strike-slip event (**Fig.12a**). The largest vertical displacement was about 15–20 cm, the roadway was temporarily re-surfaced and it was in service within a few hours after the earthquake.

The Trans-European Motorway (TEM) was damaged at three different locations by the earthquake fault. The motorway with east and west bounds having 3 lanes each is slightly elevated through embankments in the earthquake affected region. Rupturing and buckling as seen in **Fig.12 b** damaged the surface of the motorway. Furthermore, the settlement of roadway embankments was observed along the 30 km section of the motorway between Arifiye and Köseköy. The damaged surfacing of the motorway was replaced within three days and was in service again. The resurfacing of the motorway was completed in 18 days after the earthquake.

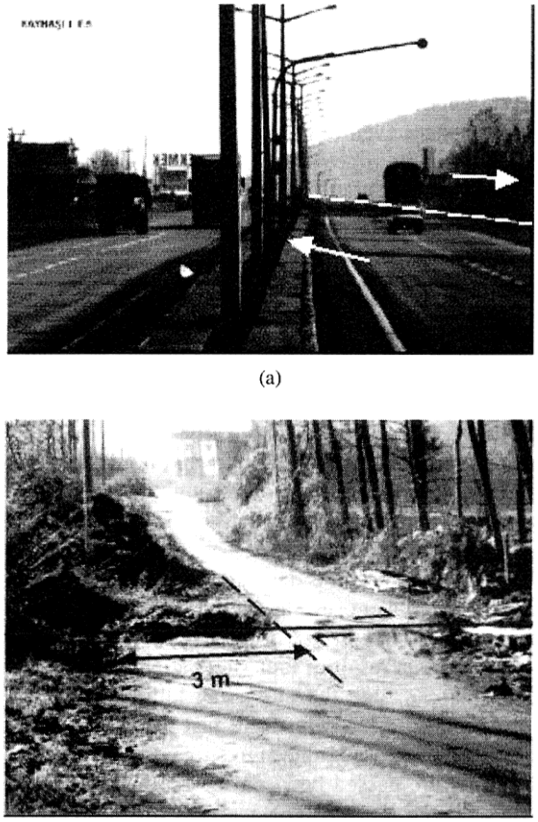
The E-5 (D-100) highway and TEM, connecting Ankara to Istanbul, also pass through the region affected by the Düzce earthquake. The fault break observed in this earthquake crossed the E-5 highway in Kaynasli town between Bolu and Düzce cities (**Fig.13a**). In addition to these, several country roads were crossed by the fault break (**Fig.13b**) and easily levelled with the dirt available on the site. The surface of the roadway directly built on existing ground surface was buckled since the maximum compres-



(a)

(b)

Fig.12 (a) Damaged D-100 highway, and (b) buckling of roadway surfacing on the motorway between Adapazari and Kocaeli.



(a)

(b)

Fig.13 (a) Damaged and repaired location of the E-5 highway in Kaynasli and (b) a displaced local road at Kaynasli.

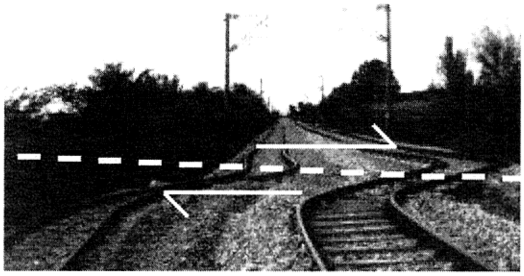


Fig.14 Buckled railway near Tepetarla station.

sion force induced by the ground movement coincided with the alignment of the highway. The highway was quickly re-surfaced in a short period of time and was operational.

From these examples it is clear that some damage to roadways could not be prevented where the relative movement of the ground occur due to faulting and non-elevation of roadways in fault zones is a key element to deal with the negative effects of faulting on roadways. There is a very important engineering decision, that is, the highways should be directly built over the existing ground surface in active fault zones.

(2) Railways

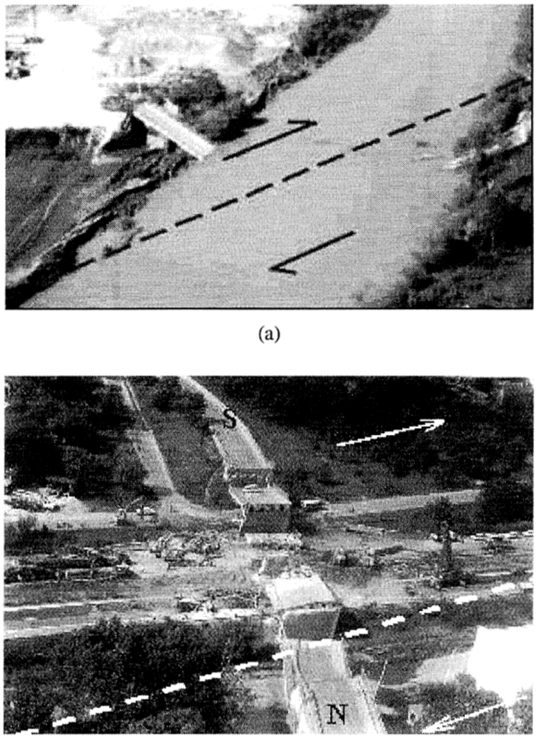
Railways are also line-like structures and they may be built directly on the existing ground surface, elevated through viaducts and/or embankments or a mixture of the both. The railways connect Istanbul to both Ankara and Adapazari and they have junctions near Tepetarla and Arifiye. Both electrical and diesel powered passenger and freight trains operate on the railways. The railways were also built on the existing ground surface. During the 1999 Kocaeli earthquake, the railways were buckled near Tepetarla station where the earthquake fault crossed the railways at an angle of 50–55° with well known 'S' shape (**Fig.14**). The fault was EW direction and crossed the rail with an angle of 60°. The right lateral offset was 2.5 m near this station. This direction is almost parallel to the maximum compression of the ground due to faulting and an approximately 200 m section of the railways was damaged. The ground was also heavily deformed by faulting for a length of 700 m resulted near the Kurtköy (close to Arifiye). The railways, however, were operational within three days after the earthquake by replacing buckled rails and damaged traverses, and the railways were completely repaired together with the correction of displaced alignment in 20 days after the earthquake, so that trains began to travel at their original speed. Particularly the damage near Kurtköy took more time to level the ground to the pre-earthquake level.

Although the damage to the railways could not also be prevented, even they are directly built on the existing ground surface where the railways must pass through an active fault zone, the recovery of railways is very quick.

(3) Bridges and viaducts

Bridges and viaducts are elevated structures. Since roadways and railways were not elevated structures, no viaducts existed in the region of the fault breaks resulted from the Kocaeli earthquake. The bridges of highways and railways over Sakarya River were intact and no direct faulting event occurred at these localities. However, the YSE bridge spanning over Sakarya River for a service road collapsed as a result of relative motion due to faulting between its abutments (**Fig.15a**). Along the damaged section of the motorway, there were several overpass bridges. Among them, a four span overpass bridge at Arifiye junction collapsed as a result of faulting (**Fig.15b**). The girders collapsed onto the motorway killing more than 10 people in a bus who were just happened underneath the overpass bridge at the time of collapse. The fault rupture passed between the northern abutment and the adjacent pier. The overpass was designed as a simply supported structure according to the modified AASHTO standards and girders had elastometric bearings. However, the girders were connected to each other through pre-stressed cables. The angle between the motorway and the strike of the earthquake fault was approximately 15°, while the angle between the axis of the overpass bridge and the strike of the fault was 65°. The measurements of the relative displacement in the vicinity of the fault ranges between 330 and 450 cm. Therefore, an average value of 390 cm could be assumed for the relative displacement between the pier and the abutment of the bridge. The girders of the bridge rotated and pulled so that the fall of the girders between the north abutment and the adjacent pier could not be prevented. However, the collapse of the other girders of the remaining part of the bridge might have been prevented if the girders were not connected to each other through the prestressed cables.

In the region affected by the Düzce earthquake, no bridge was directly crossed by the fault break. Although the bridges were very close to the fault break, there was no damage to those. A section of the Trans-European Motorway (TEM) between Bolu and Düzce is under construction. A 6 km long section of the motorways elevated through viaducts with a maximum height of 49 m and a width of 17.5 m. The maximum span is 39 m and each viaduct has 12 piles with the diameter of 180 cm. The elevated section is divided into to large segments, namely East viaducts and West viaducts. Although the viaducts exhibited a well performance in the Kocaeli earthquake, the fault break passed through the elevated section of the TEM in Asarsuyu valley at an angle of 20°–30° and caused the rotation and tilting of some of piers during the Düzce earthquake (**Fig.16**). As a result of that, the simply supported girders of the viaducts were displaced from their supports. Although no girder was fallen off and piers performed very well during the earthquake, some of the girder were very close to fall.



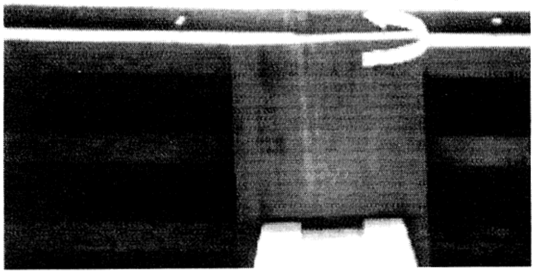
(a)

(b)

Fig.15 (a) A view from a collapsed bridge on Sakarya River at 5 km of SE of Adapazari due to faulting (view from south to north), and (b) an aerial view from the collapsed overpass bridge onto the motorway near Arifiye.

The examples mentioned above indicated that it is not desirable to elevate the roadways in fault zones where permanent deformation of the ground may take place during earthquakes. If they have to be elevated for some important reasons, such as floods or landslides, the limitation of roadway inclination, etc., as being in the case of viaducts in Asarsuyu valley, it seems better that the girders should be designed as redundant structures, and simply supported structures must be avoided as much as possible. Furthermore, T-type piers should be generally avoided as this type piers result in top-heavy situations.

(a)



(b)

Fig.16 (a) The surface rupture of the Düzce earthquake appearing below the viaducts of the motorway, and (b) a view from displaced girders of the viaducts.

(4) Dams

The failure of dams has very severe impacts on the structures as well as on the residential areas in downstream. Since such failures are not allowable whatsoever, the site selection of the dams is carried out with utmost care in dam constructions. As a result, it is very rare to see a dam failure caused by earthquakes due to active faulting.

The nearest dam was the Yuvacik dam in the area affected by the 1999 Kocaeli earthquake that is an earth-fill dam with a height of 40 m. Although this dam was at a distance of 10 km to the earthquake epicentre, no failure was observed. The rock-fill dams are also known that they could accommodate relatively large ground displacements while arch concrete dams or gravity concrete dams could rupture even at a relatively small amount of displacements of the foundation rock.

There are several dams either earth-fill or rock-fill type around the epicentre of the Düzce earthquake. The distances of the nearest dams to the earthquake epicentre are 12 and 21 km and they were built for the purposes of irrigation and flood control, respectively. Although the authors did not visit these dams, the State Hydraulic Works, DSI[7] reported it, that the dams were not damaged during the earthquake.

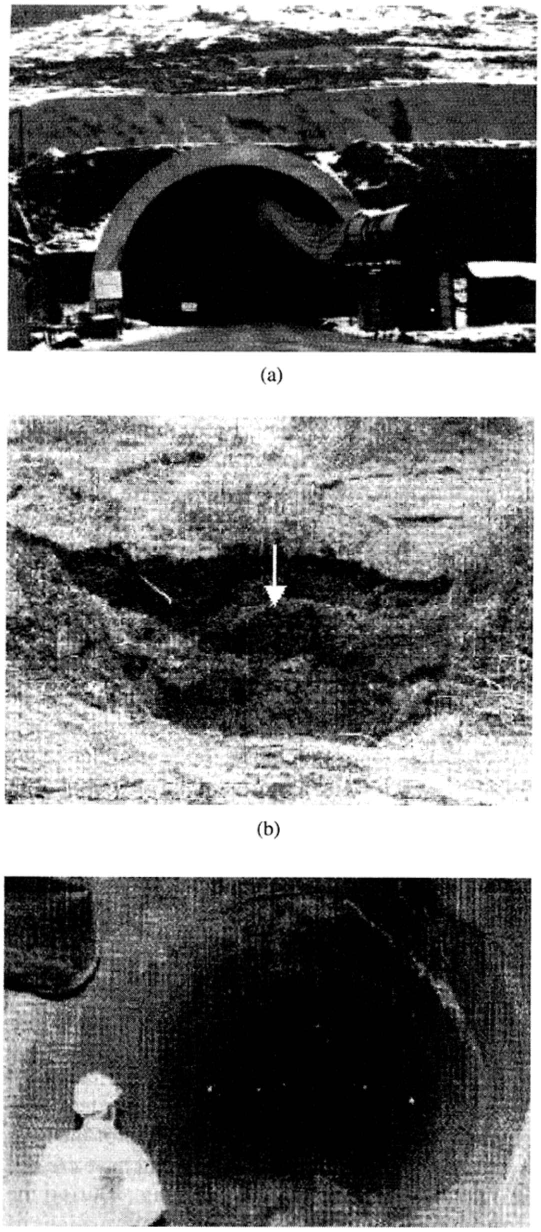
The conclusion for dams is that active fault zones in engineering sense must be avoided as dam sites. If such sites could not be avoided for some reasons, dams should be designed as rock-fill dams so that some relative displacement could be accommodated.

(5) Tunnels

Similar to roadways and railways, tunnels are also line-like tubular structures. The past experience on the performance of tunnels through active fault zones during earthquakes indicates that the damage is restricted into certain locations. During the 1999 Kocaeli earthquake, portal failures of quite limited scale were observed at the short tunnels of the TEM on the northern side of the Izmit Gulf. As the fault breaks did not cross these tunnels, no damage to tunnels was observed. In addition, a railway tunnel on the southern side of the Sapanca Lake was not damaged even though this tunnel is within the active fault zone in a geological sense.

The tunnels in the Düzce earthquake region are only the Bolu Tunnels, which are presently under construction as a link of the Anatolian Motorway between Istanbul and Ankara (see **Fig.8**). The tunnels have a cross-section of about 170–200 square-meter and each tunnel being 16 m wide and 11 m high has tree lines. The tunnel portals are at Elmalik on the Bolu side and Asarsuyu Valley on the Düzce side. The tunnels are about 3 400 m long. The rock mass on the Elmalik section is very weak and characterized as squeezing rocks[8]. Rocks in this section of the tunnels were geologically subjected to thrust type faulting and folding which took place before the North Anatolian Fault took place in Miocene. This led to the formation of low-angle fault zones, some of them up to 100 m wide. It is these fault zones that have created the major difficulties during tunnelling. During the excavation of the tunnels, very large deformations of 1 000 mm were observed in phyllites on the Asarsuyu section and in siltstone, mudstone and clayey rocks on the Elmalik section for about 800 m from the Elmalik portal.

In view of the orientation of the fault break, it is considered that the fault break should not cross the tunnels although it passed them very closely and disappears near the Asarsuyu portal in the west. Because of limited access to the tunnels, only the Elmalik portal (**Fig.17a**) could be possible to visit. Therefore, it is not known if there is any damage to the tunnels. Even if there was any damage to the tunnels due to faulting, the damage should probably be limited to locations where the fault breaks crossed the tunnels. Another



(a)

(b)

(c)

Fig.17 (a) View from the Elmalik portal of the Bolu Tunnels, (b) surface crater above tha collapsed main tunnel on the Elmalık side[9], and (c) damages to pilot tunnels[9].

type of damage to the tunnels may occur at locations where heavy squeezing problems were previously encountered. Since the loads acting on support systems at these locations are already high, the ground shaking can impose additional dynamic loads on support systems when the overburden is relatively shallow. As a result of that, if the support system is insufficient in capacity, some roof and sidewall collapses may take place.

After a certain period of time, it was reported that a collapse occurred in an unfinished portion of the tunnel in the fault gauge zone on the Elmalik side where the major difficulties had previously been experienced[9]. The collapse on the Elmalik side occurred about 50 m beyond the end of the completed inner lining section. Cracks and craters could be observed on the surface (**Fig.17 b**), although the overburden is more than 50 m at this location. This section is located at the transition from fairly good ground into a major fault zone. Damage can be observed at the inner side drift shotcrete structure. The 30 cm thick shotcrete shell was fractured in the invert and the shoulders (**Fig.17c**). The causes for this behaviour still have to be determined. It is also noted that accelerations of 0.6 to 0.8 g were measured at the stations in the vicinity of the site, far in excess of the 0.4 g design with the preliminary assessments arisen from the authors about the possible damage to the tunnel.

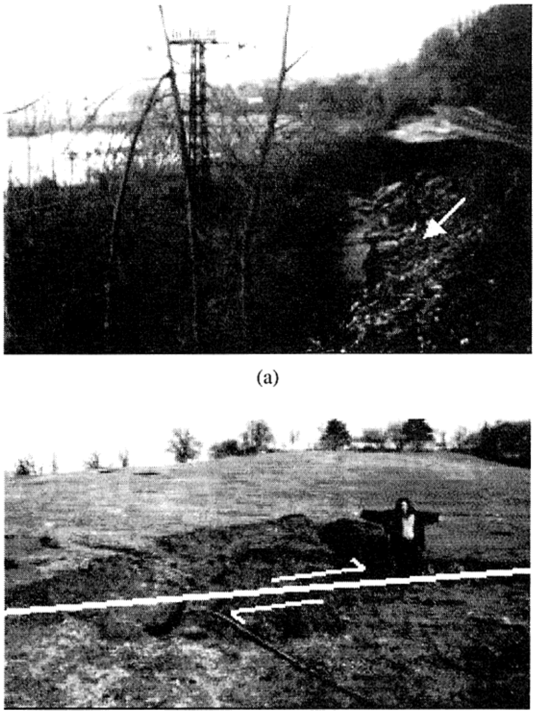
As understood from these examples, it is difficult to prevent the rupturing of tunnel linings at locations where the fault cause relative movements. Nevertheless, this type of damage is quite localised and it does not cause any danger to the overall stability of tunnels. Therefore, the current seismic design concepts for tunnels can be safely used and design should also be based on dynamic numerical calculations.

(6) Power transmission lines and tubular structures

Power transmission lines generally consist of pylons and power transmission cables. The design of pylons and cables are generally based on the wind loads and the possibility of slope failure of the pylon foundations. During the 1999 Kocaeli earthquake, only one pylon was damaged nearby Ford-Otosan automobile factory construction site near Gölcük town. At this site a normal fault, which is a secondary fault to the main lateral strike-slip faulting event, crossed through the foundations of the pylon and its vertical offset was about 240 cm. One of the foundations of the pylon was pulled out of the ground and was exposed as seen in **Fig.6**. Some of its truss elements were slightly buckled. Nevertheless, the damage to the pylon was quite limited and this damage could not hinder its function.

During the Düzce earthquake, the fault break induced damage to a minor energy transmission line occurred near Cevizli village as shown in **Fig. 18a**. The roadway embankment failure induced by the fault break nearby Efteni Lake caused the steel pylons sank to the lake and electricity cables were subsequently cut off.

Tubular structures may be specifically designated as petrol and gas pipelines, water pipes and sewage systems. These structures may fail either by buckling



(a)

(b)

Fig.18 (a) Damaged to a minor energy transmission line due to fault break induced embankment failure of a roadway on the shore of Efteni Lake, and (b) ruptured plastic pipe in Findikli village (Düzce earthquake).

or separation during a faulting event. Three such incidents were observed during the 1999 Kocaeli earthquake. These incidents took place at the pumping facility of the Seka paper-mill plant at Sapanca Lake and near Tepetarla village where the railways were buckled. The natural gas pipelines crossing the Izmit Gulf between Yalova and Pendik were undamaged.

No damage to the wells, pipes and pumps of the water supply systems during the Düzce earthquake was reported. Nevertheless, it is reported that the water supply system of Düzce city was heavily damaged as a result of breaks at pipe joints due to ground shaking and probably lateral spreading. The damage to the water supply system of Kaynasli town was quite heavy since the water pipes were damaged by either buckling or breaking as a result of ground shaking and faulting. The damage to asbestos or plastic pipes and was quite heavy (**Fig.18b**).

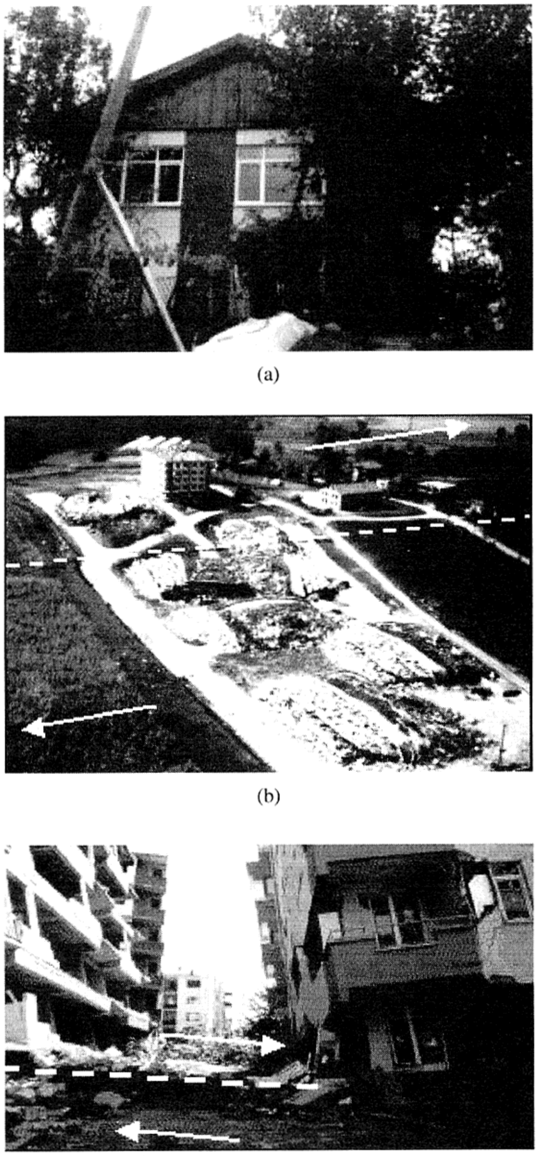
Ground failure, rather than ground shaking, is the principal cause of damage to tubular structures. The damage to tubular structures is generally difficult to prevent during faulting. The brittle sewer pipes tend to fail under much lower strains than water lines, so damage to sewer lines is considerable more extensive. Such systems are checked systematically through water flow states at manholes in cities, towns and villages. If there is any blockage, they are repaired. However, some damage may undergo unnoticed unless an indication of damage in the form of ground cave-in takes place or material or smell leaks out of the ground. Nevertheless, using the flexible joints developed originally for pipes against the lateral spreading of liquefied ground, some of damage to pipelines, however, may be prevented in such active fault zones.

(7) Buildings

The vast majority of losses to property and lives caused by an earthquake involve buildings and the people inside. Particularly the buildings located on the fault zones have more risks to damages induced by fault ruptures. Many buildings along the earthquake faults of the 1999 Kocaeli and Düzce earthquakes behaved in various manners. During the site investigations of the 1999 earthquakes in Turkey one could see either totally collapsed, severely damaged or intact buildings just on or next to the traces of the fault breaks. The examples are many[5),6)] and it is quite difficult to quote all of them. Some of typical examples from both earthquakes are given and briefly discussed.

The first example from the Kocaeli earthquake is a two-story reinforced concrete house with a raft foundation in Tepetarla village. The fault passed just underneath the foundation of the southern side of the building (**Fig.19a**). The relative displacement of the fault break was about 200 cm. Since 70% of the foundation of the building was on the stationary northern side of the fault and the southern side of the fault had a very small amount normal component, no damage to this building was observed. In other words, this implies that if the fault just slides beneath a structure with a raft foundation in the case of strike-slip faulting, no damage could be caused to the structure, provided that the structure is strong enough against shaking.

A very peculiar behaviour of an apartment complex consisting of 8 five-story apartment blocks was observed in Kullar village (**Fig.19b**). Seven apartment blocks failed in a pancake mode while one apartment block remained self-standing. One of the failed apartment blocks just crossed by the fault break that has a relative horizontal displacement of 240 cm and 20–25 cm vertical throw (north side down). The ground surface was sloping to north. One of two apartment blocks on the southern side was damaged while the other one collapsed towards east in a pancake mode in accordance with the movement of its foundation. The 5 blocks on the northern side were completely collapsed in a pancake mode towards west in accordance with the direction of shaking. Except the apartment block over the fault break, the failure of 5 blocks on the northern side of the fault break may be con-



(a)

(b)

(c)

Fig.19 (a) The behaviour of a two-storey reinforced building at Tepetarla; (b) the collapse of apartment block at Kullar, and (c) rotated buildings due to strike-slip faulting in Gölcük (Kocaeli earthquake).

sidered to be purely due to shaking. Although the intensity of shaking on the southern side of the fault break should be the same, the damaged self-standing apartment block should deserve some special consideration. The simplest explanation may be just a slight variation of the ground condition if the apartment blocks are assumed to be structurally identical. Whatever the reason is, it is of great interest that the most vulnerable buildings may also survive within a distance of 5 to 6 m to the fault break during the inland earthquakes.

Third example from the Kocaeli earthquake is concerned with the behaviour of apartment buildings beneath which a fault break with a relative horizontal displacement of 450 cm and 50 cm vertical throw passed in Yüzbasilar district of Gölcük town. As seen from **Fig.19c**, the apartment buildings were severely damaged by torsion, but did not totally collapse due to the close proximity of their foundation resulting in some lateral restrains during the interaction of their foundations and the fault break.

On the contrary to the Kocaeli earthquake, the surface rupture produced by the Düzce earthquake generally passed through the rural areas. Therefore, mostly one- or two-story village houses were affected by the ground failure induced by the fault.

The first example from the Düzce earthquake is a one-story reinforced concrete house with a raft foundation in Findikli village. The fault passed just underneath the foundation of the building (**Fig.20a**). The relative displacement of the fault break was more than about 250 cm with a vertical throw of 90 cm. Since more than 50% of foundation of the building was on the southern side of the fault, the building tilted and rotated as seen in the figure. However, no structural damage to this building was observed and the building behaved like a rigid box.

The next example is an old one-story himis (wooden) house on the fault (**Fig.20b**). The building is distorted as a result of the vertical displacement of the fault rather than the strike-slip faulting. Nevertheless, there is no total collapse of the house and diagonal wooden beams absorbed the shocks. It seems that pure lateral strike-slip movement of the fault is not of great concern as long as the building freely rotates and slides during the faulting motion. The main reason of the failure is probably due to the vertical throw of the fault.

Fig.20c shows a brick masonry house with a raft foundation and a continuous concrete slab all around the structure. The fault break with a lateral strike-slip 320 cm just passed beneath the left corner of this masonry house. There was no structural damage to this brick house from a visual inspection. In addition to this house, no structural damage to a himis house was observed at this site at a distance of 3 m from the fault break.

The reinforced concrete buildings with 4 stories or more on the alluvial plain collapsed. **Fig.20d** shows a totally collapsed 5-story reinforced concrete building in Kaynasli, beneath that the fault break passed. Of course, one may easily think of the fault break as primary culprit for the collapse of this building. Considering other totally collapsed similar type buildings, which were not directly crossed by the fault, it should be plausible to put the blame directly onto the fault break.

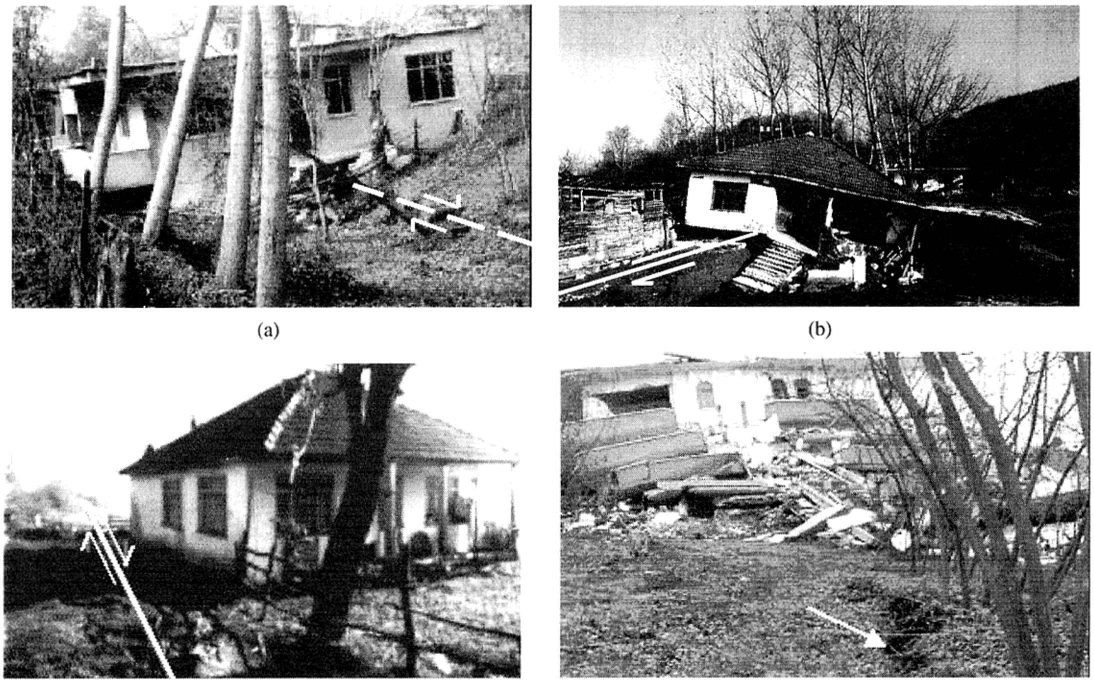

(a) (b)
(c) (d)

Fig.20 (a) Tilted and rotated one-story reinforced concrete building in Findikli, (b) one-story himis building in Çakiribrahim village, (c) a brick masonry house in Findikli village, and (d) a totally collapsed 5-story reinforced concrete building in Kaynasli (Düzce earthquake).


(a) (b)

Fig.21 (a) Partially damaged mosque in Dariyeri Hasanbey village due to fault break passing beneath the left corner of the main compound, and (b) a collapsed mosque in Kaynasli due to fault break passing beneath the main compound (Düzce earthquake).

The damage to the main compounds of mosques was generally concentrated at corners as observed in the previous earthquakes of Turkey. The main compounds of mosques generally have single dome or multiple semi-spherical domes and they are structurally symmetric. For this reason, the main compounds remain intact during shaking. They either failed or damaged when the faulting occurred right underneath the structure or hit by the falling minarets. However, some mosques having shops at ground floor, which is historically unconventional, failed as a result of weak-floor situation. Two examples from near faulting area observed in Kaynasli and Dariyeri Hasanbey village after the Düzce earthquake are shown in **Fig.21**. These examples show that the lives can be saved if the buildings are constructed like a rigid box structures with the use of reinforced concrete shear walls instead of fragile hollow brick walls having almost no structural strength.

5. GROUND SUBSIDENCE AND SUBMARINE LANDSLIDE DUE TO FAULTING

In addition to liquefaction-induced lateral spreading with a large extent (**Fig.22**), a huge scale subsidence occurred along the southeastern shore of

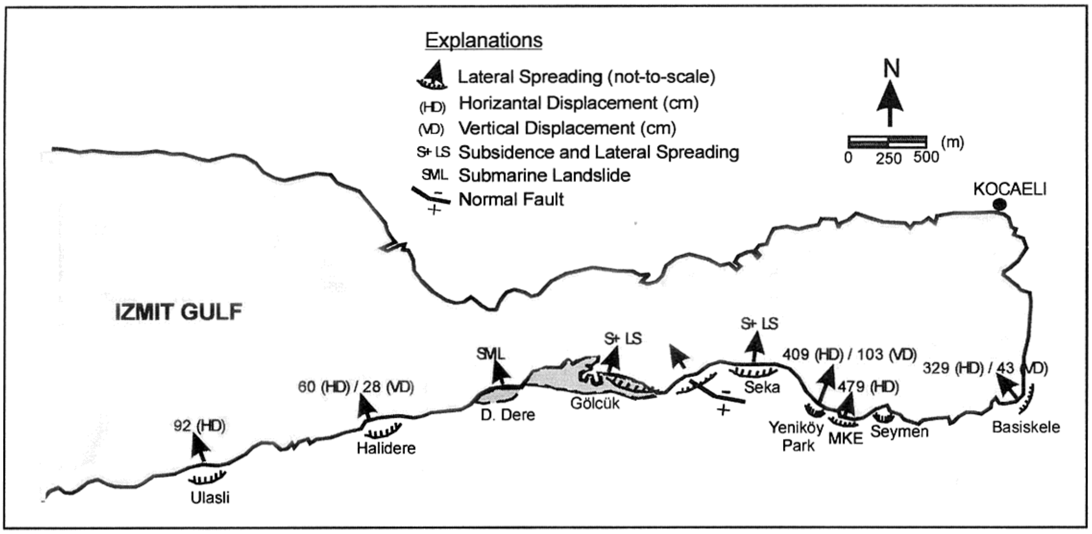
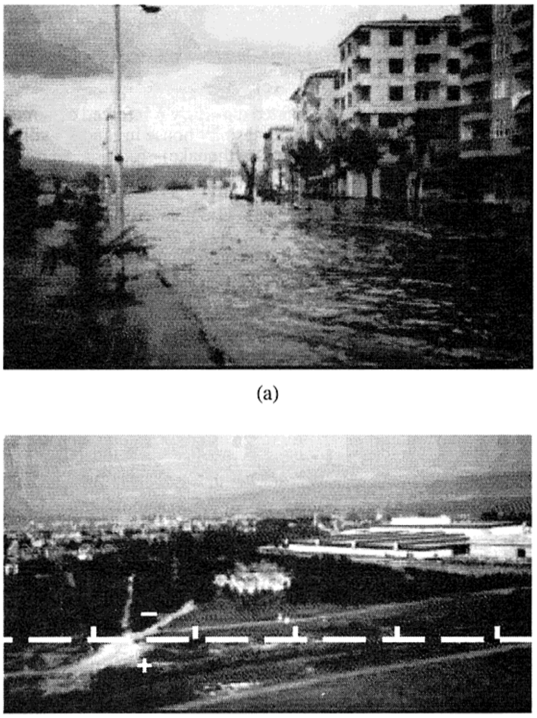


Fig.22 Locations of lateral spreading, subsidence and submarine landslides along the southern shore of Izmit Gulf[10].

the Izmit Gulf during the 1999 Kocaeli earthquake. This ground failure was typically observed between Kavakli district of Gölcük town (**Fig.23 a**) and Seymen at its east. As previously discussed in **3.(1)**, the ground subsidence took place as a result of secondary normal faulting associated with the main lateral strike-slip event (see **Fig.5**). The land on the overhanging block of the fault subsided with a gradual tilt towards the sea with the northern tip submerged into the sea. In other words, a huge land has moved as a whole towards the sea with lower relief. A large industrial plant under construction for Ford Otosan was on the overhanging wall of the fault. It was undamaged except where ground settlement and trace of the normal fault with a vertical throw of 240 cm intersected one corner of the 50.000 m^2 building (**Fig.23b**). At this location the building (steel roof trusses on concrete columns with metal cladding) experienced settlements that pulled the columns over several tens of centimetres. Particularly at Kavakli, fine sand was ejected as a result of liquefaction (see **Fig.23a**). However, the subsidence was mainly associated with the ground settlement due to normal faulting and partly lateral spreading induced by liquefaction.



(a)

(b)

Fig.23 (a) Submerged Kavakli district of Gölcük town due to normal fault induced ground subsidence, and (b) a view of Ford-Otosan factory with the normal fault scarp.

Private companies at Kavakli-Gölcük, Ihsaniye, and Yeniköy districts for a sewage project previously drilled about one hundred shallow-geotechnical boreholes with depths varying from 3 to 21 m. Some of these boreholes were located on the northern block of the normal fault. The available borehole data indicated that the groundwater table was very shallow (1 to 5 m) and the ground consisted of alluvial deposits. At the top there were generally loose sand, silty sand and sand and gravel mixtures, while clay and silty clay layers appeared at deeper elevations. Soft-to-moderately stiff clay layers with organic content were occasionally observed in these boreholes, and their shear strength seems to be low (c = 13–20 kPa and ϕ = 5–21°). The presence of shallow

Fig.24 Coastal land chopped away into the sea due to submarine landslide at Değirmendere during 1999 Kocaeli earthquake.

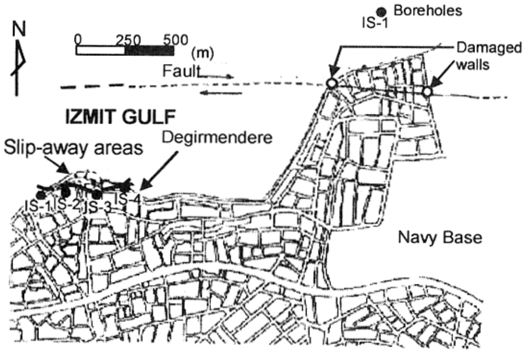
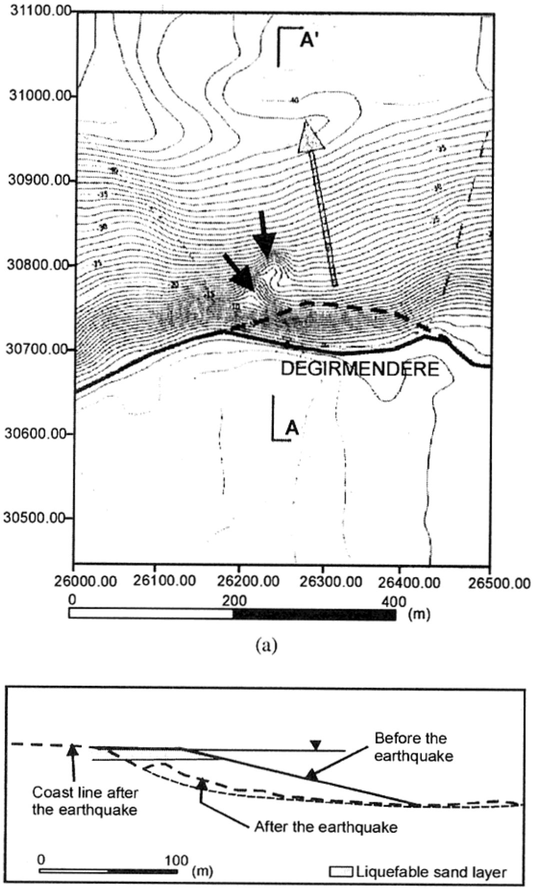


Fig.25 Locations of fault break, land submerged and geotechnical boreholes drilled after the Kocaeli earthquake (rearranged from Ishihara et al. 2000[4], and Kiper and Arel 2000[11]).

groundwater and sand levels at upper elevations generates condition favourable for liquefaction and confirm the liquefaction phenomena observed along the coastline. On the other hand, the topography gently inclined towards the sea and the presence of clay layers suggest a possible movement on one of the clay layers which acts as a basal sliding surface and on the normal fault plane acting as a rear release surface similar to landslide. Based on site observations, Ishihara et al. (2000)[4], who suggest a similar mechanism for the ground subsidence, considered the existence of a layer of stiff clays or soft rocks at great depths between 50 and 100 m. If the piers beneath the Ford automobile factory reaching to a depth of 20 m and no damage to the plants except ground settlement are taken into consideration, depth of the sliding surface seems to be greater than 20 m. However, it is still discussable at this time to conclude on the depth of this sliding surface, and further investigation is needed.

Submarine and seashore slides during the 1999 Kocaeli earthquake (see **Fig.22**) were mostly associated with reclaimed lands along the shore. It seems that in addition to ground disturbance near faulting, soil liquefaction has also some roles in submarine slides. The most publicised submarine slide took place at Degirmendere where a 5-story hotel slid into the sea together with two adjacent buildings (**Fig.24**). The site investigations showed that there were tension cracks extending into the land at a distance of 75–80 m from the post failure seashore. The spacing of these tension cracks was quite consistent. The coastal land about 250 m long was chopped away into the sea (**Fig.25**).

After the Kocaeli earthquake, depth of water was measured[4] and the bathymetry map of the seabed in the vicinity of Degirmendere was prepared[11]. From **Fig.26** it is evident that the seabed topography considerably changed after the earthquake. Abrupt changes in the configurations of contour lines at northwest of the sliding land (shown by dashed arrows in **Fig.26a**) and heaves at the bottom of the sea (**Fig.26b**) probably suggest that the sliding material spreaded about 300–350 m from the shoreline. The right- lateral offset reaches to a maximum value (4.5 m) in this area



(a)

(b)

Fig.26 (a) Bathymetry of Değirmendere coast and vicinity, and (b) configuration of the seabed before and after the Kocaeli earthquake (rearranged from Kiper and Arel 2000[11], and Ishihara et al. 2000[4]).

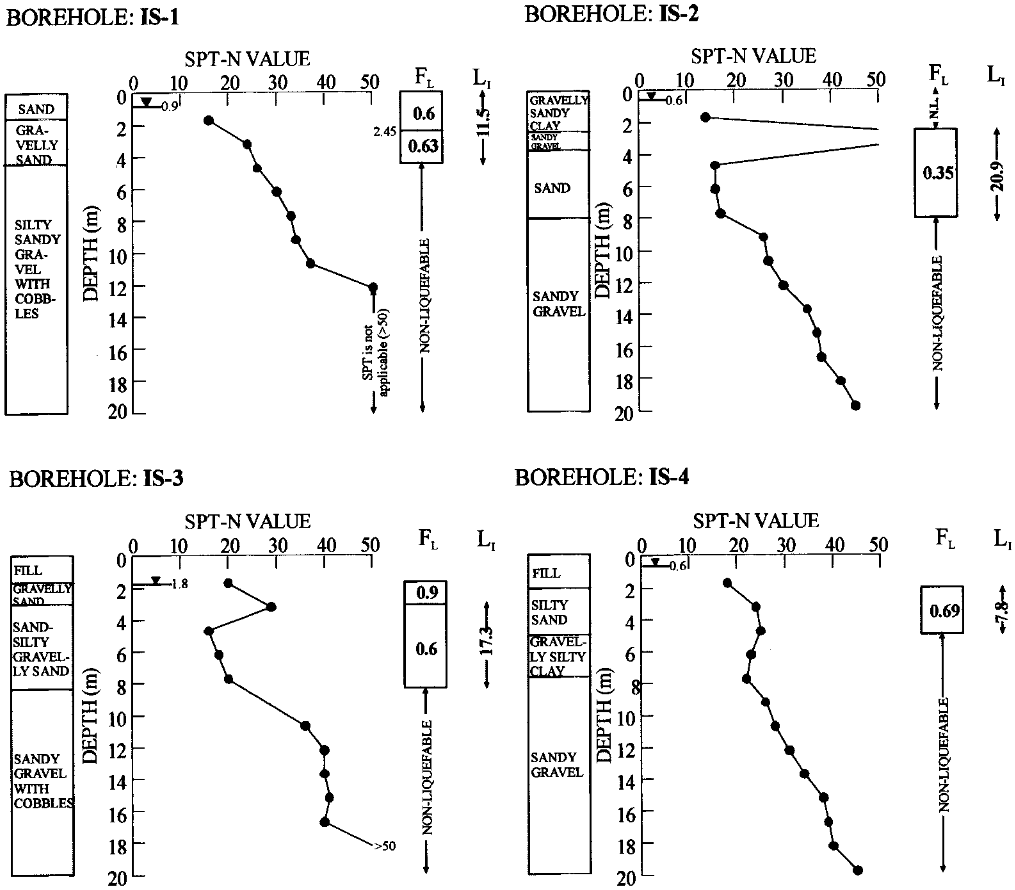


Fig.27 Simplified borehole logs illustrating ground conditions, variation of SPT-N values with depth and liquefiable layers at Degirmendere coast line (F_L: Factor of safety against liquefaction, L_I: Liquefaction potential index, N.L.: Non-liquefiable).

(see **Fig.3a**), and the fault break disappears near the shore between Gölcük and Değirmendere. Based on the general trend of the fault break at this locality, it is possible to consider that the fault break passes very close to Degirmendere coastline under the sea as illustrated in **Fig.25**. As previously stated in the previous investigations[4),11)]. it seems that the most important factor contributed to this ground failure occurred in the form of submarine landslide is the disturbance effect in the fault zone.

An attempt was made by the authors to assess the effect of liquefaction on this failure as a supplementary work to the previous observations. For the purpose, data (**Fig.27**) from four geotechnical boreholes of 20 m deep drilled after the earthquake near the slip-away coast line of Degirmendere by a private firm (see **Fig.25**) were employed. **Fig.27** suggests a very shallow groundwater table and fully saturated soils. At the top, except fill materials 1 to 1.5 m thick, there are generally silty sand (SM) layers of 3 to 7 m thick above moderately dense silty sandy gravels (GW-GM). The method based on the field performance data[12)] was employed as a mean of evaluating the resistance to liquefaction of the alluvial soils observed through these boreholes. In addition, liquefaction potential index[13)] in order to estimate the severity of the liquefaction degree at the site was also calculated for each layer. The results of the liquefaction susceptibility assessments indicated that the sand layers appearing at depths between 1.5 and 4.5 m in boreholes IS-1, IS-2 and IS-4, and between 1.5 and 8 m in borehole in IS-3 were liquefable. The values of liquefaction potential index indicate that these sand layer have high-to-very high liquefaction potential (see **Fig.27**). These preliminary assessments suggested that liquefaction occurred along the shoreline of Degirmendere at a depth between 1.5 and 8 m during the 1999 Kocaeli earthquake. If this ground failure is considered only due to liquefaction, seabed relief at a location about 75 m off the coast should be taken place approximately at −8 m. But it is evident from **Fig.26a** that water depth is about at −15 m at this distance. Another important issue is that the extension of the fault probably runs at a location where the toe of the failed slope takes place before the earthquake. All these suggested that the ground failure occurred as a submarine landslide mainly due to faulting induced shaking and liquefaction induced lateral spreading can also be considered as another factor contributing to this ground failure. However, it is still premature at this time to conclude the cause of the ground failure along Değirmendere coast and more detailed investigations involving different analysis techniques are needed to clarify the mechanism.

Whereas many buildings in the central part of Gölcük suffered severe damage, most of those built on the slump land itself were little damaged, but settled and submerged due to fault-induced submarine landslides and subsidence of huge terrains, and partly liquefaction-induced lateral spreading. Therefore, the association of materials and groundwater depths, and the orientation and extent of seismogenic and secondary faults can be used to identify the areas where site-specific studies of potential ground failure may be advisable. At such near-shore zones that are candidates to subject to ground- failure hazards, structures on the shoreline should be avoided.

6. CONCLUSIONS AND RECOMMENDATIONS

The authors tried to present the behaviour of different types of structures built in active fault zones during the last two in-land earthquakes occurred in Turkey, although it is impossible to cover every aspect of this important topic in the earthquake engineering in a short article such as the one presented here. As a conclusion, it must be clearly stated that "*it is almost impossible for mankind to prevent the damage to structures if a fault break happens to be just passing underneath the structures.*" Nevertheless, the adverse effects of fault breaks on structures can be minimised to a certain level in view of findings from the actual examples presented in this article as it would be impossible re-settle huge populations in earthquake prone countries without faults. On the basis of these findings, the following recommendations may be considered as guidelines in developing the seismic codes for structures in active fault zones.

1. Roadways and railways should not be elevated and they should be constructed on the existing ground surface in active fault zones. In doing so, the recovery of roadways and railways to be damaged by fault breaks in the event of the earthquakes would become very rapid. As a result, the effective rescue and rehabilitation works would become possible.
2. It is not desirable to build bridges and viaducts in fault zones where permanent deformation of the ground may take place during earthquakes. If they have to be constructed for some reasons, such as floods or landslides, the limitation of roadway inclination, etc., they should be constructed as redundant structures, and simply supported structures should be avoided. Although pre-stressing can be used to increase the confinement of girders along the longitudinal axis of the bridge, the structures should not be wholly pre-stressed in order to prevent domino action in the event of failure. Furthermore, T-type piers must not be used as they constitute top-heavy situations that are undesirable in case of faulting as well as shaking caused by earthquakes.
3. Dams should never be built on active faults defined in engineering sense as they have severe impacts on structures and residential areas in downstream. For some reasons, if they have to be built, their height should be kept to a minimum and the type of dams should be rock-fill.
4. The current seismic design codes for tunnels, subways and underground caverns can be safely used. As the damage to tunnel linings due to fault breaks would be localised, there is no need for extra precautions at those locations. Nevertheless, the cross sections may be kept larger than the required design size at those locations in order to allow extra space in the event of relative movements.
5. The ground failure due to faulting and liquefaction, rather than shaking, is the principal cause of damage to tubular structures. Therefore, such structures should be designed with the use of flexible joints to accommodate relative displacements with the consideration of likely relative displacement of the ground.
6. Damage to buildings on or near fault zones seems to be minimized if they are designed as rigid box-like structures with the use of shear walls. Walls, with fragile hollow bricks having no structural strength, must not be allowed to use in building construction. If the solid brick walls are to be used, the walls should be constructed before the construction of columns and beams in order to attain the structural integrity of the structure and they should be light, resistant and ductile.
7. Vertical accelerations of in-land earthquakes could be 0.65–0.75 times the maximum horizontal accelerations. Sometimes they may exceed, even the maximum horizontal acceleration as observed in Düzce during the 1999 Kocaeli earthquake. The effect of vertical accelerations must be considered in structural design.
8. In recent years, particularly during the 1994 Northridge and 1995 Kobe earthquakes, sig-

nificant number of records with large peak accelerations (e.g.~ 1 g) and with long duration pulses have been acquired in the near field (<10 km) from the fault. Consequently, to compensate for the additional demand in design strength caused by such motions, recent codes in the United States adopted the Near Fault Factors[14]. The probabilistic acceleration zoning of Turkey with a 10% probability for 475 years, prepared by Gülkan et al. (1993)[15] and adopted in the Turkish seismic design code estimated the maximum ground acceleration as 0.55 g for the North Anatolian Fault Zone in the Izmit Gulf region[16]. This value was in good agreement with the measurements. This implies that the current seismic design codes of Turkey are capable of handling the likely shaking characteristics of the ground in the active fault zones. However, it may be better to increase the level of peak ground acceleration at least within 1 km to the likely active faults in order to incorporate the near field effects of the fault breaks.

9. The structures of great importance should be sited on rock foundations rather than on loose alluvial ground, since the amplification of the loose ground may be 10 times that of the rock foundation. For example, the maximum horizontal acceleration recorded at Ceyhan situated on alluvial ground was 320 gals while the maximum horizontal acceleration recorded at Karatas situated on rock was 33 gals during the 1998 Adana-Ceyhan earthquake in Turkey[17], although the epicentral distances were the same. Therefore, the failure risk of structures during earthquakes could be drastically reduced by such a selection.
10. Global, regional and local geological, geotechnical and seismic hazards zoning maps of cities and towns for residential and industrial developments in seismically active fault zones must be put in practice. Furthermore, the detailed geological and geotechnical investigations should be required before any new development so that it may be possible to reduce and to mitigate seismic hazards to protect public health and safety during earthquakes in active fault zones[18].
11. Near - shore zones, which may subject to ground-failure hazards such as subsidence or submarine landslides due to faults and liquefaction, must be carefully identified, and construction at such localities should be avoided.

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