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The role of transcurrent fault structures in damage typology during the Izmit and Duzce earthquakes (Turkey, 1999)

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Abstract

The Turkey earthquakes of 17 August (Mw=7.4) and 12 November 1999 (Mw=7.1) took a heavy toll on human lives and properties. The meizoseismal areas included the towns of Izmit, Gölcük, Adapazari, Duzce and Bolu. Instrumental and field reconnaissance data confirm the right-lateral reactivation fault segments along the North Anatolian Fault Zone. Along the surficial fault traces, a host of tectonic forms was observed, caused by local changes in the mean geometrical, kinematic and dynamic characteristics of the fault zone. For each case, the types of building damage are described, while we give separate descriptions for building failure caused by the kinematics of the fault blocks themselves. The examination of several cases of building collapse showed that the vast majority of R/C frame structures founded on the fault zone were demolished, while the few that remained standing were rendered inoperable.

1 Introduction

On August 17, 1999, 03:01:27 local time a large earthquake occurred in northwestern Turkey (40.702 N, 29.987 E (USGS)). The epicentre was located at the southwestern outskirts of Izmit and the magnitude was M_w=7.4 (USGS, Kandilli); the focal depth was estimated to be h=17 km (USGS). The shock caused extensive damage and casualties in an area that included the cities of Adapazari, Izmit, Gölcük and Yalova, all aligned along an E-W direction. The main bulk of damage was restricted within a 140-km by 15-km zone. Moreover, the damage was significant in broader region, including Istanbul, Bursa, Eskisehir, Duzce, Bolu and others (Fig. 1).

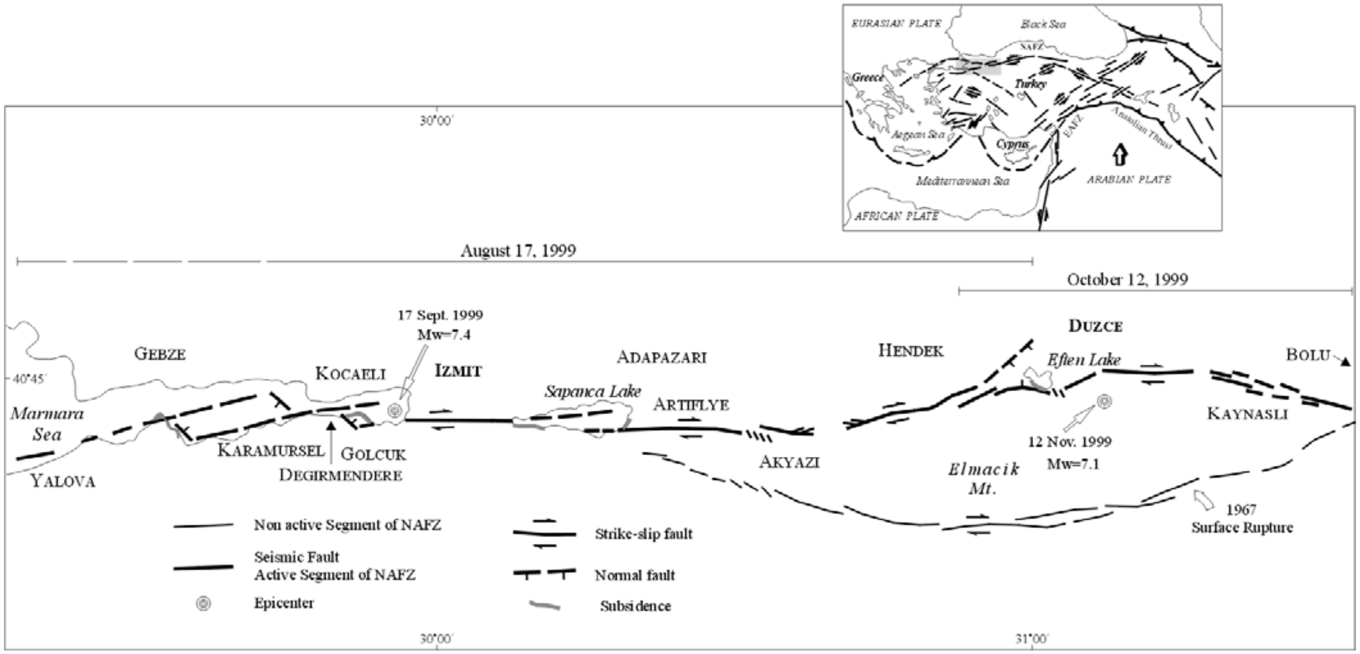

Figure 1: Map of the broader area with the epicentres and the reactivated segments of the NAFZ in the 8. 17.99 and 11.12.99 events.

According to the accounts and surveys after the shock, an estimated 17.000 people were killed, 50.000 were injured, 600.000 remained homeless, while there were still 45.000 more missing. Additionally, 2.600 buildings were reported to have collapsed totally or partially and 20.000 more suffered considerable damage. The earthquake also took its toll on large industrial facilities and public works, such as interstate and local roads, bridges, railways and so forth (Lekkas et al. [1]).

Three months later, on November 12, 1999, 19:57:21 local time, the region was hit by another shock. This one measured M_w=7.1 (USGS, Kandilli) and its epicentre was located at 40.768 N, 31.148 E, approximately 70 km east of the August event. It caused heavy damage at the cities of Duzce, Bolu, Kaynasli, Hendek, Golyaka, Adapazari and others, all lying along an E-W direction within a zone 80 km long and 10 km wide.

This second large event killed around 1.100 people, while 10.000 more were injured and 200.000 lost their homes. In addition, 500 buildings collapsed totally or partially and more than 5.000 were severely damaged. Of course, several parts of the national infrastructure were seriously affected in this case, too.

One of the most important roles in the occurrence and distribution of damage was played by the tectonic structures associated with strike-slip faulting. The importance of a fault zone of this type and the possible consequences of a reactivation on structures situated along its trace has been investigated by few researchers (Fenton & Bray [2], Lade & Cole [3], Lazarte et al. [4], Murbach et al. [5]). For this reason, our knowledge about these conditions is not yet complete.

In the following sections we shall give some basic data about the regional seismotectonic setting and the role the seismic fault played in the distribution and typology of damage as well as the corresponding tectonic structures.

2 The Seismic Fault

The broader Middle East region corresponds to the so-called Arabian plate, which pushes northwards into the Eurasian plate. One of the results of this movement is the westward lateral displacement of Turkey (Anatolia). This movement is mainly accommodated by the North Anatolian Fault Zone (NAFZ), which runs along a mean E-W direction, from Armenia in the east to the Hellespont in the west. It is a first-order tectonic structure (Ambraseys [6], Barka [7]), expressed through a dominant dextral transcurrent movement and its ongoing activity has given frequent earthquakes of magnitude 7 or greater. Ten such large events have taken place along the NAFZ since 1939 (Stein et al. [8]).

The earthquake on August 17, 1999 ruptured a segment of the NAFZ that had remained intact during the 20th century (Stein et al. [8]). Historical accounts also report that seismic fractures have been observed along the fault trace in the earthquakes of 1719 and 1754. The instrumental data and in situ measurements showed that the rupture plane was almost vertical, had an E-W strike and dextral offset.

Field reconnaissance showed that the seismic rupture had a visible length of 100 km, E-W strike and the right-lateral offset amounted up to 5 m; the latter was also confirmed by instrumental data. At the surface, it cut loose plio-quaternary deposits and caused considerable damage on the road network, with perhaps the most severe case on the Istanbul-Ankara highway.

As expected the intensity dropped away from the fault, but not evenly, as it was affected by various conditions, such as the nature of the foundation formations, the occurrence of geotechnical site effects, the type and quality of construction, etc. (Lekkas et al. [1]).

The second large shock of Nov 12 was due to the reactivation of an adjacent segment, located at the east of the previous one. This fault had not ruptured in the 20th century, either. Instrumental recordings showed that the rupture plane was vertical, oriented E-W, with dextral sense of slip. Field investigation confirmed this and also showed that the surficial trace was about 50 km long and had an offset of approximately 4 m.

In both the aforementioned cases, the strike-slip character of the fault at the surface was expressed in and could easily determined through the offset of several linear features such as tree farms, fences, roads and pavements, and so forth. All along the fault zone, however, the individual geometrical and kinematic features of the constituent breaks were subject to a certain degree of deviation from the mean values, a result of the presence of inhomogeneous material and the differential response of the various geological formations to shearing.

3 Tectonic Structures - Damage Typology

3.1 Damage typology along the trace of the seismic fault

A part of the fault was found to have cut the road connecting Gölcük with Izmit; where, it was found to have an offset of up to 3 m. A two to five meters wide deformation zone had been formed and the constituent fractures displayed characteristics typical of a strike-slip zone, such as releasing and restraining bends (Woodcock & Fischer [9]), the latter had led to localized compression and fracturing of the outcrops and the former had created local pull-aparts. A suite of R, R' and P shears (Campbell [10], Naylor et al. [11]) was also observed. The geometrical characteristics showed some local variation according to the nature of the surficial cover (alluvium, artificial fill) and the existence of technical works (pavements, roadwork, etc.).

The following types of damage were observed:

- Total collapse of low-, or medium-rise buildings founded on the trace of the main fault. Here the damage was due to the high degree of deformation at the foundations, which could not respond satisfactorily to the high degree of shear. In most cases, the poor quality of the concrete in frame structures led to pancake-type collapse, which left no room for the formation of sheltered gaps for the survival of residents.

- Collapse of low- or medium-rise buildings that lay on the trace of the secondary fractures (R, R', P shears). Although the surficial offset on these structures was considerably smaller, the foundations of the buildings could not absorb it.
- Tilting, partial collapse and heavy damage at the cases where the fault trace ran close to the building. This type of damage can be attributed to (i) the intense deformation of the foundation formation, and particularly dynamic compaction, (ii) lateral spreading of the foundation formation, especially where tensile gaps were formed along the fault, and (iii) the generalized deformation of the foundation formations due to their proximity to the main rupture surface.
- Deformation of specific construction types (sheds, industrial facilities) founded across the fault but with favorable orientation. These structures usually comprised a steel frame and their footings were sunk astride the fault. In these cases the frame was deformed but the structure did not collapse, as the footings absorbed most of the imposed shear.
- Collapse of linear-type infrastructure facilities – lifelines, as bridges, roads and rail network. One characteristic case was the bridge on the Istanbul – Ankara highway, south of Lake Sapanca. It collapsed because the deformation imposed on two successive piers exceeded the 50 cm design deformation. Additionally, damage was on the pavement of the Ankara-Istanbul highway, and the Ankara-Istanbul railroad, which was offset 2.6 m at the intersection with the fault.

3.2 Damage typology in small-scale pull-apart structures

At the eastern outskirts of Gölcük, just south of the highway exit that leads to Izmit, we observed a characteristic case of a 200 by 50 m. block that subsided, because of the formation of a pull-apart basin along the fault trace (Fig. 2).

The main fault splayed into two 200-m. long segments, which merged again after running a distance of 200 m. These two faults bounded a 200 by 50 m area (long axis oriented E-W) that was downthrown for about 80 cm maximum and corresponded to a small-scale pull-apart basin (Aydin & Nur [12]). The kinematics of the two bounding faults ranged between dip-slip and oblique-slip and this could be confirmed by the offset of linear-type features, as roads, pavements, water pipes, etc. (Fig. 3).

The occurrence of this structure was fatal for several structures. The damage type can be classified as follows:

- Along the fault trace, all structures were destroyed totally or suffered severe damage. The foundations could not absorb the imposed differential deformation at the foundation level. The type of collapse was the same as described in the previous cases (Fig. 4).
- Within the pull apart, the damage was again considerable. The collapse of R/C buildings was a common sight and the ones that remained standing had suffered heavy structural damage, mostly because of (i) settlement of the foundation formations, (ii) soil compaction close to the foundations, and (iii) block rotation

- Some light structures with clay brick bearing walls did not collapse but were severely deformed. One characteristic case was that of a school building (Fig. 5), founded within the downthrown fault block.

The overall picture was that of massive collapse along the boundaries of the subsided block, while within the micro-pull-apart, damage was slightly less, with a few buildings having remained standing. However, the occurrence of small-scale pull-aparts made the deformation zone wider, with consequent increased width of the heavily damaged zone in comparison to a single fault trace.

3.3 Damage typology in pull-apart structures

Along the coastal zone between Gölcük and Degirmendere there were certain localities that subsided, with consequent inundation of large areas and destruction of public and private facilities as housing complexes, stadiums, recreational areas, etc.

This subsidence was not caused by ground settlement or landsliding; the typical forms that accompany such site effects were absent (crown, head, and bulging toe, characteristic of landslides, or ground spreading and associated soil cracks that are connected with settlement). On the contrary, areas were subjected to block depression, or even slight block-rotation. The amount of subsidence was up to a few meters and whole areas – fault blocks were downthrown (Fig. 6).

These blocks are arranged along the NAFZ and are bounded by fault segments that create typical pull-apart basins (Aydin & Nur [12]).

The subsidence on the blocks that correspond to these pull-apart basins had the following results:

- Inhabited areas subsided by as much as 4 m, which rendered them uninhabitable and virtually useless for any purpose (Fig. 7).
- A large proportion of the existing constructions collapsed, and most of buildings suffered heavy damage. This is attributed not only to the initial seismic shaking, but also to the amplification of it, a common effect within basin-type subsiding blocks.
- Most of the structures were tilted, either in the same direction or in other directions. In the first case, the amount of tilt, which was up to 20º, is perpendicular to fault-block rotation. In the latter case, the tilting may by due to static and/or dynamic soil compaction.
- Within the subsided fault blocks, localized liquefaction, settlement and lateral spreading was observed, all of which amplified the severity of damage. Liquefaction was observed close to the coast, where the aquifer is quite shallow, while settlement and lateral spreading occurred mainly at the outcrops of quaternary deposits or artificial fill.

Another factor that aggravated the situation was the tsunamis that inundated some localities that had already subsided. The damage from the inundation could be seen up to a height of 10 m at the affected buildings.

Figure 5: A collapsed school building, made of supporting brick masonry, within the subsided block.

Figure 4: Partial view of the northern fault segment, with principal vertical offset component (normal faulting). The arrow shows a collapsed construction that lay on the prolongation of the fault.

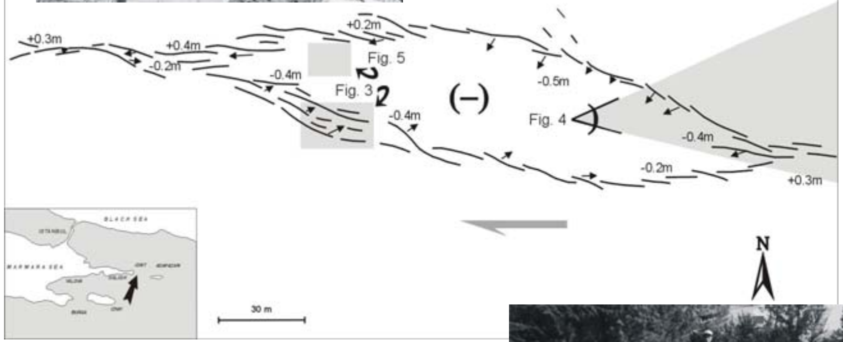

Figure 2: Map of the seismic fault trace east of Gölcük. A small-scale pull-apart basin has been formed. The kinematics of each segment is also marked. The arrows and numbers show the direction and amount of offset, respectively.

Figure 3: Partial view of the southern fault segment, with vertical (normal) and horizontal (right-lateral) offset components, marked by the dislocation of flagstones. At least five breaks are visible.

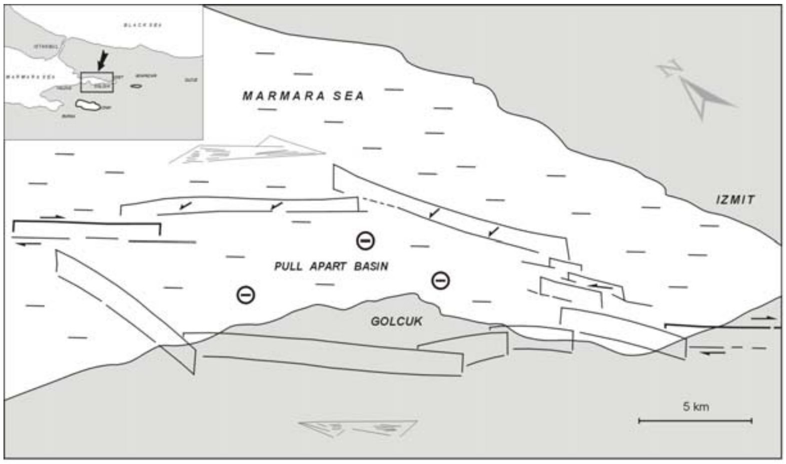

Figure 6: Interpretation of the subsidence on the Gölcük – Deringmendere coastal zone, which corresponds to a pull-apart basin, formed along the transcurrent fault zone.

Figure 7: Subsidence at the coastal zone of Gölcük. The location is within a pull-apart basin created by the distribution of strike-slip movement.

The overall impression we formed from the pull-apart deformation along the transcurrent fault zone was that extended housing areas were rendered inhabitable, regardless of the amount of collapsed or heavily damaged buildings, and this because of the added effect of inundation.

4 Damage typology in flower structures

In the broader area of Kaynasli, the surficial expression of the seismic fault consisted in consecutive breaks, parallel to one another or anastomozing, forming either tensile gaps or push-ups. The width of the fracture zone was between 50 and 200 m. The surficial cover consisted of loose silt, clay, pebbles and artificial fill and this led to multiple surficial breaks caused by the movement on the seismic fault (Harding [13]). Occasionally, the ground surface resembled the forms produced by landslides or settlement. The horizontal offset of the fractured blocks was not always easily measured and then only by the dislocation of some artificial features (water pipes, pavements) could it be determined.

The damage typology in this case was similar to that in areas with landslides, settlement and lateral spreading. The following types of damage were observed:

- Collapse of medium- and high-rise reinforced concrete buildings, caused by the intense deformation at their foundations, within the deformation zone. Only a handful of buildings did not collapse, but even these suffered considerable damage.
- Heavy damage, but not collapse of single- and two-story buildings, the foundations of which comprised raft foundation, concrete apron_or concrete frame. Some of the buildings were tilted because of subsidence or differential settlement of the foundation formations.
- Sinking of constructions, as much as 5 m, accompanied by partial collapse or not. This was caused by intense fracturing of the foundation formations, usually accompanied by lateral spreading, settlement, etc. (Fig. 8).
- Light damage on “linear” public works, as roads and power lines. In this case, the damage was limited because the deformation was taken up by subsequent parts of these constructions, each one receiving a part of the total deformation.
- Occasionally, the extent of the deformation at the loose foundation formations was impeded by the relatively higher rigidity of the foundations themselves. In these cases, the constructions suffered minor damage, including slight tilting and the surficial breaks were clearly deflected to various directions.

The overall impression is that of a broad zone in which the deformation was diffused through the surficial loose sediment cover and considerable damage, but not necessarily collapse of buildings; however, most of them were rendered demolishable.

Figure 8: A construction with R/C frame, sunk into the loose surficial formations within a flower structure.

5 Directivity of Collapse

As mentioned above, the length of the surficial expression of the seismic fault was 100 km for the earthquake of 17 August and 50 km for the 12 November event. In both cases, the faults ran through small or large urban complexes, while, outside them, they were close to or ran underneath several public infrastructure facilities.

Besides the cases and the damage types described above, all related to the right-lateral strike-slip fault zone, there was another noteworthy effect. It is the impressively systematic directivity of collapsed buildings that were close to the surficial fault trace. This is connected to the kinematics of the rupture and the offset of fault blocks.

The vast majority of collapses - toppling were directed towards the east or west, that is, parallel to the fault strike and sense of offset, regardless of construction type, height, morphology, plan, etc. (Fig. 9). Systematic eastward or westward collapse was also observed at buildings whose plan did not favor it -- high E-W/N-S aspect ratio.

Because the majority of buildings did not have ground- and first-story shear walls, the collapse was facilitated (Lekkas et al. [1]). The absence of beams, existence of slab-beams, insufficient ties hooks, and the poor quality of concrete as well as primary and secondary reinforcing steel contributed to collapse. In these cases the vast majority of construction collapsed or toppled to the east or west.

Figure 9: Collapsed multi-story buildings, lying close to the seismic fault. Eastward and westward card-deck collapse is indicative of large surficial displacement, a fact confirmed by instrumental recordings.

In addition, systematic eastward or westward collapse was observed even at buildings with structural elements as E-W-oriented elongated columns that could provide better resistance to the imposed deformation. Furthermore, collapse towards the same direction was observed even at buildings with E-W shear walls.

It should also be noted that the many buildings suffered pancake-type collapse which was indicating of surficial dislocation and repeated loading cycles coupled with relatively low acceleration, which was confirmed by instrumental data (Lekkas et al. [1]).

6 Conclusions

From the five characteristic cases of deformation along the reactivated segments of the North Anatolian Fault Zone presented above we can conclude that in all cases in both events there has been strong correlation between the fault ruptures and their surficial expressions. Of course, there were local deviations from the mean geometrical and kinematical values, and these were due to the occurrence of the propagation of deformation through the loose surficial sediment cover.

The types of damage vary according to the surficial expression of the earthquake rupture and can be summarized in the following:

- Along the main fault trace, almost all structures, regardless of type, collapsed.
- Only a handful of structures avoided collapse, and these were mainly steel structures, with foundations that could absorb large amounts of deformation.
- Within micro-pull-apart basins, the majority of reinforced concrete structures collapsed totally and the remainder only partially. Relatively better was the performance of buildings with supporting brick masonry, some of which, in spite of suffering considerable damage, did not collapse. The width of the heavy-damage zone was greater in this case, compared to that of a single fault trace.
- In pull-apart basins, the reinforced concrete buildings performed relatively better than the ones with supporting brick masonry, in terms of collapse. A large percentage of damage was due to partial collapse of structural elements, deformation of frame, and tilting, caused by fault block rotation. This tilting rendered most structures inoperable.
- In the above case the site effects (liquefaction, differential settlement, and lateral spreading) played a significant part.
- On the coastal zone, the tsunamis, which hit an area that corresponded to a downthrown fault block, amplified the severity of damage.
- When the large buildings founded in flower structures they were affected more than the smaller R/C or brick masonry ones and collapsed totally or partially. A typical effect in this case was the “sinking” of buildings into the loose surficial formations.
- The vast majority of near-fault collapses were eastward or westward, that is, parallel to the fault strike. The directivity of collapse was obvious even at buildings with structural elements oriented in such a way that did not favor this type of damage.

In conclusion, we should say that the margin for avoidance of collapse along the fault zone was very narrow, both for the reinforced concrete or clay-brick masonry bearing wall structures. Besides, the resulting tectonic structures (pull-apart basins at various scales, flower structures) aggravated that situation locally. Furthermore, some specific types of damage, such as preferential collapse directions, tilting, subsidence and sinking, were observed.

In a nutshell, we should note that the cost for earthquake-proof structures is too high for the average construction. Therefore, the problem now lies in the earthquake zonation and mapping of strike-slip faults and accompanying structures, so that the high-risk areas are excluded from urban or other development schemes.

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