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Intensities distribution and parameters controlling their geographic differentiation during the earthquakes of Izmit and Düzce (Turkey 1999)

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Е. Е. Леккас – Распределение интенсивностей и параметры, контролирующие их географическое размещение во время землетрясений в городах Измит и Дюзче (Турция, 1999 г). В 1999 году (17-ого августа и 12-ого ноября) обширные территории к ЮЮЗ от Стамбула (районы городов Ялова, Гюлчук, Измит, Адапазары, Дюзче, Кайназлы и Болу — Турция) были охвачены двумя сейсмическими ударами магнитудой в M_w=7,4 и M_w =7.1 соответственно. Эти сейсмические события связаны с реактивацией двух соседних сегментов Североанатолийской разломной зоны — крупной восток-западной правое двиговой структуры, проходящей через Турцию. В результате землетрясений на протяжении по меньшей мере 150 km образовались разрывные нарушения. Они сопровождались оседаниями, образованием трещин в почве, явлениями ликвифекции, оползнями, цунами и погружением. В обоих случаях разрушения приурочены главным образом к восток-западной зоне длиной в 180 km и шириной в несколько km. Разрушения и интенсивность землетрясений вычислены по двум шкалам: по EMS_{1992} и по актуализированной EMS_{1998}. Максимальные интинсивности приближались к XII для обеих землетресений. Карты интенсивностей показывают удлинения, которые соответствуют простираниям сейсмических разломов с локальными вариациями, обусловленными геометрическими особенностями и кинематикой некоторых разломов. Местами интенсивности были значительно усилены наложением сопутствующих геодинамических явлений. Высокие интенсивности были установлены и в удлиненной эпицентр альной зоне, где они сочетались с такими факторами, как повторяемость землетрясений, локальное местоположение данных объектов, типы конструкций. В заключение — интенсивности показывают экспотенциальное развитие на тех участках, где конструкции попали последователно под воздействие обеих землетрясений.

Abstract. On 17th August and 12th November 1999 the wider area of Yalova, Gölcük, Izmit, Adapazari, Düzce, Kaynasli and Bolu, to the south-southeast of Istanbul (Turkey) was hit by two seismic shocks with magnitude MW = 7.4 and MW = 7.1, respectively. The two events are attributed to reactivation of two adjacent segments of the North Anatolian Fault Zone, a major E-W right-lateral strike-slip fault zone that runs across Turkey. The earthquakes produced surface ruptures over a distance of at least 150 km, as well as settlement, soil fissures, liquefaction, landslides, tsunamis and subsidence. In both cases, the damage distributed was mainly along an E-W aligned zone more than 180 km long and a few km wide. Damage and intensity evaluation followed the EMS_{1992} and the updated EMS_{1998} scales. The maximum intensities approached XII in both earthquakes. Intensity maps show alignment parallel to the strike of the seismic faults, with local variations due to geometry and kinematics of certain tectonic structures. Intensities were considerably amplified locally by accompanying geodynamic phenomena. High intensities were also recorded at long epicentral due to a combination of factors, such as earthquake frequency content, local site conditions and construction type. Finally, intensities exhibited an exponential development in places where the two earthquakes affected the constructions sequentially.

Keywords: EMS-1998, earthquake, Turkey, tectonics, site effect, concomitant phenomena

Introduction

On 17 August, 03:01:37 local time, a severe earthquake occurred, with an epicenter at the southwestern suburbs of Izmit town in Turkey. The earthquake magnitude was Mw = 7,4 and the seismic source depth was estimated at 15-17 km. Extensive damage was recorded along an E-W zone of about 100 km in length that includes the towns of Adapazari, Izmit, Gölcük and Yalova. Heavy damage was also reported farther away, as in Istanbul, Bursa, Eskisehir, Düzce, Bolu and other towns (Fig. 1).

About 14.000 people lost their lives, 45.000 were injured and 600.000 became homeless, while 45.000 were missing. Additionally, 2.600 buildings collapsed utterly or partially and more than about 20.000 suffered heavy damage. Damage was sustained also by large industrial plants and by transportation infrastructure, including roadways, bridges, railways and port facilities (Lekkas et al., 1999). Economic losses were of the order of 40 billion dollars (which equals 10% of Turkey's GNP) with further not counting the long-term impact on the country's economy. It should also be mentioned that about 38% of Turkey's GNP is produced in the affected area.

Almost three months later, on 12th November 1999, 19:57:21 local time another severe seismic event of magnitude Mw = 7.1 took place with epicentre about 90 km to the east of the former. The earthquake caused significant damage along an E-W zone about 70 km long, which included Adapazari, Hendek, Düzce, Kaynasli, Bolu and other population centres (Fig. 1).

This earthquake caused 1.100 deaths, 10.000 injuries and left more than 200 000 homeless. Furthermore, 800 buildings collapsed completely or partially and more than 5.000 sustained heavy damage. Severe damage was caused also to large industrial plants, roadways, bridges, etc.

The surficial expression of the seismic fault and the manifestation of concomitant geodynamic effects largely contributed to the damage at both events. The effects included soil fissures, liquefaction, landslides, settlement, lateral spreading, coastline changes, tsunamis, and so on, as well as fires (Lekkas et al., 1999). Additionally, tectonic structures related to strike-slip deformation, such as pull apart basins, oversteps, en echelon arranged fractures and so on, as well as the local geotechnical conditions and construction type, all played a part in the manifestation and extent of damage.

The purpose of this paper is to determine the parameters that contributed qualitatively and quantitatively to damage manifestation and intensity distribution during the earthquakes.

Seismotectonic setting

It is well known that Middle East belongs to the Arabian plate that moves northwards. As a result, Turkey is being squeezed between the northward-moving Arabian and African tectonic plates and the relatively stable Eurasian plate. A wedge of continental crust incorporating much of Turkey is being extruded westwards, towards the Aegean. This westward movement is facilitated by the E-W North Anatolian Fault Zone that runs from Armenia to Marmara Sea (Figure 1), and constitutes a major tectonic structure of the Eurasian plate (Ambraseys 1970, Barka 1992, Sengor 1979). The North Anatolian Fault Zone is a major right-lateral strike-slip fault that allows the region south of the fault to move to the west relatively to the region north of the fault and is responsible for a multitude of severe earthquakes that very often exceed the magnitude of 7R. For example, more than 10 severe events have been described since 1939, causing heavy damage (Stein et al., 1997).

The NAFZ is well expressed in relief and drainage network, and is accompanied by local block subsidence, uplift and rotation, which manifest the right-lateral character of the fault. This movement is also responsible for the successive small and large scale depressions, such as Sapanca and Iznik lakes, as well as for Marmara bay, which is characterized as an active pull-apart basin (Armijo et al., 1999).

The existence of NAFZ in the wider epicentral area is emphasized by the occurrence of geological formations and specifically Plio-quaternary sediments, which develop in E-W elongated outcrops, coinciding with the strike of the fault zone and form a mild relief. This area is the industrial heartland and the most densely populated section of Turkey. Additionally, Alpine formations crop out along the fault zone, too, and form an intense relief that accommodates areas of relatively poor industry, but locally increased urbanization.

Seismic faults

The 17th August 1999 earthquake was centered in the outskirts of Izmit town. The earthquake

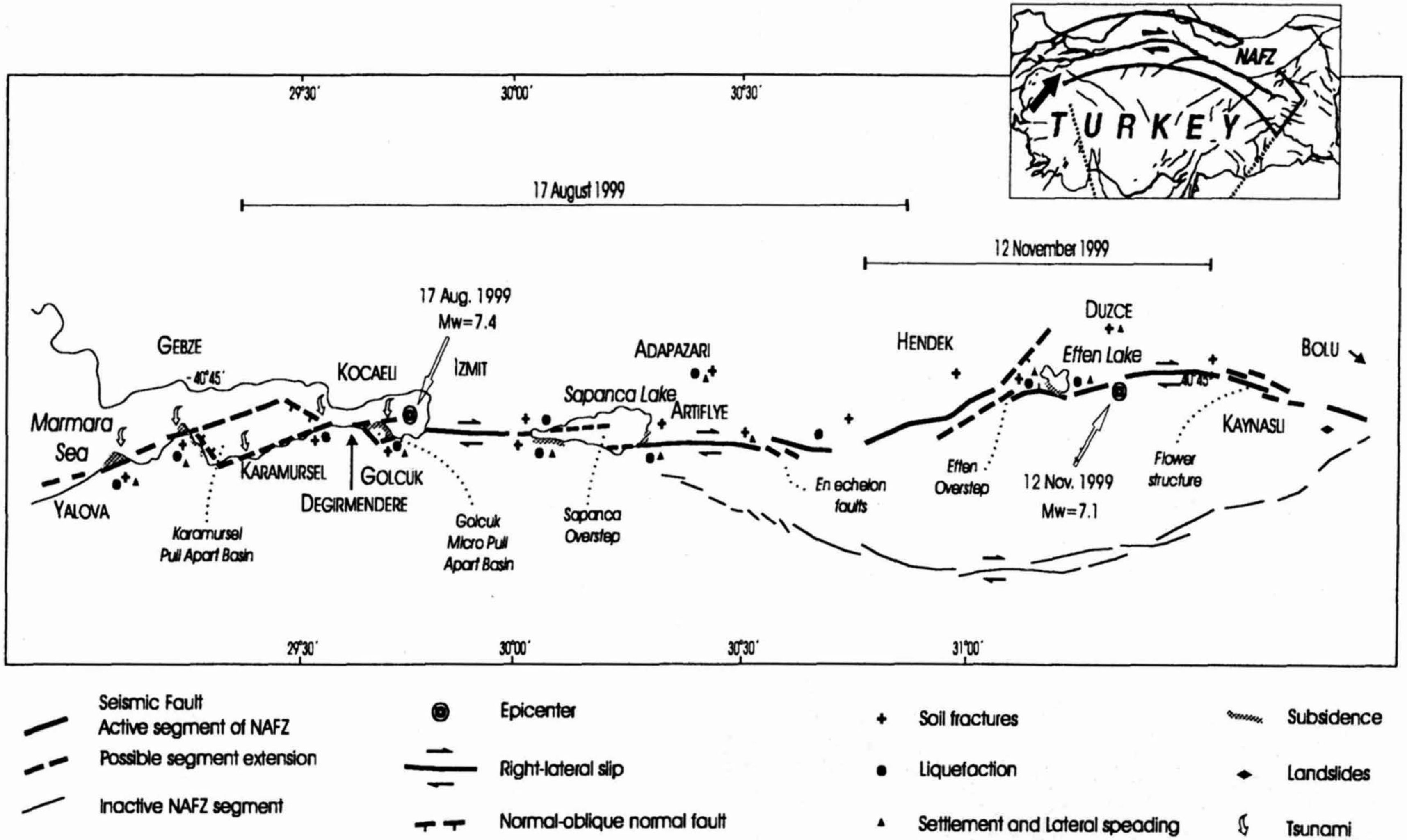

Fig. 1. Map of the segments of the North Anatolian Fault Zone reactivated during the earthquakes of 17th August and 12th November 1999 and the concomitant geodynamic phenomena

Fig. 2. Surficial occurrence of the portions of the North Anatolian Fault Zone that ruptured during the 12th November 1999 earthquake in Kaynasli

was the result of the reactivation of the North Anatolian Fault Zone, and particularly of a portion of it that was dormant in previous seismic events of the 20th century (Stein et al., 1997). Before the earthquake, repeated GPS surveys indicated an average creep displacement of 10-15 mm in this portion of the fault zone (Armijo et al., 1999, Straub et al., 1997). Instrumental data indicate that the fault plane was almost vertical striking E-W with a right-lateral strike-slip movement.

Field observations show that the surficial rupture was more than 90 km long (Lekkas et al., 1999), vertical with right-lateral displacement in excess of 3 meters, in good agreement with the instrumental data (Fig. 1, 2). This seismic fault extended into the submarine area of Marmara bay, west of Gölcük.

On the surface, the seismic fault cut mainly across loose Plio-quaternary sediments and led to heavy damage in the transportation infrastructure, particularly on the Istanbul — Ankara motorway, and to extensive damage to a multitude of constructions, networks and plants. The Ariflye overpass collapsed, due to surface fault rupture under its northern abutment.

The 12th November 1999 earthquake, the epicenter of which was south of Düzce, occurred at the eastern end of the previously activated segment of the NAFZ (Fig. 1). Also, this section remained dormant in other earthquakes of our century. Instrumental data show that the fault plane is almost vertical, strikes E-W and is characterized by a right-lateral slip. Field data showed that the seismic rupture surface was vertical and more than 40 km long and the horizontal offset locally exceeded 3 meters.

The fault displaced mainly Plio-quaternary formations and caused severe damage to constructions, transportation infrastructure, public facilities, networks, industrial plants, etc.

The two activated fault segments of the NAFZ caused impressive displacements of rows of trees, fences, roads, pavements and canals, which allowed determination of the geometric and kinematic characteristics of the seismic fault on each section of it. The geometry and kinematics varied locally along the deformation zone; these local variations are attributed to the mode of fracture, the stress field and the occurrence of heterogeneous media — particularly the differential performance of geological formations under shear stress.

Such variations usually appear along strike-slip faults and are strongly related to oversteps, en echelon structures, flower structures, micro (a few tens of m) and macro (several hundreds of m to a few km) pull-apart basins (Aydin & Nur 1982, Harding 1985, Lade & Cole 1984, Mann et al., 1983, and others) and are held responsible for local differentiation in damage manifestation and intensity distribution (Figure 1).

Concomitant geodynamic phenomena

During the earthquakes of 17th August and 12th November 1999 a number of geodynamic phenomena took place in the broader epicentral area (Fig. 1). These phenomena are not only of academic interest, as they aggravated the impact, amplified the intensities, and contributed to intensity differentiation from place to place either in the meizoseismal area or at longer distances. These effects are briefly described below:

- Soil fissures. Soil fissures were reported in many places that loose recent sediments occur. The most characteristic ones were described around Sapanca Lake, along the coastal zone among Gölcük, Degirmen-

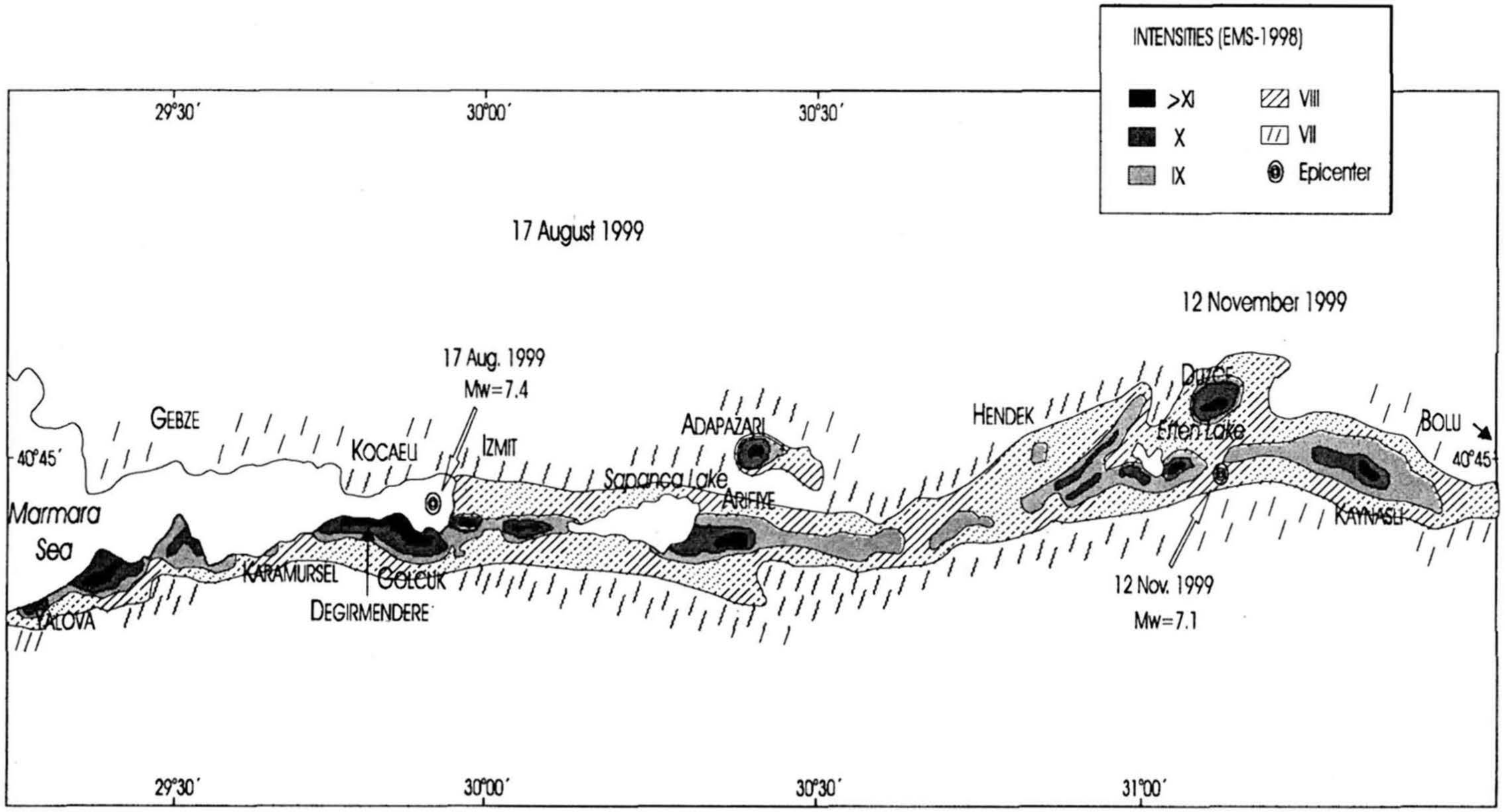

Fig. 3. Intensity distribution (EMS-1998) after the earthquakes of 17th August and 12th November 1999

Fig. 4. Representative view of a portion of Adapazari that suffered total damage (IEMS-98 = XII) after the 17th August earthquake

Fig. 5. Reinforced concrete frame structure that collapsed in Gölcük town (damage degree 5)

dere and Yalova, in Düzce and Kaynasli. They did not usually belong to any oriented system and were attributed to compaction of loose sediments, lateral stability problems, and so on, which were results of both seismic events. They caused damage to public beautification works (parks, etc.), and to infrastructure, as well as to many small infill wall constructions.

- Liquefaction. It was recorded in the plain area around Sapanca lake, in Adapazari, as well as in the coastal area of Gölcük-Degirmendere-Yalova and in the region of Eften lake. This effect became noticeable at the surface by the occurrence fine-grained subsurface sediments that vented to the surface and the accompanying soil fissures, lateral spreading, as well as irregular surficial undulations. At both seismic events, liquefaction caused severe damage to every type of construction and technical works mainly in the areas around the coasts.
- Landslides. Despite the high magnitude of the 17th August 1999 earthquake, few landslides occurred in the epicentral area. Only few and restricted rockfalls took place along several very steep slopes built of highly fractured rocky formations. A significant landslide was observed along the Istanbul-Ankara motorway, at the region of Düzce-Bolu in the 12th November 1999 earthquake.
- Settlement. It appeared in many places of the epicentral area, mainly where recent loose formations crop out. Lateral spreading and soil fissures were also present, resulting from the differential settlement of the upper geological strata, as was the case in the neighbouring area of Adapazari and around the lakes of Sapanca and Eften. The extent of settlement varied from tens of m^2 to a few thousands of m^2 each time. At both seismic events, buildings toppled, were partially overturned or totally collapsed, and generally, severe damage was caused because of extensive settlement.
- Tsunamis. The 17th August earthquake generated a tidal wave, which affected the coastal region of Marmara bay, mainly the Gölcük-Yalova area. The submergence of Gölcük-Degirmendere coastal area is believed to have amplified the influence of the tsunami, the height of which was approximately 4 meters. Tsunamis aggravated the impact of the earthquake, increasing the number of fatalities, building collapses and infrastructure damage in the coastal area.
- Subsidence. The recent seismic activity observed in this area of Turkey is a consequence of geodynamic processes that take place in the broader epicentral area. The earthquakes of 17th August and 12th November 1999 produced right-lateral displacements or slip on surface ruptures over a distance of at least 130 km and were nucleated at a depth of 15-17 km. The fault rupture was very often characterised by en echelon, R, R? and P shear structures, and so on. These structures caused subsidence, uplift and rotation on micro and macroscale (from tens to thousands of m.). The submergence of many coastal areas (from tens of m^2 to some km^2) was the result of pull apart basin formation (Aydin, Nur, 1982; Mann et al., 1983). The most representative example is the extended subsidence that occurred in the eastern part of Gölcük. The subsidence of the coast near Gölcük caused a maximum submergence about 3.5 m so that constructions, port and sport facilities, transportation infrastructure and public beautification works sank into the sea.

The submergence of some regions as well as the manifestation of accompanying geodynamic phenomena are particular cases that aggravated the severity of the earthquake in urban areas and the environment. In these cases the augmentation of intensities is not solely or directly attributed to seismic shaking itself.

Fig. 6. Reinforced concrete frame structure that sustained collapse of ground floor in the area of Gölcük -Degirmendere (damage degree 5)

Intensity evaluation — geographic distribution

Intensity evaluation of the affected area employed the European Macroseismic Scale (EMS-1992) (Grünthal, ed. 1993) and the updated EMS-1998 (Grünthal, ed. 1998).

Intensity evaluation was primarily based on damage recordings assessment that contributed to the compilation of an intensity map of the affected area for each seismic event separately (17th August 1999 and 12th November 1999 earthquakes), wherever possible. Additionally, recordings of other effects (not only construction damage) were taken into account in the final evaluation, according to the given guidelines (Grünthal ed. 1993, 1998). In order to elaborate damage data, areas with dimensions of about 500×500 m were considered as the basic units, each one corresponding to a few urban blocks. Airphotos and satellite data were indispensable, particularly in areas that were razed and almost all of the buildings collapsed (e.g. Adapazari, Gölcük, Kaynasli).

After evaluation of data recordings, an intensity map was obtained according to the EMS-1998 scale, as depicted in fig. 3. The intensity evaluation was done separately for each earthquake, when it was possible. The map shows that:

- The maximum intensities exceeded I_{EMS98}=XI and locally reached XII (Fig. 4) for both seismic of 17th August and 12th November 1999. During the first earthquake, maximum intensities occurred in the coastal area of Gölcük, in Degirmendere, in Yalova and in Adapazari (Figs. 5, 6). Particularly, total collapse of the constructions occurred in the coastal area of Gölcük, due to the submergence of the region into the Marmara sea. Constructions were not only affected by seismic loading but also by subsidence, tsunamis, lateral spreading and liquefaction. A similar picture was present in the coastal region of Degirmendere. On the other hand, the situation was better in parts of Yalova, because only liquefaction, soil fissures and lateral spreading took place. Parts of Adapazari town were devastated and all buildings collapsed. These sites were dominated by soil fissures, liquefaction, effects of "sedimentary basin" and "basin edge" effects and so on (Kawase, 1996; Lekkas, 2000b), which played a significant part in intensity distribution. In Adapazari, tens of buildings sank into the ground, toppled, were partially overturned or collapsed because the soil beneath them liquefied and weakened the foundations (Fig. 4). On the contrary, damage was lighter in areas of the town where none of the above phenomena occurred. Intensities that exceeded I_{EMS98}=XI degree were recorded after the 12th November 1999 earthquake in a portion of Kaynasli, which collapsed thoroughly due to the surface impact of a zone of seismic fissures in the form of a negative flower structure (Lade & Cole, 1984; Harding, 1985), and also due to settlement, lateral spreading and liquefaction. Furthermore, maximum intensities that exceeded XI degree were recorded locally in Düzce.
- I_{EMS-98} = X intensities were present in a wider area that formed two elongated zones in both seismic events. Specifically after the 17th August earthquake, X intensities occurred in an E-W zone that

Fig. 7. Reinforced concrete frame structure in Yalova that displayed first storey column-hinge deformation, but did not collapse (damage degree 4)

Fig. 8. Reinforced concrete frame structure with light structural damage but heavy damage in the infill brick walls at Gölcük (damage degree 3)

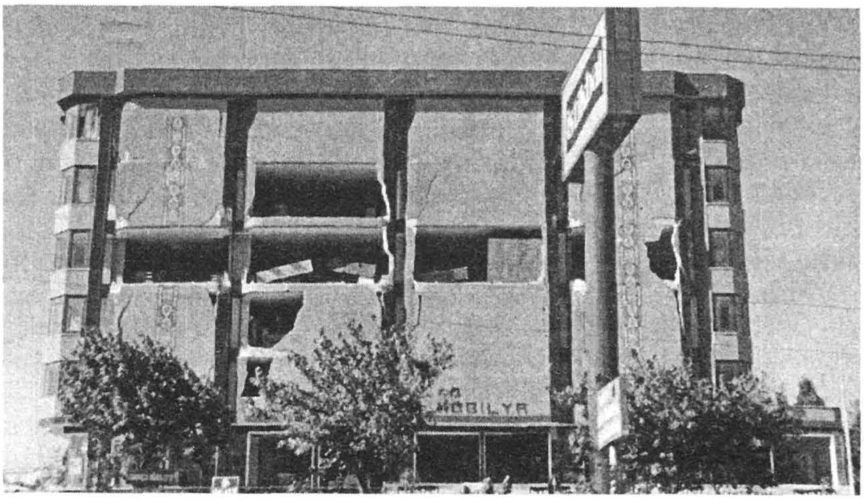

Fig. 9. Reinforced concrete frame structure that suffered damage only in the infill brick walls in Degirmendere (damage degree 2)

began at Yalova, was found again at Gölcük, passed through Izmit and stopped in Sapanca lake. The zone reappeared in Adapazari and terminated east of the town (Figs. 7, 8, 9). The width of the zone ranged from 100 m to 200 m. After the 12th November 1999 earthquake, I_{EMS-98} = X contours were arranged in a similar E-W trending zone, which covered the areas of Hendek, Düzce, Kaynasli and is up to 800 m wide at places. The exact estimation of the intensities that were attributed to the second earthquake was quite hard to make (12th November 1999) in the area between Adapazari-Düzce, because constructions had already been damaged by the earthquake of 17th August 1999. In this case, the cumulative effect of both earthquakes was estimated, incorporating the damage from both earthquakes. In Düzce, about 30% of the damage is attributed to the first earthquake and 70% to the second earthquake. This estimate regards only the structural elements of reinforced concrete constructions. It was found that the first earthquake exhibited maximum intensities that reached I_{EMS98}=VIII in an E-W zone at Düzce area, while after the second earthquake intensities exceeded I_{EMS98}=X and locally approached XI. This may be attributed to the fact that the resistance of the constructions had already been weakened by the first earthquake.

I_{EMS-98} = IX contours covered a wider E-W zone after each earthquake. This intensity zone coincides with the deformation zone, and is wider where pull apart basins, oversteps flo-wer structures and other strike-slip deformation fea-tures occurred.

- I_{EMS-98} = VIII intensities also developed in an E-W zone after each earthqua-ke. The arrangement of these intensity contours is not so linear as of the high intensity ones. In this case, intensities seem to have been significantly controlled by site effects or by remarkably poor performance of constructions. More specifically, the distribution of VIII contours depended on the foundation soil response and mainly the amplification of seismic waves when, for example, loose thin surficial formations overlay the alpine basement. It also depended on the alpine basement geometry that controls the seismic energy propagation. Additionally, structural alterations and poor quality of constructions, as well failure to enforce the local building participated into the intensity distribution locally. An example of this case was at the western suburbs of Gölcük, where modern large constructions collapsed or sustained structural damage due to contractors' irresponsibilities, according to the official authorities.
- It is noteworthy that high intensities were also recorded at rather long epicentral distances, particularly in Istanbul, Eskisehir, Bursa, and so on. These intensities appeared as islets within urban areas, which displayed lighter damage. At the suburb of Avcilar in Istanbul, I_{EMS-98} = X intensities are attributed to (i) the frequency content of the seismic vibration (Lekkas et al., 1999), i.e. the relatively high periods and the long duration of the vibration; (ii) the geological formations; and (iii) the relatively high natural period of the six-storey constructions, most of which collapsed (Cranswick et al., 2000).

Conclusions

The earthquakes of 17th August and 12th November 1999 that hit Turkey and caused thousands of fatalities and widespread damage were attributed to the successive reactivation of two parts of the North Anatolian Fault Zone; these segments had not slipped before in the 20th century. The overall rupture could be traced for a distance of 150 km. The fault rupture was accompanied by pull-apart basins, oversteps, en echelon arranged fractures, flower structures and other strike-slip related features both on a small and large scale.

Damage recording and intensity evaluation was made according to the EMS-1992 and to the updated EMS-1998 scales, soon after both seismic events in the affected area.

Based on already mentioned data, intensities exceeded I_{EMS98}=XI and even approximated XII in many urban blocks. X intensities occupied extended regions, whereas much wider areas displayed IX and VIII intensities. This was the lower limit of our intensity evaluation, as lower intensities occupied vast areas and the amount of data was overwhelming.

All intensity contours but mainly the $I_{EMS-98} \geq$ X, developed in an E-W orientation, which coincides with the fault strike. Intensity contours follow, and become broader at strike-slip deformation structures as micro- and macro-pull apart basins, flower structures and so forth. On the contrary, when the fault ruptured linearly, without these accompanying structures, intensity contours developed in an E-W elongated zone of significantly small width.

Moreover, intensity distribution directly depended on the concomitant geodynamic phenomena, namely liquefaction, uplift, subsidence, settlements, lateral spreading and so on. Therefore, earthquake vibration was not solely responsible for damage occurrence but it is also the concomitant geodynamic phenomena that must be seriously considered in the future. EMS-1992 and the updated EMS-1998 scales do not incorporate such phenomena due to the rarity of actualistic models.

In the wider area of Adapazari-Düzce that was hit by both earthquakes (17th August and 12th November 1999), it was difficult to assess separately the participation of each seismic event in damage manifestation and, thus, in intensity estimation. Intensity evaluation, in this area was approximated and is based on data and recordings collected mainly after the first earthquake, but also after the second one. So, it is apparent that in this area the recorded intensities do not correspond to the damage caused by the second event only, since the first earthquake had already seriously damaged constructions.

The recorded intensities were distributed similarly on both fault blocks as a consequence of the predominant horizontal movement of the NAFZ. On the contrary, intensities vary significantly on the two blocks of a rupture in the case of reverse or normal faulting (hanging wall and footwall) (Lekkas, 2000a).

Finally, besides the meizoseismal area of Yalova, Gölcük, Izmit, Adapazari, Düzce, Kaynasli, and Bolu, islets of high intensities were observed in the wider area (e.g. Istanbul) as a result of the frequency content of the seismic vibration, as it was modified in that epicentral distance, and was coupled with soil response and the characteristics of constructions.

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