Bull Earthquake Eng (2007) 5:253–275
DOI 10.1007/s10518-007-9029-2

ORIGINAL RESEARCH PAPER

Foundation–structure systems over a rupturing normal fault: Part I. Observations after the Kocaeli 1999 earthquake

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Received: 19 April 2006 / Accepted: 07 January 2007 / Published online: 6 April 2007

Abstract Triggered by reactivation of the strike-slip North Anatolian Fault, the disastrous M_w 7.4 Kocaeli (Turkey) earthquake also produced normal faulting in the pull-apart basin of Gölcük. Surface scarps from such faulting reached almost 2.5 m in height. Several structures were crossed by the surface rupture. As expected, many of them either collapsed or were severely damaged. But, surprisingly, several structures survived the outcropping dislocation essentially unscathed. In fact, in some cases the surface rupture path seemed to have deviated, as if to "avoid" rupturing directly underneath a structure. In other cases damage was substantial even though the fault rupture was "masked" by the near-surface soil and did not create a scarp. The rigidity and continuity of the foundation appears to have been one of the crucial factors affecting structural performance. Interestingly, the examined structures were supported on a variety of foundation types, ranging from isolated footings, to rigid box-type foundations, to piled foundations. The paper outlines a reconnaissance of the area, providing a documented description of the observed interplay between the rupturing fault, the soil, and the structure, along with the results of soil exploration and geological trenching. In the companion paper, Part II, each system is analysed numerically to confirm the conclusions of the present paper, reveal the main aspects of Fault Rupture-Soil-Foundation-Structure Interaction (FR-SFSI), and help develop deeper insights into the mechanics of successful performance of structures built on top of such faults.

Keywords Kocaeli earthquake · Fault rupture propagation · Case history · Soil-structure-interaction · Normal fault

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1 Introduction

In a seismic event, the rupture of an earthquake fault generates two types of ground displacement : permanent quasi-static offsets on the fault itself, and transient dynamic oscillations away from the fault (Ambraseys and Jackson 1984; Jackson 2001). The second type of displacement is the result of waves originating successively at each "point" on the fault (as "slippage" takes place) and propagating over large distances in the earth. Such waves always affect the ground surface and are thus of prime significance for the safety of engineered structures. By contrast, the permanent offset on a fault affects the ground surface only in some cases — when the fault rupture extends all the way to the surface.

Naturally, therefore, earthquake engineering research and practice has (over the last four decades) emphasised on the dynamic response of soil and structural systems to ground oscillations. Much less effort has been devoted to understanding the effect of a rock-rupturing seismic fault on the overlying soil and on structures/facilities founded on/in it. The three notorious 1999 earthquakes in Turkey and Taiwan (Kocaeli, Düzce, and Chi–Chi), having offered numerous examples of detrimental effects of (large) surface fault ruptures, prompted the increased interest on the subject.

Seismic codes and engineering practice had in the past invariably demanded that *"buildings and important structures not be erected in the immediate vicinity of active faults"*(e.g.: EC8 1994). However, such a strict prohibition is difficult (and sometimes meaningless) to obey for a number of reasons:

(a) It is difficult to reliably determine which of the numerous geologic faults encountered in engineering practice is potentially active in the earthquake sense (i.e., it is capable of generating a significant earthquake rupture). For long structures, such as bridges, tunnels, pipelines, and embankments, which often cannot avoid crossing such geologic faults, the question of their potential activity often culminates into a hotly debated, scientifically un-resolvable, issue…

(b) Along the surface break of the fault (the "fault outcrop"), *"ruptures are neither continuous, nor do they follow precisely the surface outcrop of pre-existing faults"* (in the words of Ambraseys and Jackson 1984). Instead, they follow planes of weakness within a rather broad shear zone (which sometimes may be of the order of kilometers). Thus, predicting the exact location of a fault break-out on the surface is a formidable task, even when on a large-scale map the fault line is depicted with clarity. For instance, the northern part of the Chelungpu Fault (thrust type) which produced the Chi–Chi 21 September 1999 M_w 7.4 earthquake in Taiwan emerged (with a scarp of almost 10 m) at a distance of about 1 km east of the mapped Chelungpu Fault that had ruptured in earlier times (Heermance et al. 2003). Even worse, the Düzce 12 November 1999 M_w 7.1 earthquake in Turkey ruptured (by 3 m on average) an unbroken part of the North Anatolian Fault system (strike-slip type), about 20 km north of the notorious, well-mapped fault (Ambraseys 1970) that had ruptured in the earthquakes of 1944, 1957, and 1967 (Akyüz et al. 2000). Although that part of the fault was also mapped, this "migration" caught by surprise the engineers of both the Düzce–Bolu 2.5 km Viaduct, which narrowly avoided collapse but was damaged substantially by the crossing of the outcropping fault (Bray 2001), and of the Düzce–Bolu under-construction 3.5 km twin tunnels that experienced collapse, arguably due to the direct and indirect effects of the fault crossing. The importance of a detailed geological study needs not be emphasised more.

(c) A related phenomenon is the propagation of the fault rupture from the base rock to the ground surface, through the overlying soil deposit. *If, where*, and *how large* will the dislocation emerge on the ground surface (i.e., the fault will outcrop) depends not only on the type and magnitude of the fault rupture, but also on the geometry and material characteristics of the overlying soils. Field observations and analytical and experimental research findings (Bray 1990; Bray et al. 1994a,b; Cole and Lade 1984; Lade et al. 1984; Lazarte and Bray 1995) show that deep and loose soil deposits may mask a small-magnitude fault rupture which occurs at their base; whereas by contrast with a cohesive deposit of small thickness, a large-magnitude offset in the base rock will develop a distinct fault scarp of nearly the same displacement magnitude. One important finding of the above studies is that the rupture path in the soil is not a simple extension of the base fault plane : phenomena such as "diffraction" and "bifurcation", affect the direction of the rupture path, and make its outcropping location and offset magnitude difficult to predict.

(d) Finally, the presence of a structure on top of the soil deposit may further modify the path of the rupture, as the latter propagates from the base rock to the ground surface. Depending on the rigidity of the foundation and the weight of the structure, even complete diversion of the fault path before it outcrops may take place (Niccum et al. 1976; Youd 1989; Kelson et al. 2001; Bray and Kelson 2006). Obviously, the damage that a given structure will suffer depends not only on its location with respect to the fault outcrop in the "free-field" but also on whether and by how much such a diversion may occur. In other words, an interplay develops between the propagating fault rupture, the deforming soil under the structure, and the differentially displacing foundation. This interplay is of profound significance for the performance of the structure. To the best of our knowledge, the phenomenon, named hereafter "Fault Rupture-Soil-Foundation-Structure Interaction" (FR-SFSI), has not been so far studied systematically or extensively. A prime objective of the research presented herein is to explore the role of this interaction, both theoretically and through field observations.

The motivation for our research came from observing the numerous failures and successes of structures built directly on the fault, during the Kocaeli (Izmit) M_w 7.4 devastating earthquake of 17 August 1999 in Turkey. Thus, the first part of our work, summarised in the present paper, provides a rather detailed documentation of case histories for a number of structures on top of an about 2 m normal fault rupture in the Kocaeli earthquake. The second part, presented in the companion paper (Anastasopoulos and Gazetas 2007), is our theoretical work which:

1. Develops a non-linear finite element (FE) modeling methodology to study fault rupture propagation through soil, emphasising on the deformation of the ground surface (this is the "free-field" part of the problem).
2. Applies the same methodology to study the interaction between an outcropping normal fault and foundation-structure systems [this is the Soil-Foundation-Structure Interaction problem, triggered by the propagating Fault Rupture (FR-SFSI)].
3. Validates the developed methodology through successful Class "A" predictions of centrifuge model tests of : (i) free-field fault rupture propagation, and (ii) interaction between fault rupture and strip footings.

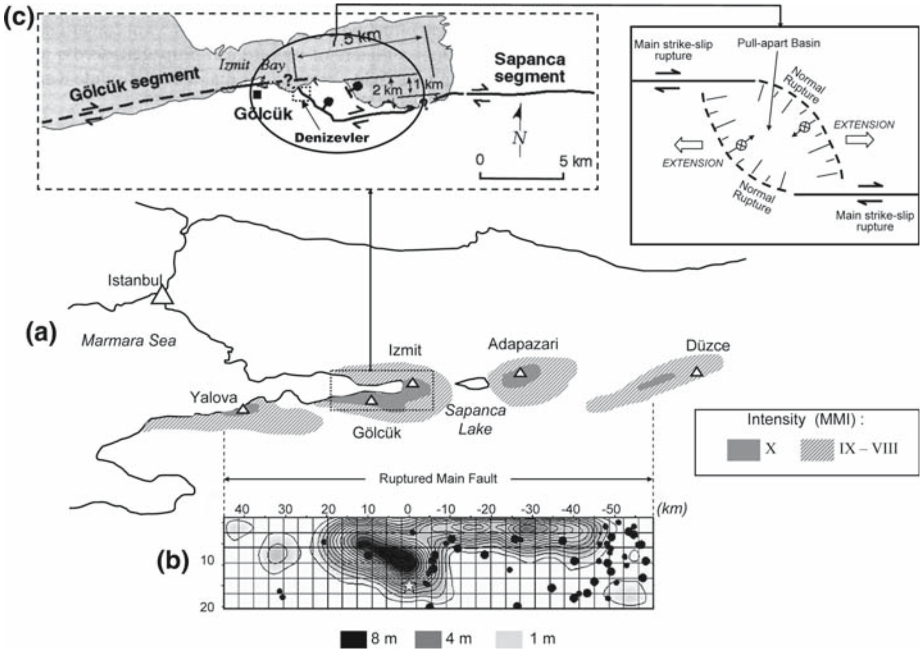


Fig. 1 The 17 August 1999 Kocaeli Earthquake: (**a**) Damage Intensity Distribution in terms of the Modified Mercalli Intensity Scale (MMI), (**b**) Horizontal Slip Distribution on the vertical plane of the seismogenic fault (Yagi and Kikuchi 1999), and (**c**) the step-over mechanism which is responsible for the normal faulting east of Gölcük (adapted from Youd et al. 2000)

4. Applies the validated FE modelling methodology to analyse one-by-one the Kocaeli case histories of the present paper, developing further insights into the mechanics of fault-rupture effects on soil-foundation-structure systems.

2 The 1999 Kocaeli (Izmit) earthquake and fault ruptures

The M_w 7.4 1999 Izmit earthquake was caused by re-activation of a 125 km portion of the North Anatolian Fault (Barka 1999; Papadimitriou et al. 2001). With its epicenter only 5 km southwest of the city of Izmit, the earthquake struck the industrialised corridor around the Marmara Sea, in the northwestern part of Turkey, causing more than 15,000 fatalities (Sahin and Tari 2000). From Yalova to Düzce, in a densely populated area, over 100,000 structures were severely damaged or collapsed (Ural 2001). In Izmit, Gölcük, and Adapazari more than a third of the buildings either collapsed or sustained non-repairable damage, with the Modified Mercalli Intensity (MMI) ranging from VIII to X (Fig. 1a). The damaging mechanisms involved one or more of the following: (a) seismic shaking, (b) liquefaction, (c) subsidence, and (d) fault rupturing. This and the companion paper will solely focus on the latter.

The earthquake caused tectonic surface rupture over an area exceeding 110 km in length. Surface ruptures generally appeared in a 5–25 m wide zone of multiple successive east-west strike-slip ruptures, with maximum right-lateral displacement ("offset") reaching 5 m. More typical values of the offset were about 2 m to 3 m, decreasing gradually to the east (Yagi and Kikuchi 1999) (Fig. 1b). Crossing Degirmendere Bay the faulting displacement caused sinking of a whole part of the town. Given the population of the area, it is not surprising that surface ruptures crossed several urban areas. It is, however, surprising that there were several structures that survived the faulting without serious damage. General overviews of the behaviour of numerous structures affected by fault ruptures in various locations can be found in Youd et al. (2000), Erdik (2001), Bray 2001, Ulusay et al. (2002), and Pamuk et al. (2005).

Although the main faulting mechanism of the North Anatolian Fault (NAF) was strike-slip, this paper focuses on normal faulting. It concerns the pull-apart basin of Gölcük, where the strike-slip displacement of the NAF was locally converted into normal (downward) displacement. The pull-apart basin of Gölcük (Fig. 1c) was one of four that were associated with the 1999 earthquake: Karamürsel, Gölcük, Sapanca Lake, and Eften Lake. The differential displacement of the Gölcük segment relative to Sapanca produced a 4 km NW–SE (110°) normal fault east of the city of Gölcük, crossing the small community of Denizevler. The maximum vertical downward displacement reached 2.4 m, accompanied by a right lateral component of 1.3 m. Although the fault rupture crossed several simple residential structures, the extent of damage was not devastating. Some of these structures were severely damaged, but others survived the rupturing almost totally unharmed. The normal faulting also caused sinking of the coastline by 2–3 m, for a total length of about 4 km. The geometry of the ruptures, as well as the geomorphology of the area, in combination with palaeo-seismicity studies confirm the tectonic origin of the event (Tutkun et al. 2001; Pavlides et al. 2002, 2003).

3 The "natural experiment" of Denizevler: Overview

As already discussed, in the area of Denizevler the normal surface rupture crossed several structures. Within an area barely exceeding 1 km, five residential buildings, a mosque, a basketball stadium, buildings of a just-constructed automobile factory, and a high-voltage electricity pylon were all crossed by the outcropping dislocation. Although vertical differential displacement exceeded 2 m, few of these structures collapsed. Four buildings survived with minor or no damage, with the fault rupture emerging at a distance of only 0.5–1.0 m away. It is even more "amazing" that in some cases the surface rupture appeared to deviate from its original path so as to "avoid" crossing the structure. With the foundation systems of these structures ranging from simple isolated footings to box-type foundations and to pile groups, and with the location of fault crossing with respect to the plan of the structure being different in each case, Denizevler can be seen as a multiple real-scale experiment. Equally interesting is that soil conditions, to be shown later, do not differ significantly from point to point; therefore differences in behaviour can persuasively be (mainly) attributed to differences in foundation and structural rigidity, in addition to the location of the rupture relative to the building

Figure 2 illustrates a plan sketch of the investigated area along with the surface trace of the dislocation. As depicted in the figure, the rupture emerged at the surface creating fault scarps of up to 2.4 m. In contrast, in some cases the dislocation could not be easily identified seeming to disappear, converted to widespread differential settlement of the ground surface rather than a distinct scarp. From east to west, a first

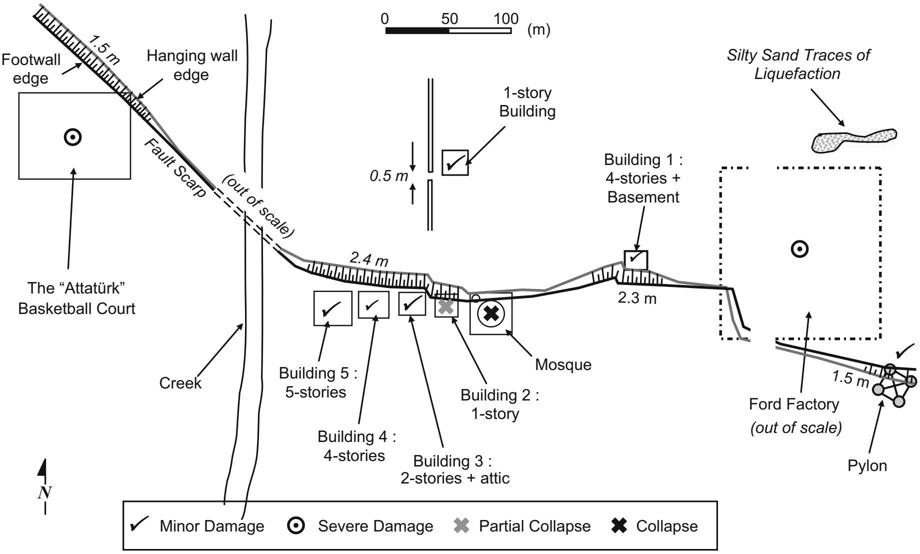


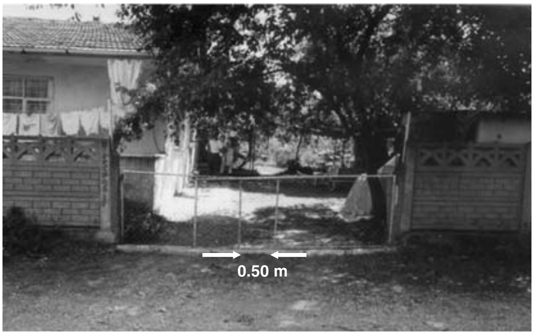
Fig. 2 Sketch of the region of Denizevler (east of Gölcük) under study : the normal fault trace passed through a number of buildings, a mosque, the Ford factory, a high-voltage pylon, and a basketball court. The extent of damage ranged from minor to full collapse (the limits of the factory are out of scale). Values indicate the vertical component of the fault offset at the ground surface.

impressive (even though perhaps merely fortuitous) success was that of a high-voltage electricity pylon : crossed by the fault rupture, the pylon did not collapse, sustaining only minor damage despite the "loss" of two of its four supports. Then, a major building of an under-construction car factory of Ford also survived the faulting, but with damage (Fig. 3a, b, c). While parts of it were later demolished and reconstructed, it is interesting to note that the main dislocation practically went around the factory complex, emerging along its fence. Consequently, some portion of the fence bases were pulled out (Fig. 3d, e). Outside the factory, some traces of liquefaction (silty sand boils) were evident (Fig. 3f).

Further west, a 4-story building (denoted as Building 1) on the hanging wall, sustained no damage at all, with the fault rupture deviating around it. To the west, the Mosque was heavily damaged and demolished later. Next to it a 1-story lightly-founded building (Building 2) was literally cut by the fault and partially collapsed. Building 3 (2 stories + attic) remained on the un-moved "footwall" block and showed no damage at all, avoiding a direct "hit" thanks to diversion of the rupture path. The next two buildings (4 and 5), of 4 and 5 stories respectively, also did not suffer any visible damage. Then, further to the west, the rupture crossed a small creek heading to the "Attatürk" Basketball Gymnasium. This recently built facility, despite its "sophisticated" piled foundation, sustained severe damage. The fault trace "disappeared" before the Gymnasium, and thus a small 1-story guard building, showed no visible damage. Finally, about 50 m to the north of the fault trace, in the downthrown block, we identified a garden gate (Fig. 4) that had shrunk by about 0.5 m, indicating horizontal compression. Yet, the adjacent 1-story house displayed no damage at all.

Fig. 3 Ford factory: (**a**) differential settlement of about 1 m, (**b**) tilting of concrete columns, (**c**) cracking at the base of the columns, (**d**) fault rupture right through the fence, (**e**) fence footing pulled out, (**f**) traces of liquefaction north of the building

Fig. 4 Garden gate subjected to shrinking of about 0.5 m: indication of horizontal compression at a 50 m distance from the fault scarp



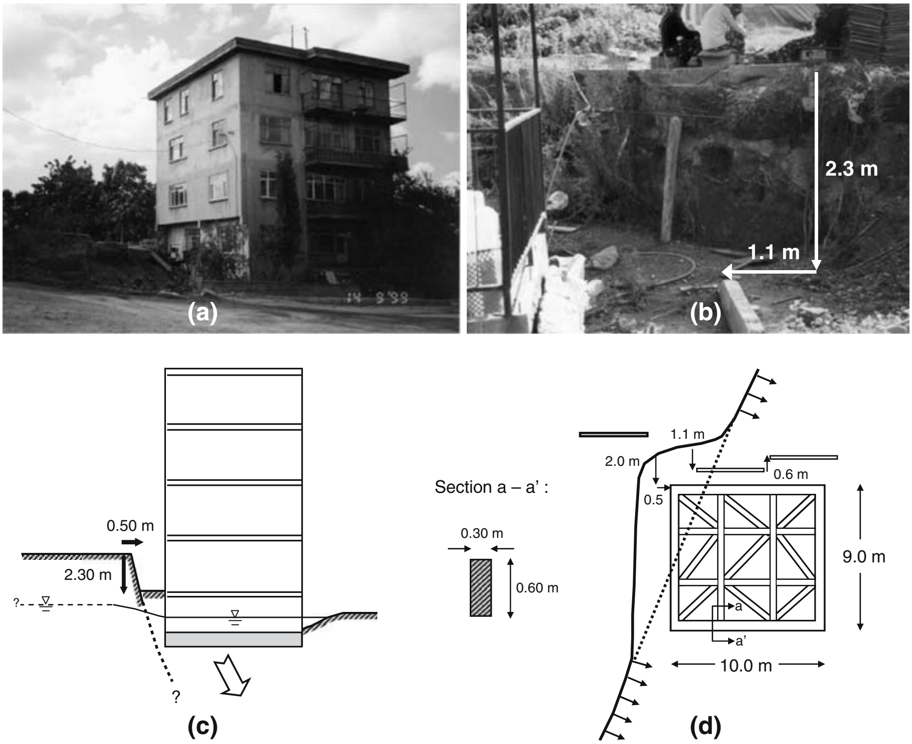


Fig. 5 Building 1, four stories plus basement; Minor Damage: (**a**) photograph of the building showing the fault trace directed towards the building, before being diverted, (**b**) photograph showing the vertical displacement reaching 2.3 m, along with a horizontal component of 1.1 m measured on the torn apart fence of the building, (**c**) cross-section of the building, and (**d**) plan view of the foundation (box-type foundation with cross tie beams), along with the horizontal displacements measured around the building

4 Detailed field investigation

This section documents our field investigation in the area of Denizevler. The focus is on Buildings 1, 2 and 3, the Mosque, and the Basketball Court. Our soil exploration and trenching is also presented and compared to other available published data.

4.1 Building 1

Building 1 is a 4-story reinforced-concrete structure with basement. As depicted in Fig. 5a the surface rupture diverted and just avoided the structure, leaving it unharmed. The downward settlement (dislocation) reached 2.3 m, being accompanied by a horizontal component of 1.1 m (Fig. 5b). The only apparent damage to the building was the flooding of its basement, due to local modification of the water table (Fig. 5c). One year after the seismic event the basement was still filled with water, showing that the water table had changed permanently. Since the basement was flooded with about 1 m of water, and the vertical displacement was 2.3 m, it was concluded that the water table should be at a depth of about 1.5 m.

Figure 5d sketches a plan view of the fault scarp that formed around the building, as well as the consequences of differential displacement to the fence of the building. It is interesting to note that the maximum horizontal displacement occurred at the point where the rupture was re-aligned with its original path, after diverting due to the presence of the structure. This curving of the dislocation must have apparently produced the horizontal (strike component) displacement vector measured on the fence. According to the owner, who was inside the house during the earthquake, no vertical falling was felt, despite the fact that the building was on the “downthrown” hanging-wall. Instead, they only felt a torsional motion, something that agrees with the geometry of the observed dislocations and horizontal displacements around the building. Evidently, the vertical displacement should have been of quasi-static nature.

Figure 5d depicts the main characteristics of the foundation of this building. Its plan dimensions are approximately 9 m × 10 m, and it consists of strip footings approximately 0.60 m × 0.30 m (height × width) transversely connected through tie beams of similar dimensions. Interestingly, the owners of this building had detailed knowledge of the foundation (they had actually built it themselves).

In the literature we found several cases where (in the words of Duncan and Lefebvre 1973) *“a strong structure built across a fault causes diversion of the fault”*. Here are two examples from the Kocaeli earthquake:

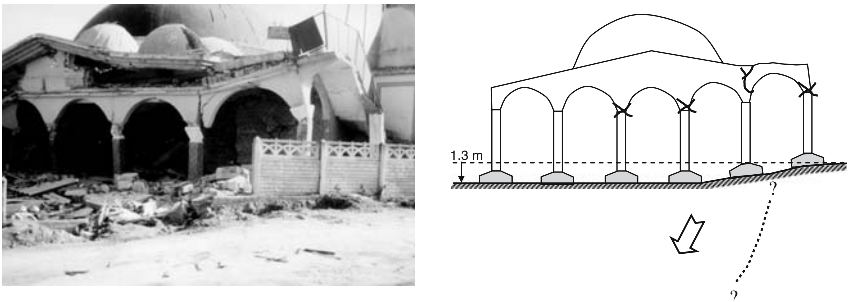
- a heavily-reinforced concrete bunker in the Gölcük Naval Base which forced a directly intersecting fault rupture of 4 m strike-slip dislocation to go around the structure, causing only a small rotation (Youd et al. 2000; Ansal et al. 2000)
- A Koran school along the Sapanca fault segment was intersected by 1–2 m of shear surface rupture, which “turned” around the building forming a left *en echelon* step; the building foundation and walls were not damaged (Youd et al. 2000).

4.2 The Mosque

As shown in Fig. 6, in the area of the Mosque (less than 150 m west of Building 1) the rupture did not create a visible fault scarp. On the contrary, the dislocation appeared at the surface as a widespread differential settlement, not easily observable. Despite this seemingly “favourable” situation, the Mosque partially collapsed, and was fully demolished later. The superstructure of the mosque was also of reinforced concrete, but its foundation comprised several isolated footings, apparently without any connection between them. No shear walls or stiff tie beams existed between the columns. In conjunction with its rather “heavy” arched roof, its structural system was less stiff than that of Building 1. Its foundation is, obviously, discontinuous and thus quite flexible. Hence, the differential settlements were transmitted to the superstructure practically unaltered. We have to exclude the intensity of ground shaking from being a principal cause of the collapse, since the observed damage and cracking did not indicate horizontal shear failure. The minaret of the mosque confirms this hypothesis: in most of the regions where ground shaking was the main cause of damage, the minarets of the Mosques were quite susceptible to collapse. In this case, the minaret did not collapse.

4.3 Building 2

Building 2 was a simple poorly-constructed 1-story structure. Its wooden tile-covered roof was supported directly on cinder block walls. Between the roof and the walls, poorly-reinforced concrete beams had been cast, presumably to tie the walls together.



(a) (b)

Fig. 6 Mosque; Collapse: (**a**) photograph of the Mosque showing the differential settlement of the un-scarped ground surface and the distress of its superstructure, and (**b**) sketch of its cross section and foundation (separate footings)

The walls were practically founded directly on the soil, without the interference of foundation. This poor building would *not* have been expected to perform well in an imposed differential displacement of the order of 1.5 m, and indeed it was torn apart by the rupture as depicted in Fig. 7a and b. However, it did not collapse completely, and its partial collapse did not cause fatalities. The rupture crossed its north-east corner tearing it apart from the rest (Fig. 7c and d). Given the limited tensile resistance of the cinder-block walls, the structure was unable to resist the rupturing significantly, leaving the rest of it almost un-harmed.

Compared to the adjacent Mosque, this building can be seen to have behaved a little better: a part of it collapsed, but the rest was left intact. We believe that one could attribute the partial survival of this modest building to its "compliance", in terms of strength. On the other hand, the Mosque, a better-built structure, offered more resistance to the differential settlement (this is attested by its deformation), but was obviously not strong enough to completely sustain it. A small, yet possibly important difference between the two, is the geometry of rupture crossing : Building 2 was crossed by the rupture very close to the corner (at ~ 2 m distance), while the Mosque was traversed at ~ 4 m from its northern corner. Furthermore, while the Mosque was subjected to widespread differential settlement, Building 2 was forced to endure a distinct fault scarp. Although, such a situation would seem to be favourable for the Mosque, this was not the case here. Apart from these differences, the two structures were quite similar in the discontinuity and flexibility of their foundation. Both were significantly different in this respect from Buildings 1 and 3, which both rested on rigid and continuous foundations.

4.4 Building 3

Building 3, along with Buildings 4 and 5 (Fig. 8) managed to survive the tectonic dislocation without any externally visible damage other than a hairline crack on one of their brick walls. Most importantly, it seems to have effectively diverted the rupture, as was the case with Building 1. But whereas Building 1 is founded on the hanging-wall, managing to divert the rupture to the South (towards the footwall), Building 3 is founded on the footwall, and the rupture was slightly diverted to the North, towards the hanging-wall (Fig. 9a). The vertical displacement in this case reached 2.1 m (Fig. 9b

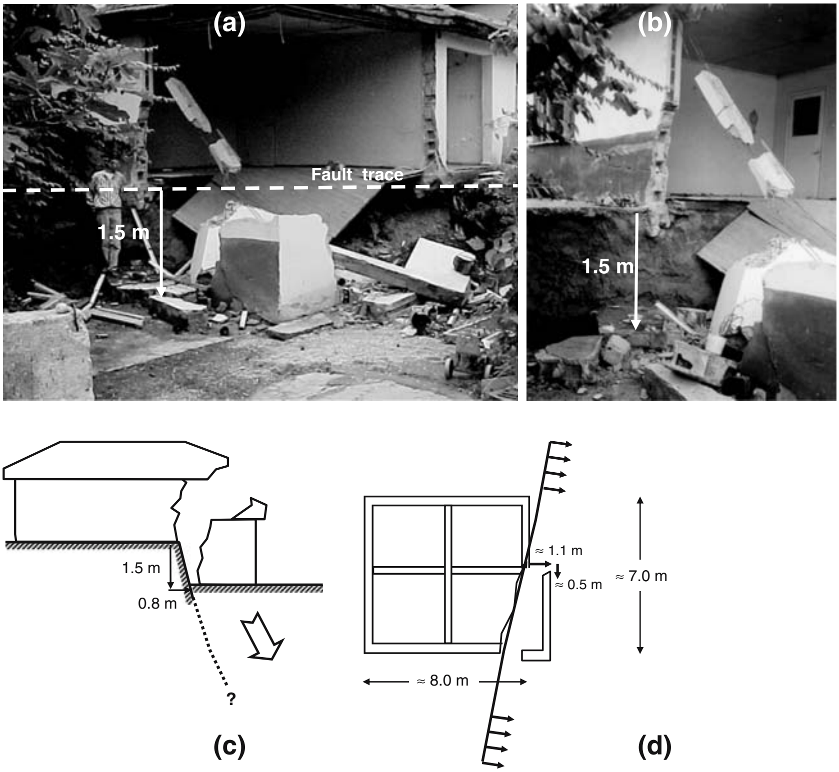


Fig. 7 Building 2, single story; Partial Collapse: (**a**) photo of the fault trace passing through the building (adapted from Youd et al. 2000), (**b**) photo of the rupture-produced cross section of the building (cinder-block walls directly founded on the ground), (**c**) schematic cross-section of the building, and (**d**) plan view of the foundation and the measured offset displacements

and c). The reinforced concrete building comprises 2 stories and an attic. As depicted in Fig. 9d its box-type foundation system is quite rigid, comprising stiff concrete beams "sandwiched" between a mat and a top slab. The voids between the concrete beams and the slabs are filled with gravelly soil. The slabs are about 0.3 m thick, and the concrete beams 0.5–0.6 m wide, while the thickness of the whole box reaches $\sim$ 1.4 m.

It appears that rigid box-type foundation is quite common in the provincial regions of Turkey with poor soil conditions. The box-type foundation is considered as a relatively inexpensive but rigid foundation system. Obviously, the constructors (usually the owners themselves) did not have in mind resistance to faulting-induced differential settlements. Their aim was to secure their inexpensive, and therefore vulnerable, superstructures from excessive differential settlements due to soil compliance. This type of foundation is also widely used in Adapazari, where most of the failures were of the bearing capacity type (Gazetas et al. 2003). In Adapazari, although many buildings had even toppled, the foundation and superstructure remained structurally un-harmed. This offers additional confirmation of the ability of rigid and continuous box-type foundations to safeguard vulnerable superstructures.

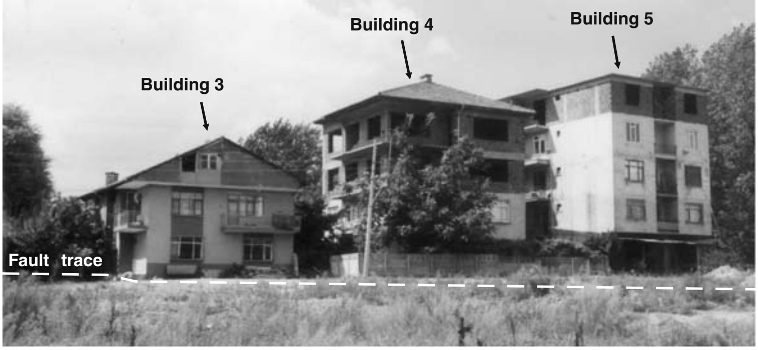


Fig. 8 Panoramic photo of Buildings 3, 4, and 5: all of them survived the dislocation with only minor damage. Most interesting is the case of Building 3, in which case the fault rupture was effectively diverted.

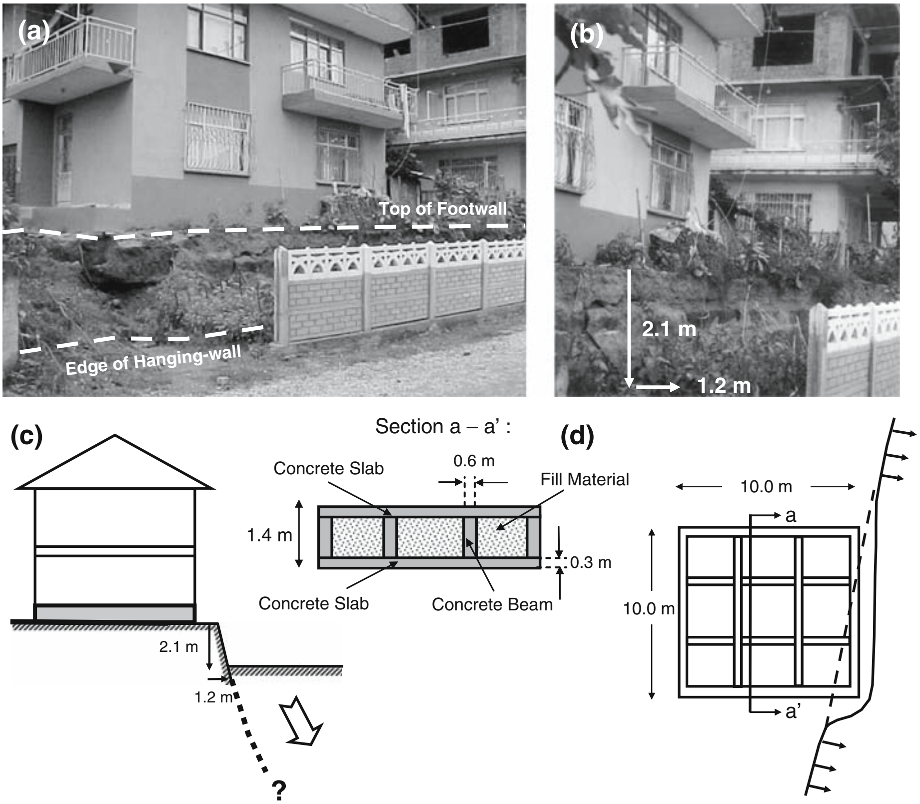


Fig. 9 Building 3, two stories plus attic; Minor Damage: (**a**) photo of the building, showing the fault scarp right next to the building (adapted from Youd et al. 2000), (**b**) photo of the rupture scarp in front of the building, showing the measured vertical and horizontal displacement, (**c**) schematic cross-section of the building, and (**d**) plan view of its box-type foundation along with a representation of the diverted rupture.

4.5 The “Attatürk” basketball court

The Basketball Court, named “Attaturk”, had just been constructed when the 1999 earthquake struck. As shown in Fig. 10a the rupture crossed its northeastern corner causing significant local damage to its reinforced concrete superstructure. Figure 10b shows the southern part of the building, which sustained practically no damage. Again, the damage can be attributed solely to differential tectonic displacement and not strong seismic shaking. Figure 10c depicts the extent of damage suffered by the northeastern part of the building, near the corner struck by the dislocation. Several of its concrete shear walls failed, while its non-bearing brick walls were diagonally cracked, indicating tensile failure at 45° due to differential settlement. Figure 10d depicts the damage to the piled foundation. The pile at the photo had been pulled downward and outward, and tensile cracking was easily observable. Its adjacent pile (not seen in the photo) had failed in tension completely, and was totally detached from the pile cap.

The plan view of the Basketball Court is sketched in Fig. 10e. Its structural system comprised shear-wall type columns 0.25 m × 0.80 m in plan, positioned along the perimeter. As depicted in Fig. 10f, each column is founded through a 2 × 2 pile group. The piles are 0.6 m in diameter, connected together through a 2.4 m-square pile cap, 1.2 m in thickness. Although the building survived the induced differential displacement, the extent of damage was quite significant; the structure was deemed as “beyond the limit of repair” (BLR). It will be argued in the companion paper (Anastasopoulos and Gazetas 2007), that this constitutes a case where the piled foundation possibly contributed to the damage, by forcing the superstructure to follow the imposed displacement. In fact, if the piles had not failed (in tension), the situation might have been even worse.

4.6 High-voltage electricity pylon

Figure 11a shows an aerial photo of the high-voltage pylon, east of the FORD factory, crossed by the fault rupture. The vertical displacement in this case reached about 1.5 m (Fig. 11b) with a relatively minor horizontal component. The pylon superstructure was a typical metal space-frame, while the foundation comprised four small concrete piers, 1 m × 1 m in cross section, and 2.5 m deep. The rupture crossed its northeast corner, forcing two of the piers to follow the downward displacement of the hanging-wall, while the other two remained attached to the footwall. One of the two foundation piers founded on the hanging-wall was completely pulled-out, while the other was just “crossed” by the dislocation and remained attached. Surprisingly, not only the pylon did not collapse, but it actually suffered only minor local damage. The question that logically arises is how the pylon succeeded in carrying its dead load while supported on only 2 of its 4 foundation points. We identify two plausible explanations : (a) the pylon was in fact still supported on at least three foundation points, i.e. assuming that the pier directly “hit” by the rupture remained more- or less in place; and (b) the “favourable” orientation of the cables permitted development of the necessary horizontal force to counter-balance the eccentric vertical reaction of the two remaining foundation points. Naturally, both (a) and (b) may have contributed to its survival.

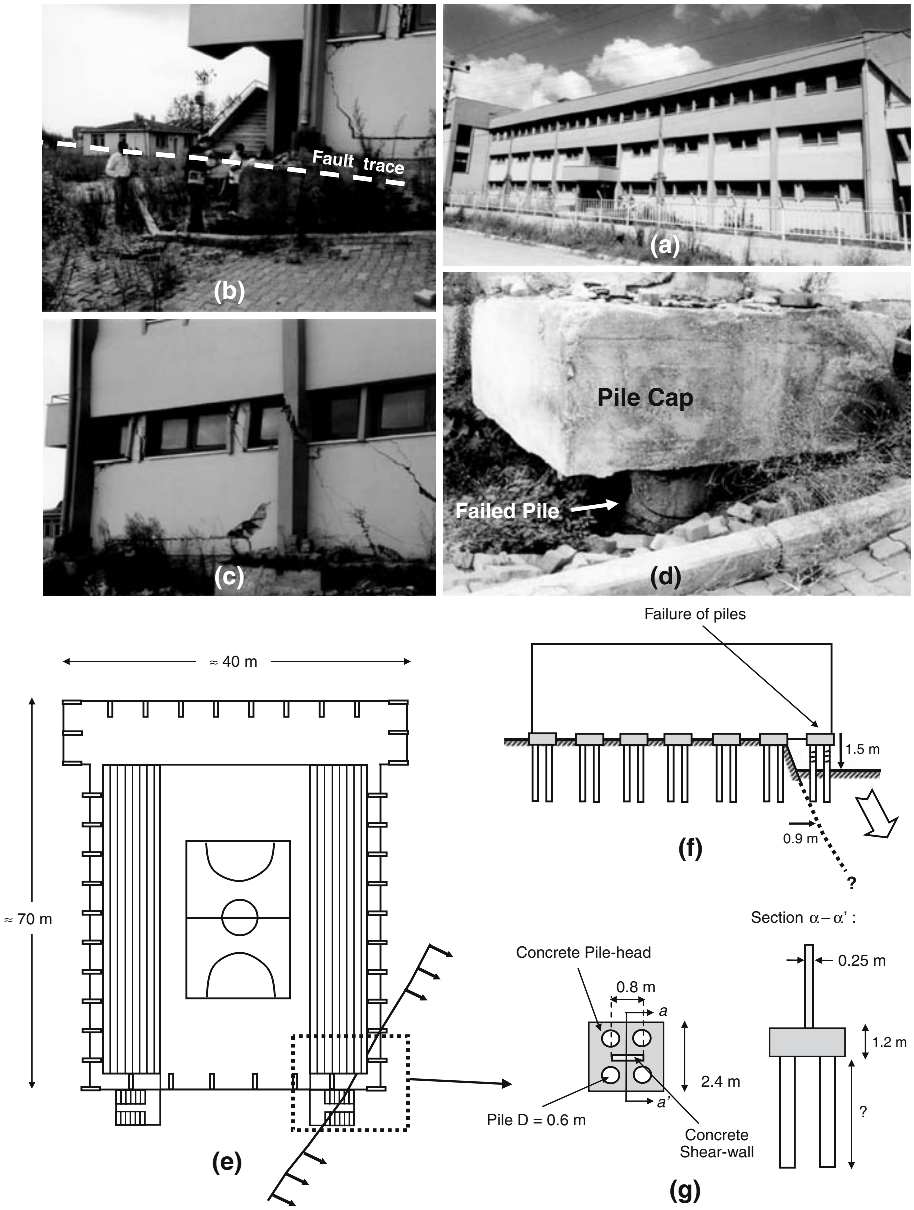


Fig. 10 Basketball Court; Severe Local Damage: (**a**) panoramic photo of the building, (**b**) photo of the building's corner crossed by the fault trace, (**c**) shear damage due to the imposed differential settlement, (**d**) tensile failure of the piled foundation, (**e**) schematic plan view of the building, along with the rupture trace, (**f**) cross-section showing the fault displacement and the damage to the (pulled-down) piles, and (**g**) detail of the foundation

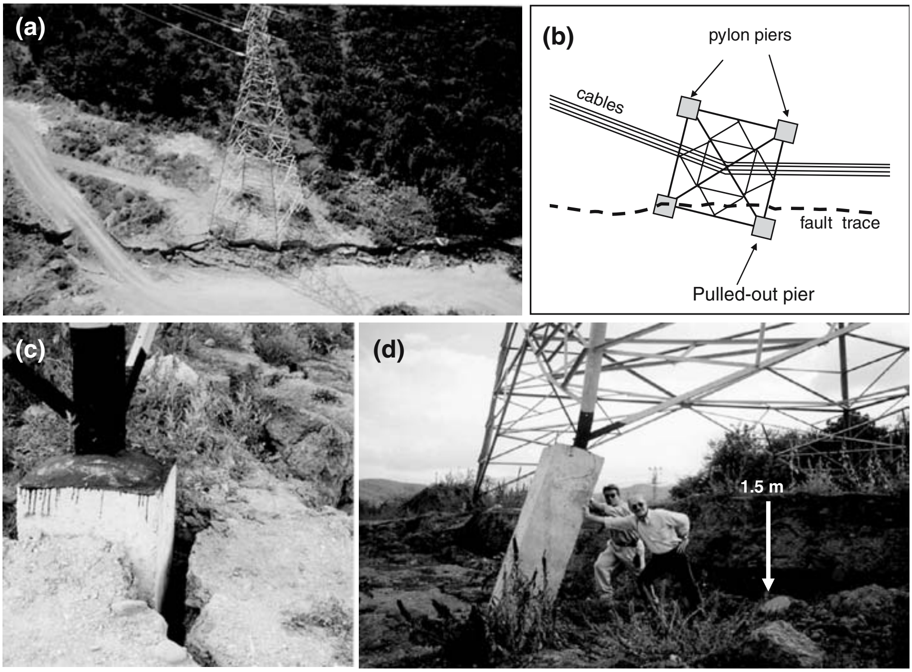


Fig. 11 High Voltage Pylon; Minor Damage: (**a**) aerial photo (adapted from Youd et al. 2000), (**b**) plan-view sketch of the pylon and the fault rupture, (**c**) photo of the directly-hit left foundation pier, and (**d**) photo of the pulled-out right foundation pier

5 Soil investigation and trenching

In the area of study we conducted an (admittedly limited) soil investigation, comprising four boreholes and an approximately 6 m × 4 m × 4 m (length × width × depth) trench. The soil exploration took place right beside Building 3, where a vertical displacement of 2.1 m was observed. Fig. 12a shows the locations of the boreholes and the trench. The exploration was performed about 18 months after the earthquake. Regrettably, the fault scarp had been covered with fill; only in the area around Building 1 was the scarp still visible. Boreholes B1 and B3 were located within the hanging wall, while B2 and B5 within the footwall. Figure 12b summarises the key results of this exploration, in the form of soil layer characterisation and number of blows N_{SPT} of the Standard Penetration Test (SPT). As revealed by the N_{SPT} graphs the first 6–8 m consist of relatively loose, to medium soil layers with N_{SPT} ranging from 17 to 33, while deeper the soil becomes much stiffer, with N_{SPT} reaching 50 at a $\sim$ 15 m depth. The soil profile comprises alternating layers of silty to fine sand, and sand. The presence of clayey materials is only limited to some thin layers of clayey silt to silty sand with clay. The water table was found to be very close to the surface, at approximately −2 m. We found it very difficult to excavate the trench at depths >3 m: due to the high water table trench walls destabilised easily.

Besides from our soil exploration, we also acquired the Geotechnical Reports (GEOS 2000) for the Gölcük Kücük Industrial Project, a major industrial project right on the east of the FORD factory, not very far from the area under study.

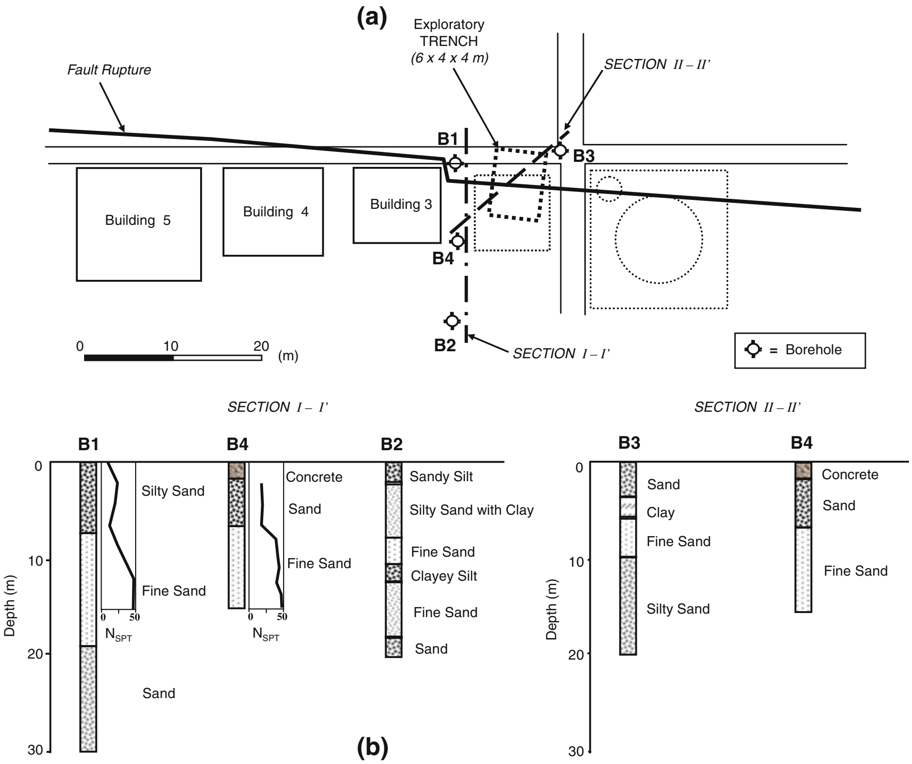


Fig. 12 Geotechnical exploration conducted near Building 3: (**a**) plan view of the area, showing the approximate position of the boreholes and of the exploratory trench, and (**b**) geotechnical cross-sections I–I′ and II–II′. [Note that typical N_{SPT} values correspond to about $1.25 N_{SPT,60}$, since the delivered energy ratio has been measured at about 48%.]

Figure 13a depicts the map of the greater area of Denizevler showing the position of the Gölcük Kücük Industrial Project.

Now, it is interesting to follow the fault trace along the map of Fig. 13a from east to west. Interestingly, the fault trace follows the southern border of the FORD complex almost precisely. We believe that this is a significant observation and cannot be attributed to a mere coincidence. Observe also that the border of the FORD complex coincides with a regional road. It is reasonable to assume that the road pre-existed, and that the setting of the plant border was based on the alignment of the road. Since most roads tend to adapt to local topography, it may be argued that there must have been some topographic feature that caused the road to be formed this way. The most likely such feature is a pre-existing fault scarp at the same exact location. If such hypothesis is true, then the observed normal faulting must indeed be *tectonic and not co-seismic*. Its creation lasts several minutes and is of a quasi-static nature, as the cushioned movement of a block supported with elastic springs on a downward displacing base [Ambraseys 2002 personal communication]. The results of the trenching will shed more light to this hypothesis. Figure 13b summarizes the results of soil investigation at the Gölcük Kücük site. A total of 10 boreholes, S1–S10, indicate similar soil layering with our exploration. Again, the soil profile comprises layers of silty to fine

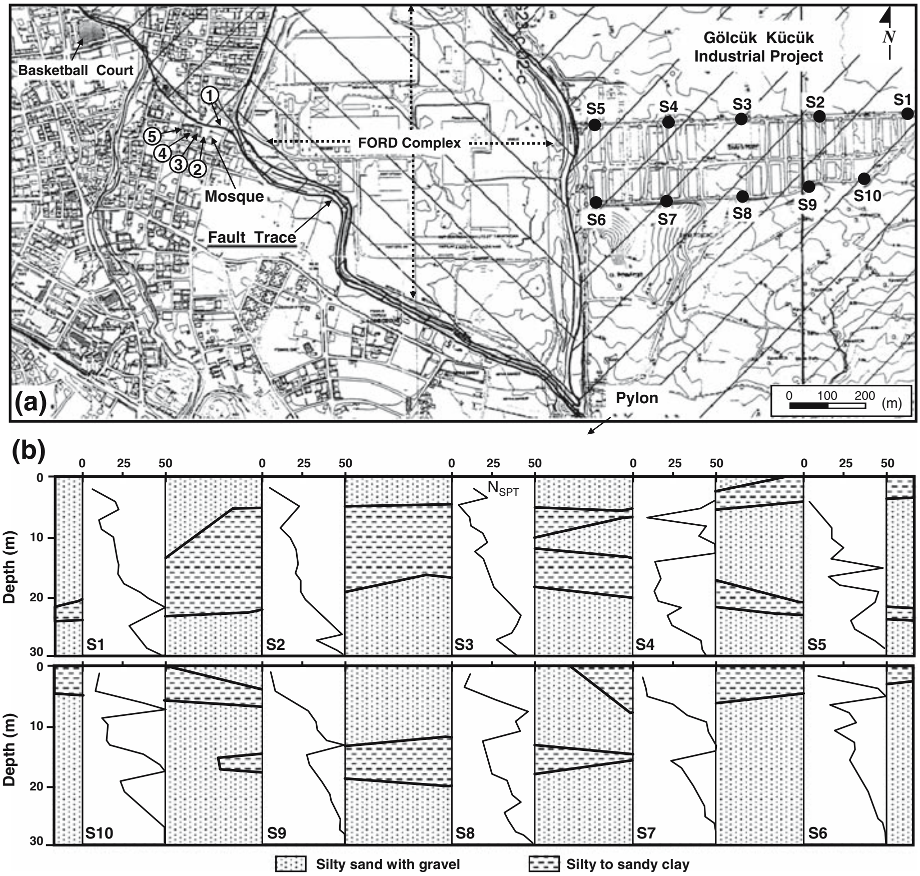


Fig. 13 (**a**) Map of the greater area of Denizevler showing the position of the Gölcük Kücük Industrial Project relative to the points of interest of our study, and (**b**) Longitudinal geotechnical cross-sections along lines S1-S5 and S10-S6, and super-imposed N_{SPT} variation at each of the 10 locations (Geotechnical Report GEOS, 2000)

sand, alternating with silty to sandy clay. The soil is moderately dense for depths up to 20 m. In most boreholes the water table was also found at −2 to −3 m. The obvious similarity with the findings of our soil exploration confirms that soil conditions do not differ significantly from one point of interest to another.

Figure 14 depicts the shear wave velocity, V_s, profile based on microtremor measurements that were conducted in close proximity to our study area by Arai et al. 2000. The measurements were performed at five sites (G01 to G05), extending from the southern hills to the shore of Izmit bay. The two-dimensional V_s profile was estimated by inverse analysis, applying the improved H/V (horizontal-to-vertical) spectrum method (Arai and Tokimatsu 1998). As shown in the figure, the bedrock outcrops to the south with $V_s \approx 1300$ m/s. Then, it dips steeply for about 100 m and continues dipping northwards. At site G04, which is the closest to our study area, the first (near-surface) soil layer with $V_s \approx 280$ m/s extends to −20 m depth. This first layer is the one encountered in both our and the Gölcük Kücük soil exploration. It

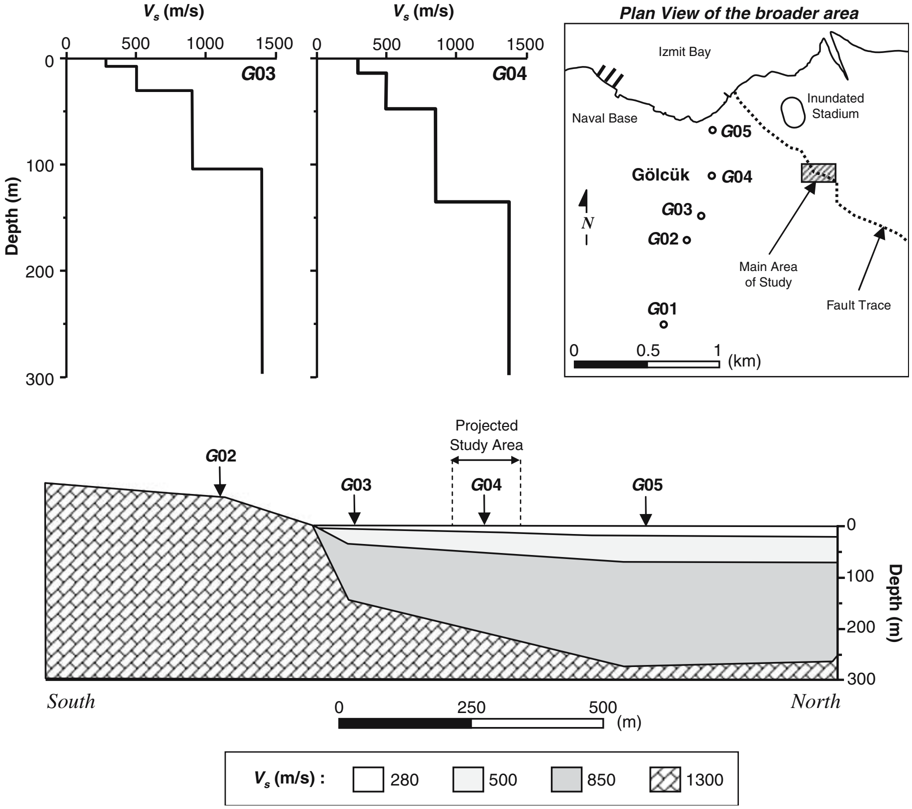


Fig. 14 Shear wave velocity V_S profile based on microtremor measurements (after Arai et al. 2000)

is followed by a stiffer layer of $V_S \approx 500$ m/s ending at −45 m depth, and a third one with $V_S \approx 850$ m/s extending down to the bedrock at −130 m depth.

The geological cross-section produced by the excavated trench at the area of Denizevler is shown in Fig. 15a. As foresaid, the sidewalls of the trench we excavated right beside Building 3 could not be stabilised. Therefore, the results shown herein refer to a nearby location, where the water table was a little deeper. In any case, the aim of trenching was not to determine soil composition with exactness, but to conclude on the tectonic origin of the outcropped rupture. As shown in the geological cross-section, besides the current 1.5 m dislocation, a second one also exists. This second rupture does not reach the ground surface, stopping within layer 6 (conglomerate). This older rupture is apparently the result of older seismic events [Pavlides 2003] confirming the tectonic nature of the observed dislocation. In fact, the trenching showed that the investigated normal fault had been activated at least 3 times in the past. The measured offset (observe layer 6) is almost twice the height of the 1999 dislocation (≈ 2.8 m) compared with 1.5 m. This offset is cumulative, incorporating the effect of the 1999 dislocation and that of the aforementioned older seismic episodes.

It is worth comparing the results of our exploration with the recently published study by Klinger et al. (2003), a typical result of which is reproduced in Fig. 15b. In this case the measured scarp is similarly equal to 1.6 m. Klinger et al., after an extremely

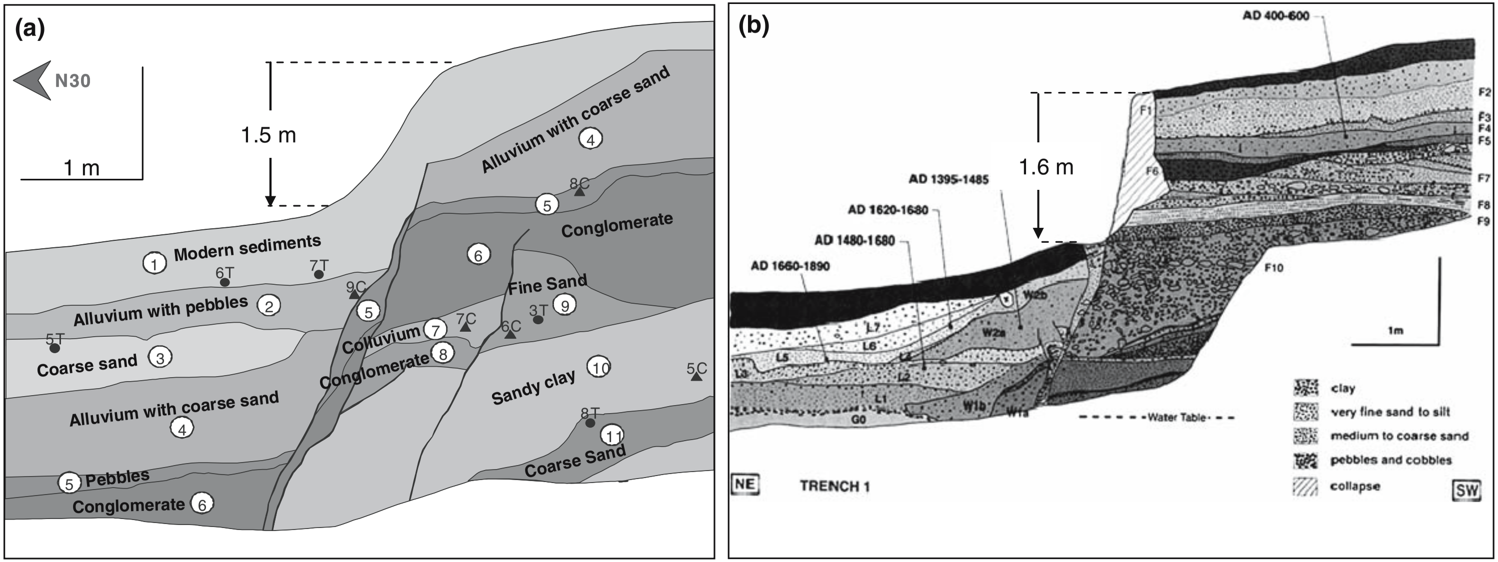


Fig. 15 Geological cross-sections trenched in the area of Denizevler: (**a**) the exploration by Pavlides et al. (2003), compared to (**b**) the detailed study of Klinger et al. (2003)

detailed paleoseismic study conclude that their trenching reveals 3 distinct seismic episodes, with the 1999 earthquake being of course the latest. They explain that the oldest earthquake is responsible for the formation of wedge W1, while the penultimate one for wedge W2. These wedges are formed after each earthquake from the unavoidable erosion of the fault scarp. After a seismic event nature smoothens the scarp (erosion). Soil material is eroded from the upper half (footwall) and deposited downslope (hanging-wall). This implies that the material of each wedge was originally on top of the footwall. The height of each wedge is practically equal to the height of the eroded material (assuming that the volume of the wedge is equal to the soil volume that was detached from the top half), and hence the height of each wedge is roughly equal to half of the fault offset that triggered it. Thus, measuring the height of wedges W1 and W2, it was concluded that they must have been formed by two seismic offsets, 1.6 m and 1.4 m, respectively. From radio carbon dating, it was estimated that the oldest event took place around 1509, followed by the penultimate at about 1,719, and the latest earthquake in 1999. The three offsets and their approximate periodicity persuasively confirm the tectonic origin of the 1999 episode.

Comparing the results of our exploration (Fig. 14a) with the detailed study of Klinger at al. (Fig. 14b) we confirm our findings and conclude on the tectonic origin of the observed normal fault. The periodicity shows that almost the same magnitude events (offsets of ~ 1.5 m at this particular location) occur almost every 200–300 years. Deeper trenches might reveal additional data for the existence of seismic episodes that preceded.

6 Conclusions

The main conclusions arising from our field exploration are as follows:

(1) Although the causative faulting mechanism of the 1999 M_w 7.4 Kocaeli earthquake was strike-slip, i.e., involving horizontal shearing on the vertical fault plane, there were several pull-apart basins where the rupture was converted to normal. The 4 km normal rupture investigated herein, east of the city of Gölcük, is proven (by indirect and direct evidence) to be of tectonic origin. Our trenching exploration agrees qualitatively fairly well with the results of the detailed studies of Pavlides et al. (2002) and Klinger et al. (2003), confirming the tectonic origin of the event. Normal ruptures have been activated many times in the past, showing a periodicity of the order of 200–300 years for similar magnitude events.

(2) Soil conditions in the investigated area do not differ significantly from one point of interest to another. Our limited soil exploration agrees qualitatively with the results of a nearby detailed soil exploration comprising 10 boreholes (for an industrial project). The soil profile comprises layers of silty to fine sand, alternating with silty to sandy clay. The soil is only moderately dense for depths up to 20 m, while the water table is near the ground surface.

(3) Several buildings with different foundation systems were "involved" in the Denizevler (real-scale) natural "experiment". With the type of the foundation system ranging from isolated footings to box-type foundations and to piles, and with the geometry of building-rupture crossing being different for each case,

Denizevler provides a unique case history of Fault Rupture-Soil-Foundation-Structure Interaction (“FR-SFSI”).

(4) The type of foundation system seems to play a crucial role in the response of the structure to the emerging dislocation. Structures supported on rigid mat or box-type foundations performed quite well, in contrast to those on isolated footings or on piles. Stiff buildings founded on rigid box-type foundations may force the fault rupture to divert.

(5) Even moderately reinforced buildings, such as the ones of Denizevler, are proven to be capable of performing as cantilevers bridging locally-generated “gaps”, provided that they are founded on rigid and continuous foundation systems. Buildings 1 and 3 are real examples of this encouraging performance, which will be verified in the companion paper (Part II) through detailed “FR-SFSI” analyses.

(6) Buildings on isolated footings are unable to “avoid” a direct “hit” of an outcropping fault rupture. Consequently, the dislocation emerges within the structure, causing significant deformation and distress. Such structures are susceptible to partial or full collapse when subjected to severe fault dislocations. Building 2 and the Mosque are the actual proof of the inferior performance of buildings founded on isolated footings.

(7) Buildings on piles may perform worse than the ones on rigid and continuous foundations. Piles may tend to force the superstructure to follow the imposed deformation. The relatively inferior performance of the corner of the basketball court was not due to structural deficiencies, but rather to its piled foundation. In fact, the tensile *failure* of the piles at their top may have played a beneficial role, limiting the magnitude of transmitted forces and hence the level of damage to the superstructure.

(8) Structures in the vicinity of faults *can withstand* fault dislocations of the order of 1 m or 2 m. Simple residential buildings can be designed to perform well. The secrets of their success are investigated thoroughly in Part II through finite element analyses of “FR-SFSI”. The stiffness, rigidity, and continuity of box-type foundations is believed to be responsible for a significant part of this success.

Acknowledgements Part of this work has been conducted under the financing of the Research Project *QUAKER*, funded by the EU (EVG1-CT-2002-00064), while the geological exploration was financed by the Organization for Anti-Seismic Protection—OASP. We would like to thank I. N. Sigalas for his valuable support, and Professor S. Pavlides for conducting the geological cross-sections and providing all relevant information. We have benefited greatly from discussions with Professor N.N. Ambraseys : his thoughtful comments on the slow rate of fault outcropping have substantially influenced our thinking. We also thank Dr. A. Erken for helping us interview several residents of Denizevler. Our field investigation would not have been successfully accomplished without the help of the hospitable residents of the area. Their help is greatly acknowledged.

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