Bull Earthquake Eng
DOI 10.1007/s10518-008-9089-y

ORIGINAL RESEARCH PAPER

Fault rupture–foundation interaction: selected case histories

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Received: 22 October 2007 / Accepted: 23 August 2008

Abstract The 1999 earthquakes in Turkey and Taiwan, offering a variety of case histories with structures subjected to large tectonic displacements, have refueled the interest of the earthquake engineering community on the subject. While several structures were severely damaged or even collapsed, there were numerous examples of satisfactory performance. Even more astonishingly, in specific cases the surface fault rupture was effectively diverted due to the presence of a structure. For the purpose of developing deeper insights into the main mechanisms controlling this fascinating interplay, this article documents selected field case histories of fault rupture–foundation interaction from (a) the M_W 7.4 Kocaeli (August 17) 1999 earthquake in Turkey, (b) the M_W 7.1 Düzce-Bolu (November 12) 1999 earthquake in Turkey, (c) the M_W 7.6 Chi–Chi (September 21) 1999 earthquake in Taiwan, and (d) surface faulting in Mount Etna. A subset of the case histories presented herein is analysed numerically, using the methods developed in the companion paper. It is shown that relatively "heavy" or stiff structures supported by continuous and rigid foundations may divert the fault rupture. Such structures are subjected to rigid body rotation, without substantial structural distress. In contrast, structures on structurally–resilient foundation systems or on isolated supports are prone to substantial damage.

Keywords Fault rupture propagation · Soil–structure interaction · Kocaeli · Düzce-Bolu · Chi–Chi · Mount Etna

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1 Introduction

Over the past few decades, earthquake engineering research and practice has mainly focused on the dynamic response of structures and soil–structure systems to strong seismic ground shaking. These transient dynamic oscillations are the result of waves originating from different patches of a seismogenic fault, produced in sequence as rupture propagates and "slippage" takes place (Ambraseys and Jackson 1984). In contrast, the engineering community has paid little attention to the more direct result of the faulting process: the quasi-static offset of the two sides of the fault. This is due to the fact that seismic waves travel long distances affecting large areas, while permanent fault offsets are only important when the fault rupture outcrops at the ground surface, and only along the fault trace.

Extensive literature is available on the phenomenon of fault rupture propagation through soil deposits. Field studies on the 1954 Dixie Valley-Fairview Peak M_S 7.1 earthquake in Nevada (Slemmons 1957; Oakeshott 1973), one of the first *normal fault* earthquakes to be thoroughly investigated in such terms, documented that: (a) a normal fault tends to become increasingly more-vertical and "diffuse" as it propagates towards the ground surface; (b) surface fault scarps may be substantially less than the bedrock offset; (c) loose and deformable soils may "absorb" the faulting-induced relative displacement, converting it to distributed differential settlement of the ground surface; and (d) the surface offset may be amplified due to formation of secondary ruptures and gravity grabens. Similar observations were made after the 1959 Hebgen Lake M_S 7.1 earthquake in Montana (Brune and Allen 1967; Witkind et al. 1962; Steinbrugge and Cloud 1962; Hadley 1964; Witkind 1964), and the 1983 M_S 7.3 Borah Peak earthquake in Idaho, USA (Taylor et al. 1985; Barrientos et al. 1985; Stein and Barrientos 1985; Crone et al. 1987; Doser and Smith 1988).

The 1945 M_S 7.1 Mikawa earthquake in Japan, was probably one of the first *thrust fault* earthquakes to be studied from the viewpoint of fault rupture propagation (Department of Water Resources 1974), clearly indicating that thrust faults usually bend over the footwall, becoming progressively flatter as they approach the ground surface. Of similar importance were the field observations after the 1952 White Wolf M_S 7.7 earthquake in California (Oakeshott 1973), the 1967 M_S 8.4 Montague Island earthquake in Alaska (Plafker 1967; Bonilla 1970), the 1971 M_S 6.7 San Fernando earthquake (Yerkes 1973), the 1980 M_S 7.0 El-Asnam earthquake in Algeria (Ambraseys and Jackson 1984), and the 1988 M_S 6.8 Spitak earthquake in Armenia (Yegian et al. 1994).

On the other hand, until recently little field evidence was available on the interaction of foundations and structures with surface fault ruptures. One of the first such examples was provided by the basement of the Banco Central de Nicaragua (Niccum et al. 1976), a 15-storey reinforced concrete building severely damaged by strong ground shaking during the M_S 6.3 Managua (Nicaragua) earthquake of 1972. At the same time, the basement of this building, containing the bank vault, was crossed by the strike-slip rupture of the seismogenic fault. Interestingly, the vault survived the faulting without any damage, other than some hairline cracks. Most importantly, the rigid structure (walls of 0.45 m in thickness) was apparently capable of diverting the surface fault rupture. Duncan and Lefebvre (1973) had earlier conducted small-scale tests and finite element (FE) analyses to investigate the interaction between strike-slip faults and rigid embedded structures. They concluded that such structures may actually divert the fault rupture, surviving the dislocation without any damage, if designed appropriately. Their results can be regarded as an actual qualitative Class A prediction (Lambe 1973) of the observed performance of the Banco Central de Nicaragua building.

The 1999 earthquakes Kocaeli, Düzce-Bolu, and Chi–Chi earthquakes in Turkey and Taiwan have refueled the interest of the earthquake engineering community on the subject.

In these events, a large number and a wide variety of structures were subjected to tectonic displacements ranging from 2 to 8 m. Although many of these structures were destroyed or severely damaged, there were also several cases of satisfactory performance (Youd et al. 2000; Erdik 2001; Bray 2001; Ural 2001; Ulusay et al. 2002; Pamuk et al. 2005), confirming the earlier idea (Duncan and Lefebvre 1973; Niccum et al. 1976; Youd 1989; Berrill 1983) that structures can be designed to withstand large tectonic displacements.

This paper documents selected field case histories of fault rupture–foundation interaction. Apart from the aforementioned earthquakes, case histories from Mount Etna are also presented and discussed, where smaller faults are at play that undergo tectonic movements both through aseismic creep and during small earthquakes. The work presented herein was prompted by the need of gaining deeper insights on the main mechanisms controlling this fascinating interplay. A subset of the case histories presented herein is analysed numerically, using the methods described in (Anastasopoulos et al. 2007a).

2 The three earthquakes of 1999

The Kocaeli, Düzce-Bolu, and Chi–Chi earthquakes generated substantial fault rupturing at the ground surface, crossing numerous structures, and providing a great variety of real case-histories of fault–foundation–structure interaction. The first two were produced by strike-slip faulting accompanied by normal-type faulting, while the latter by a thrust fault. Thus, these three events can be claimed to comprise almost all the possible faulting mechanisms.

The 1999 M_w 7.4 Kocaeli (or Izmit) earthquake in Turkey produced surface rupturing over a total length of 110 km (Tutkun and Pavlides 2001; Pavlides et al. 2002, 2003, 2006). Caused by re-activation of a 125 km portion of the North Anatolian Fault (Barka 1999; Papadimitriou et al. 2001), and with its epicenter 5 km southwest of Izmit (Fig. 1), the earthquake caused over 20,000 fatalities (Sahin and Tari 2000), and severe damage or collapse of some 100,000 structures (Ural 2001). Izmit, Adapazari, and Gölcük were the cities that suffered the heaviest damage, with Modified Mercalli Intensities (MMI) ranging from VIII to X.

The typical right-lateral offset along the fault was of the order of 2 m to 3 m Yagi and Kikuchi (1999), with a maximum of about 5 m. The rupture zone at the ground surface was typically 5–25 m wide (Awata et al. 2003), comprising a multitude of *en echelon* ruptures oriented E–W. As expected, the rupture crossed several types of structures, with the degree of damage ranging from collapse to (perhaps surprisingly) no damage at all. Overviews of the behaviour of such structures subjected to tectonic dislocations can be found in Youd et al. (2000), Erdik (2001), Ulusay et al. (2002), Pamuk et al. (2005).

From W to E, four pull-apart basins were created in Karamürsel, Gölcük, Sapanca Lake, and Eften Lake. Due to step-over of the main fault line, and the associated extension in between, normal faulting was also observed along the edges of these basins. As illustrated schematically in Fig. 1, the differential displacement of the segment of Gölcük relative to Sapanca was responsible for the development of a 4 km NW-SE normal fault east of the city of Gölcük. The latter crossed Denizevler (a small community east of Gölcük) with a maximum vertical downward displacement of 2.4 m. Several structures were crossed by the normal fault trace, with the degree of damage ranging from collapse to no damage (Anastasopoulos and Gazetas 2007a). More details on the geometry of these ruptures, as well as the geomorphology and the palaeo-seismicity of the area can be found in Tutkun and Pavlides (2001), Pavlides et al. (2002, 2003, 2006).

Barely 3 months later, on November 12 of the same year, a second seismic episode struck the province of Bolu in eastern Turkey: the M_W 7.2 Düzce-Bolu earthquake. With its epicenter

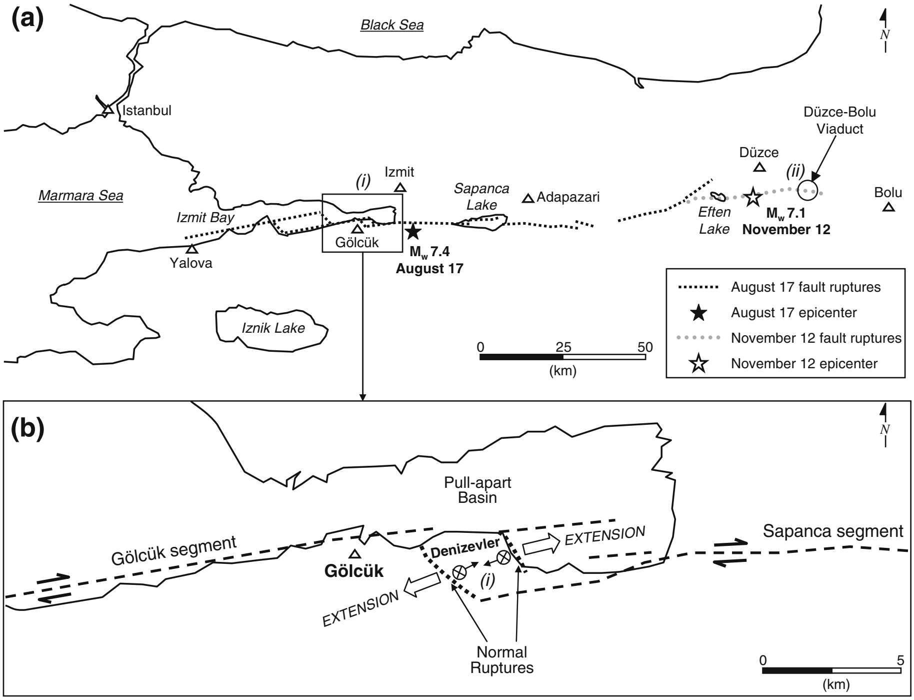

Fig. 1 **a** Surface fault ruptures of the Turkey 1999 Mw 7.4 Kocaeli (August 17) and Mw 7.1 Düzce (November 12) Earthquakes, along with the two areas of interest: (i) Denizeveler, east of Gölcük, (ii) the Düzce-Bolu Viaduct; **b** the step-over mechanism responsible for the normal fault ruptures that passed through Denizevler (based on Youd et al. 2000)

about 110 km east of the Kocaeli epicenter (Fig. 1), this event produced right-lateral strike slip surface faulting of about 40 km in length. The towns of Düzce, Bolu, and Kaynaşli suffered substantial damage, with more than 7000 buildings severely damaged and about 1350 collapsed (Ulusay et al. 2002). Both the average and the maximum lateral offsets were practically the same with the Kocaeli earthquake: 3 and 5 m, respectively. Vertical normal-type offsets, ranging from 0.1 to 1.5 m, were also observed at some locations. The width of the rupture zone at the ground surface typically ranged from 1 to 50 m, with characteristics similar to those of the Kocaeli event.

However, in contrast to the Kocaeli earthquake, the surface fault ruptures of the November 12 earthquake did not cross as many structures. An important exception was the just constructed 2.3 km viaduct of the Trans-European Motorway near Kaynasli, at a location where surface faulting was partially responsible for the substantial degree of damage. Just to the E of the viaduct, a 300 m and a 100 m section of the twin Bolu tunnels on the same Motorway collapsed during the Düzce earthquake (Dalgic 2002; Amberg and Russo 2001). Although this collapse was mostly caused by strong seismic shaking combined with "squeezing" ground conditions (Giannakou et al. 2005), faulting-induced deformation may have also played a role: the part of the tunnel that collapsed lied inside fault gouge material.

Five weeks after the Kocaeli earthquake, a great seismic episode occurred in central-western Taiwan (Fig. 2). With aftershocks of M_s up to 6.8, the devastating 1999 M_w 7.6 Chi–Chi earthquake caused 2400 fatalities and several thousand building collapses. The Chelungpu fault, responsible for this extreme seismic event and oriented N–S, gave rise to

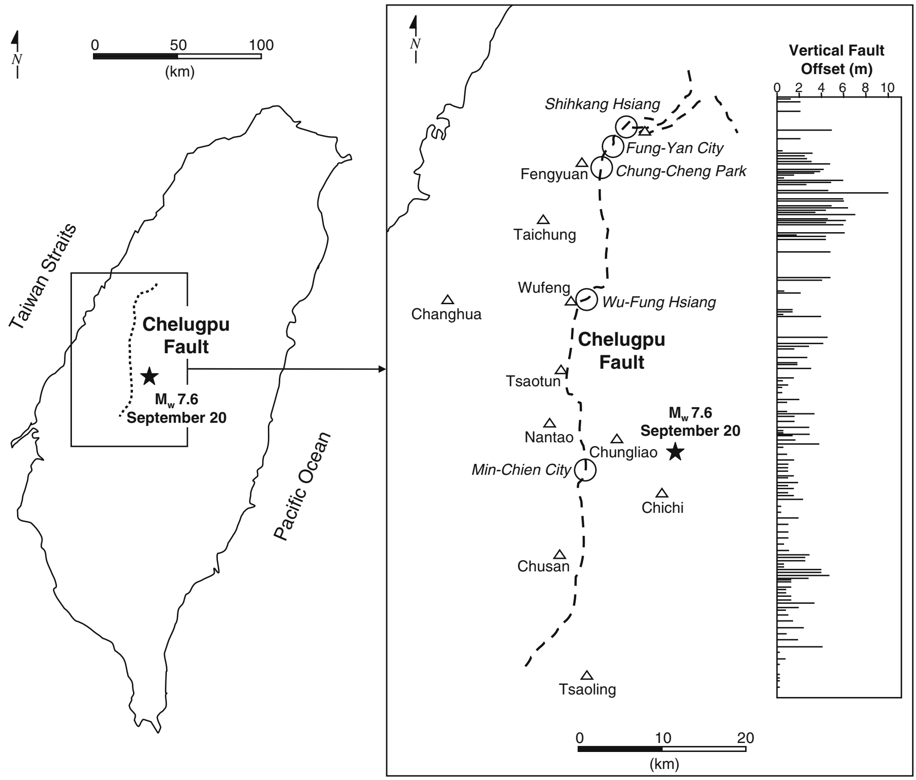

Fig. 2 Surface fault ruptures of the Taiwan 1999 Mw 7.6 Chi–Chi earthquake, along with measured vertical fault offsets (adapted from Chen et al. 2001), and the areas of interest: (i) Shihkang Hsiang, (ii) Fung-Yan City, (iii) Chung-Cheng Park, (iv) Wu-Fung Hsiang, and (v) Min-Chien City

a practically continuous surface fault rupture, extending for a distance of more than 100 km (Angelier et al. 2003). Its orientation reveals its association with over-thrust of Miocene over Meso-Pleistocene formations (Kelson et al. 2001). The dip of these formations ranges from 20 to 30°, reaching 40° close to the fault.

As illustrated in Fig. 2, the vertical offset ranged from a few meters in the South, to about 10 m in the North (Chen et al. 2001). Most of the tectonic deformation was concentrated within a rupture zone lying on the hanging wall, ranging in width from several meters to about 100 m. A great variety of rupture propagation mechanisms were observed, ranging from pure thrust or pure warp, to thrust with multiple bending axes, and other combinations (Bilham and Yu 2000). From North to South, the surface fault rupture crossed several rural areas (Fig. 2), affecting a great number of structures, and providing a broad spectrum of case-histories of fault rupture–foundation–structure interaction. The failure of the Shih-Kang Dam (Chen-Shan et al. 2001; Sugimura et al. 2001) is perhaps the most famous. General overviews of the performance of structures subjected to fault rupturing can be found in Chang et al. (2000), Tsai et al. (2000), Kelson et al. (2001), Uzarski and Arnold (2001), Dong et al. (2003).

3 Surface faulting at Mount Etna

Mount Etna in Sicily, Italy is a remarkably active volcanic zone, densely populated in its lower part. The eastern slope of the volcano is prone to sliding towards the sea, due to a combination of tectonic stressing and gravity-induced instability e.g. (Neri et al. 1991; Lo Giudice and Rasà 1992; McGuire et al. 1996). The faults that control the seismicity of the area are small-scale surficial structures, that accommodate the down-slope displacement of the eastern side of the volcano (Azzaro et al. 1998) and, as a result, are characterised by large slip rates (Stewart et al. 1993). Earthquakes occur quite frequently, albeit of moderate magnitude: among the largest magnitudes observed in the last several decades was M_d 4.9, in a 1952 event on the Santa Tecla fault (Azzaro 1999), shown in Fig. 3. However, due to the special features of these seismically active faults, the earthquakes in question occur at shallow focal depths (less than 2 km), causing substantial damage: MMI close to the epicentre may reach VIII, or even IX (Lo Giudice and Rasà 1992; Azzaro 1999).

The Pernicana fault (Fig. 3), on the north-eastern slope of the volcano, is one of the main tectonic structures of the area, and has been thoroughly investigated. With a total length of some 11 km and oriented East–West, this left-lateral strike-slip fault forms the northern boundary of the unstable sector of the volcano (Azzaro et al. 1998). It is characterised by remarkably high slip rates, estimated to be in the order of 2 cm/yr (Rasà et al. 1996). After a small magnitude earthquake with M_d 3.3 (December 1985), Luongo et al. (1986) conducted precise leveling measurements and measured a ground offset of about 10 cm. Astonishingly, this small earthquake was also responsible for the collapse of a hotel building (Azzaro et al. 1998). Surface slippage along this fault is mainly co-seismic along its western and central segments, but occurs in the form of "aseismic" creep on its eastern segment. For this reason, Mount Etna can be considered as a natural laboratory of outmost interest for studying the effects of surface faulting on structures, even in the absence of large seismic events. A general overview of such faulting effects on buildings, bridges, tunnels, and roads can be found in Azzaro et al. (1998).

4 Case histories of fault–foundation interaction

For the purpose of gaining deeper insights on the factors controlling the performance of structures subjected to faulting-induced deformation, we have documented and comparatively assessed a number of selected case-histories. We did not intend to provide a complete and accurate documentation of these case-histories. Our aim was, rather, to classify different case-histories from different sites, so as to highlight common behavioural characteristics and to strengthen the validity of the derived general conclusions. The four earthquake sites (Kocaeli, Düzce, Taiwan, and Mount Etna) investigated herein provide an ideal basis for such a generalisation, because: (a) all faulting mechanisms (normal, thrust, and strike-slip) are represented; (b) both co-seismic (Kocaeli, Düzce, and Taiwan) and aseismic-creep (Mount Etna) fault offsets are investigated; and (c) a variety of building styles and types are covered (Turkey, Taiwan, and Italy). A subset of these case histories is analysed numerically, using the methods described in a companion paper (Anastasopoulos et al. 2007a).

The case histories are grouped in three categories: (i) structures on rigid and continuous (raft) foundation; (ii) structures on flexible foundation, and (iii) structures on discrete supports. As it will be shown in the sequel, the cases with similar foundation systems tend to exhibit similar performance, irrespective of the type of faulting. Naturally, the conclusions derived herein are mostly qualitative. The quantitative aspects of the problem are

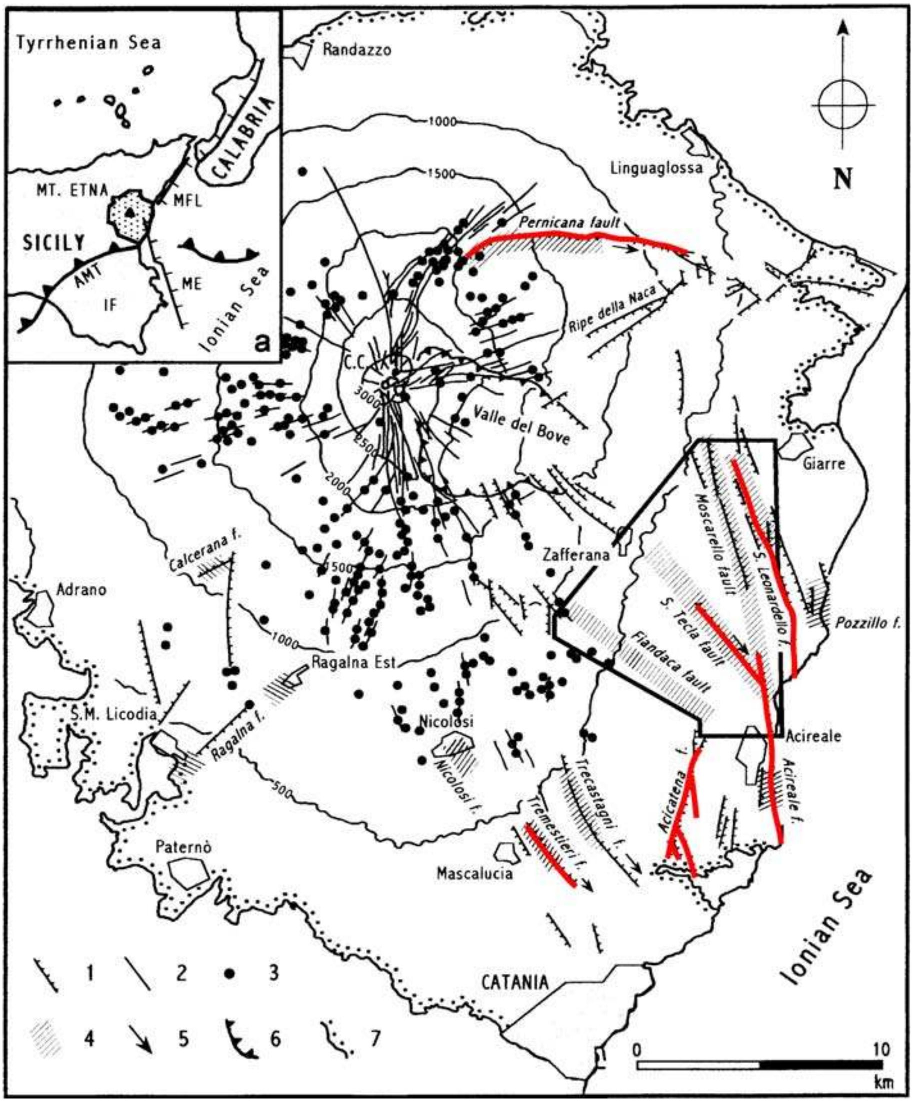

Fig. 3 Simplified structural map of Mt. Etna with the surface fault traces. The faults in the area of interest are indicated with the red lines. The Pernicana fault, discussed later, is near the top of the figure. After (Rasà et al. 1996; Azzaro 1999)

more complex, requiring detailed knowledge of the characteristics of the structure and the foundation soil.

4.1 Structures on rigid and continuous foundation

Among several structures that have been affected by surface fault ruptures of the Pernicana fault (Mount Etna), a 1-storey building in Roccacampana, on the eastern fault segment, is selected as a representative case-history of fault-foundation interaction. As depicted in Fig. 4, the building is a modern mixed reinforced concrete and masonry structure, lying on

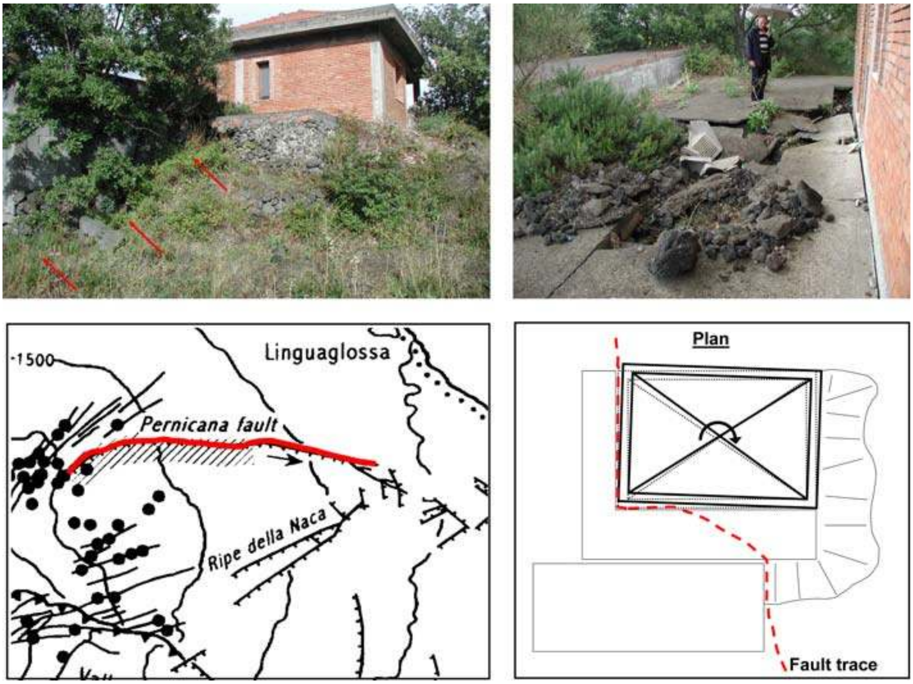

Fig. 4 Mt. Etna—Pernicana strike-slip fault: 1-story building resting on a rigid raft foundation. The continuity and stiffness of the foundation forced the surface fault rupture to divert away from the structure, leaving it almost completely unscathed, but with some rigid-body torsion around its vertical axis

a rigid and continuous raft foundation with reinforcing ring beams at the perimeter. During an earthquake sequence that lasted from 1981 to 1988, the structure was crossed by the surface trace of the strike-slip Pernicana fault almost diagonally. But the greatest amount of the imposed deformation was most likely caused by continuous "aseismic" creep over the years. Interestingly, the fault rupture did not cause significant structural damage to this modern but modest structure. In fact, the continuity and stiffness of its foundation (mainly provided by RC ring beams as shown in Fig. 5), seems to have forced the surface fault rupture to divert, leaving the building largely unscathed, but causing visible rigid-body torsion around its vertical axis. Severe non-structural damage, in the form of cracking of partition walls, occurred at a lower level on the side of the building opposite to that shown in Fig. 4. The similarities with Banco Central de Nicaragua (Duncan and Lefebvre 1973) are notable, despite the differences in the foundation system (slab, instead of a vault).

To shed more light on the performance of this structure, a 3-D numerical simulation of the soil–structure system was conducted. The analysis was conducted using the open-source FE code Tochnog (http://tochnog.sourceforge.net). A Mohr-Coulomb constitutive soil model was adopted as a first practical approximation, calibrated as described in Anastasopoulos et al. (2007a). As illustrated in Fig. 6, the FE model is 80 m × 80 m in plan, and 25 m in height, consisting of 5120 hexahedral elements. The 1-storey structure, modeled with beam elements, was placed at the centre of the soil model. The analysis was conducted in two steps. In a first step, the geostatic stresses were imposed. Then, the fault displacement was applied to soil elements quasi-statically, in small consecutive steps. Although this analysis was rather simple, the results can be seen to be in qualitative agreement with field observations: the fault rupture is diverted due to the rigidity of the foundation, and the structure is subjected to

Fig. 5 Mt. Etna—1-story building of Fig. 4. Detail of the reinforced concrete ring beam around the raft foundation

clockwise rigid-body torsion around its vertical axis (Fig. 6). Both the simulation results and the field observations are in qualitative agreement with the work of Berrill (1983), who studied analytically the behaviour of buildings on continuous–rigid shallow foundations, subjected to strike-slip faulting.

As already said, during the 1999 Chi–Chi earthquake in Taiwan a great variety of structures were crossed by the Chelungpu thrust fault. Among several other rural areas, the fault passed through Fung-Yan City in Chung-Cheng Park (see Fig. 2). Although several buildings were severely damaged or even collapsed, there were some cases of exceptional performance (see also Dong et al. 2003). One such case is the 4-storey reinforced concrete building of Fig. 7 (photos adapted from Hwang 2000). This structure survived almost 4 m of upthrust, without substantial structural damage (given the circumstances). As in the case of the 1-story building of Roccacampana, due to the rigidity and continuity of its foundation system, the building underwent a rigid-body rotation (with respect to its horizontal axis, this time) of approximately 10°, without suffering much distortion.

A 2-D plane-strain FE analysis has been conducted, making use of the FE code (ABAQUS 2004). An elastoplastic constitutive model with Mohr-Coulomb failure criterion and isotropic strain softening was adopted and encoded in ABAQUS (Anastasopoulos 2005). Strain–softening was introduced by reducing the mobilised friction angle φ_{mob} and the mobilised dilation angle ψ_{mob} with the increase of plastic octahedral shear strain (Anastasopoulos et al. 2007a). More details on the calibration of the constitutive model and the validation of the FE methodology can be found in Anastasopoulos et al. (2007b,c). A bedrock offset of vertical amplitude $h = 4$ m was imposed in the numerical model at the base of an idealised dense sand soil deposit of thickness $H = 20$ m. The latter was selected based on the results

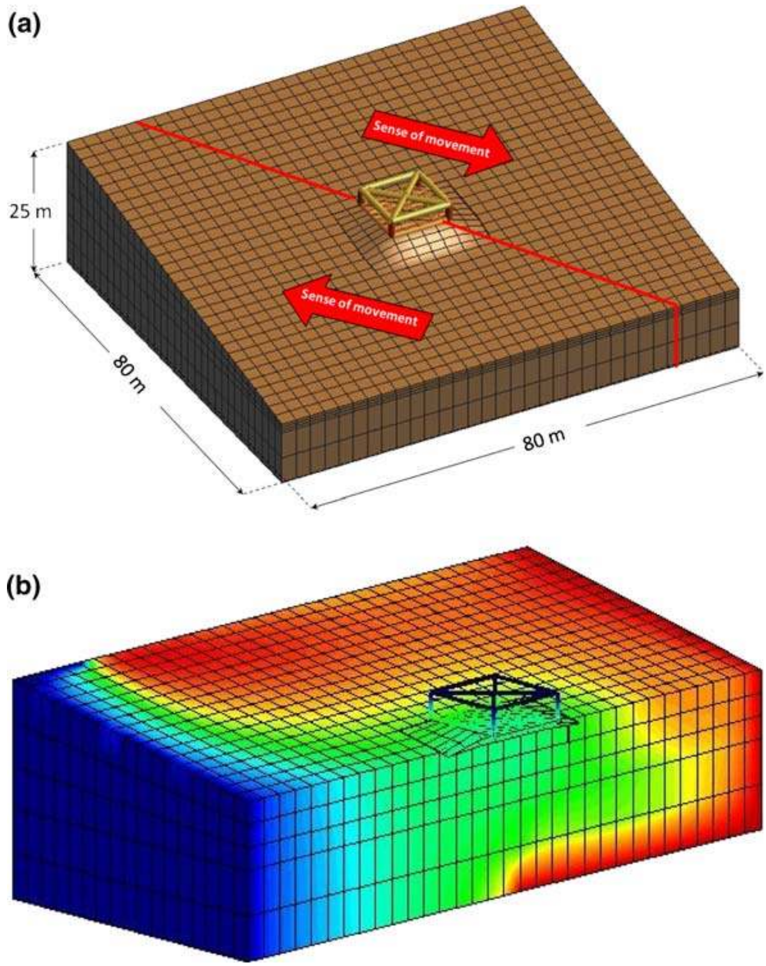

Fig. 6 Mt. Etna—Pernicana strike-slip fault—3-D finite element analysis of the 1-story building of Fig. 4: **a** 3-D mesh layout, and **b** horizontal displacement contours. Due to the rigidity of the foundation, the fault rupture is diverted, with the structure being subjected to rigid-body rotation. Analysis results can be seen to be in qualitative agreement with field observations

of seismic refraction measurements (Dong et al. 2003). While the idealised superstructure was simulated with beam elements, the soil–foundation interface was modelled with special gap elements, allowing for detachment and slippage. As illustrated in Fig. 8, the 4-story model experienced a rigid-body rotation of 9.2° (compared to the 10° observed in reality), without excessive stressing: the maximum bending moment M_{max} in the superstructure did not exceed 458 kN m. The vertical displacement Δy of the ground surface clearly indicates that the building rotates as a rigid body (tilting without significant distortion): region AB in Fig. 8 is of constant inclination. The numerical results are in good agreement with field observations.

As described in Sect. 2, due to the step-over mechanism (see Fig. 1b) a 4 km NW–SE normal fault rupture occurred E of Gölcük during the 1999 Kocaeli earthquake, crossing the little community of Denizevler. A detailed documentation, discussion, and analysis of the case-histories of Denizevler can be found in Anastasopoulos and Gazetas (2007a,b). Figure 9

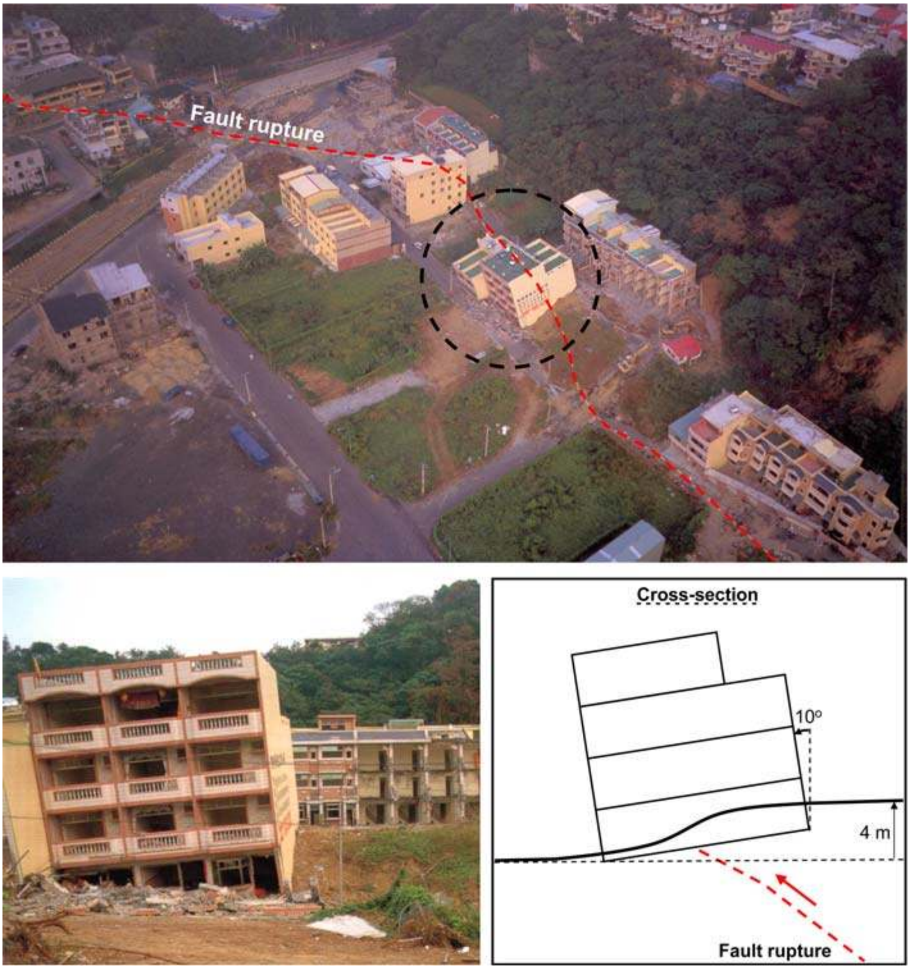

Fig. 7 Chelungpu thrust fault, Chi–Chi, Taiwan 1999 earthquake—Chung-Cheng Park, Fung-Yan City: 4-story building resting on a continuous and rigid foundation (photos adapted from Hwang 2000). The building survived 4 m of upthrust without substantial structural damage, but subjected to approximately 10° of rigid-body rotation

illustrates the main features of one such example, i. e. a 4-storey building with basement, resting on a continuous rigid box-type foundation. This building survived 2.3 m of downward displacement without any visible damage and, moreover, it effectively diverted the surface rupture.

The same method was applied to analyse this case-history: a bedrock offset of vertical amplitude $h = 2$ m was imposed on an idealised soil deposit of thickness $H = 40$ m. As described in (Anastasopoulos and Gazetas 2007b, the thickness of the soil deposit was estimated based on microtremor measurements by Arai et al. (2000). As illustrated in Fig. 10, the rupture path is clearly diverted towards the footwall as it approaches the ground surface. The building is subjected to some rigid-body rotation resulting in a differential settlement $Dy = 59$ cm, without being distressed: $M_{max} = 86$ kN m. As in the two previous cases, the rigid and continuous foundation is responsible for this favorable response. The analysis compares well with field observations, except that in reality the rotation was less conspicuous.

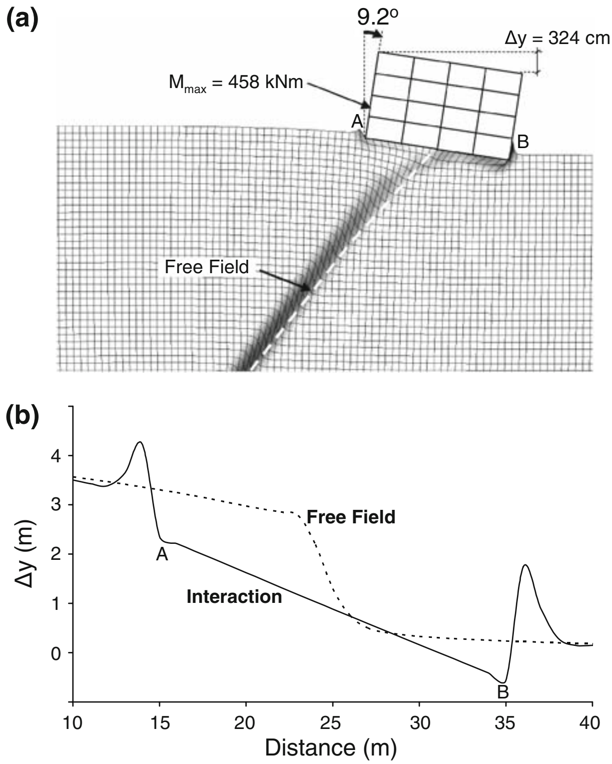

Fig. 8 Chelungpu thrust fault, Chi–Chi, Taiwan 1999 earthquake—Chung-Cheng Park, Fung-Yan City—s2-D finite element analysis of the 4-story building of Fig. 6 ($h = 4$ m): **a** Deformed mesh and plastic strain, **b** Vertical displacement Δy at the ground surface. The structure is subjected to rigid-body rotation, without excessive stressing. Analysis results can be seen to be in qualitative agreement with field observations

This discrepancy may stem from the plane strain simplification of our analysis: the actual fault rupture crossed the corner of the building.

Figure 11 (photo adapted from Hwang 2000) depicts one final example from the Chi–Chi 1999 earthquake in Taiwan. It refers to a high-voltage electric line pylon in Min-Chien City (see Fig. 2b). The Chelungpu thrust fault crossed this pylon almost perpendicularly, imposing an upthrust of about 4 m. Quite interestingly, due to its rigid caisson foundation, the pylon survived the dislocation without any visible structural damage, although it underwent substantial rigid-body rotation of approximately 18°. This case-history is believed to be of particular significance, proving beyond doubt the beneficial role of such foundation systems. In the previous cases, one might conceivably have argued that the rigidity of the superstructure may have played an equally important role. However, in this case the superstructure is definitely quite flexible, and the survival of the structure can be attributed solely to its foundation.

4.2 Structures on flexible foundation

In the previous Section, the satisfactory performance of structures resting on rigid and continuous foundation was demonstrated through a variety of case-histories from different earthquake sites. To further highlight the importance of the rigidity and continuity of the

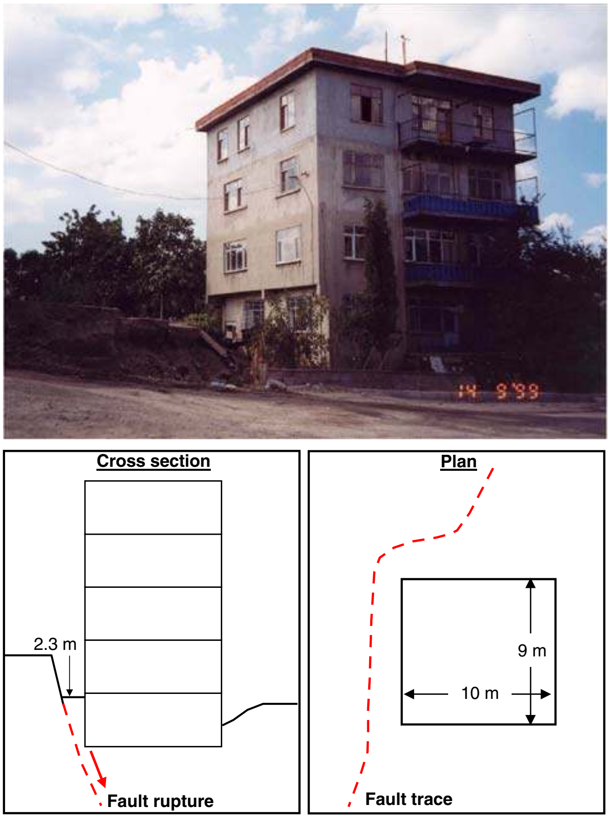

Fig. 9 Normal fault east of Gölcük, Kocaeli, Turkey 1999 earthquake—Denizevler: 4-story building with basement resting on continuous and rigid box-type foundation. The building survived 2.3 m of downward displacement without any visible damage. Moreover, the surface rupture was diverted away from the building

foundation, this section presents a selection of case histories of structures resting on flexible foundation systems.

Figure 12 (photos adapted from Hwang 2000) illustrates a first such example from the Chi–Chi 1999 earthquake. It refers to a 4-storey reinforced concrete building in Fung-Yan City (see Fig. 2), the corner of which was crossed by the Chelungpu thrust fault. Subjected to 6 m of upthrust, this building barely survived the imposed deformation, having experienced substantial structural damage. Apparently, its relatively flexible foundation system did not manage to convert all of the differential displacement to rigid-body rotation. The latter ranged from approximately 7° close to the corner that was crossed by the rupture (section b-b in Fig. 12), to about 4° at the other end (section a-a). This indicates that the building did not only rotate with respect to horizontal axis, but was also subject to some torsion. Had the foundation been stiffer, the rotations at the two edges should have been almost the same.

Another example from the same earthquake is given in Fig. 13 (photos adapted from Hwang 2000): a 5-storey building of the Tze-Min Commerce and Technical College in Wu-Fung Hsiang (see Fig. 2). This reinforced concrete building was crossed by the Chelungpu fault, was subjected to 3 m of upthrust. Resting on a relatively flexible foundation, this structure survived the earthquake but with heavy structural damage. Observe that there was practically no rigid-body rotation: the structure essentially followed the imposed ground

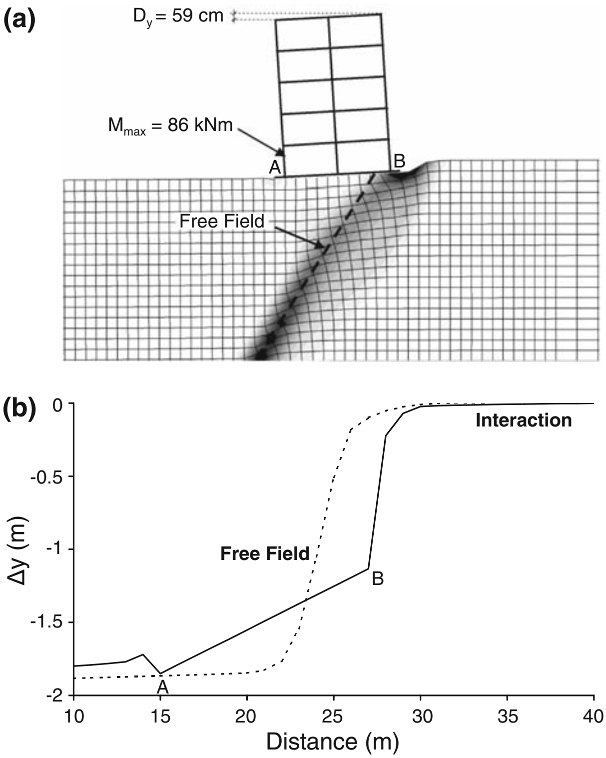

Fig. 10 Normal fault east of Gölcük, Kocaeli, Turkey 1999 earthquake—Denizevler—2-D finite element analysis of the 5-story building of Fig. 9 ($h = 2$ m): **a** Deformed mesh and plastic strain, **b** Vertical displacement Δy at the ground surface. Due to the rigidity and continuity of the box-type foundation, the fault rupture is diverted towards the footwall; the structure is only subjected to limited rigid-body rotation, without significant stressing. Analysis results are in qualitative agreement with field observations

deformation profile. Compared to the previous case (Fig. 12), a noticeable difference is that this building was crossed perpendicularly to its large plan dimension. This difference in the geometry of crossing is quite crucial: the same foundation behaves much more flexibly when subjected to bending along its larger plan dimension.

Figure 14 (photos adapted from Hwang 2000) depicts a 3-storey building in Fung-Yan City, Chung-Cheng Park (see Fig. 2). This building was also intersected by the Chelungpu fault perpendicularly to its larger dimension. Subjected to about 4 m of upthrust, the first floor of the building "pancake" collapsed. Evidently, the flexible foundation did not offer any significant bending resistance: the imposed ground deformation was practically transmitted unaltered to the superstructure, leading unavoidably to the observed collapse.

Two examples from Denizevler (Kocaeli 1999 earthquake) are illustrated in Fig. 15: (a) a Mosque resting on isolated footings (definitely a flexible foundation), and (b) a modest 1-storey cinder-block building (photo adapted from Youd et al. 2000) directly founded on the ground (an extremely flexible foundation). Both buildings were crossed by the normal fault rupture close to their corners. Subjected to about 1.5 m of differential displacement, the two structures partially collapsed, and were later demolished. As in the previous case (Chi–Chi), the differential displacements were transferred to the superstructures practically unaltered. In stark contrast to the previous case, the intensity of ground shaking is not believed to have played a major role here: the minaret of the mosque did not collapse.

The previously discussed method was applied for the analysis of the Mosque. A bedrock offset of vertical amplitude $h = 2$ m was imposed at the base of a soil deposit of thickness $H = 40$ m. As illustrated in Fig. 16, the rupture path was not substantially affected by the structure. Most of the deformation is found to occur between the isolated footings of

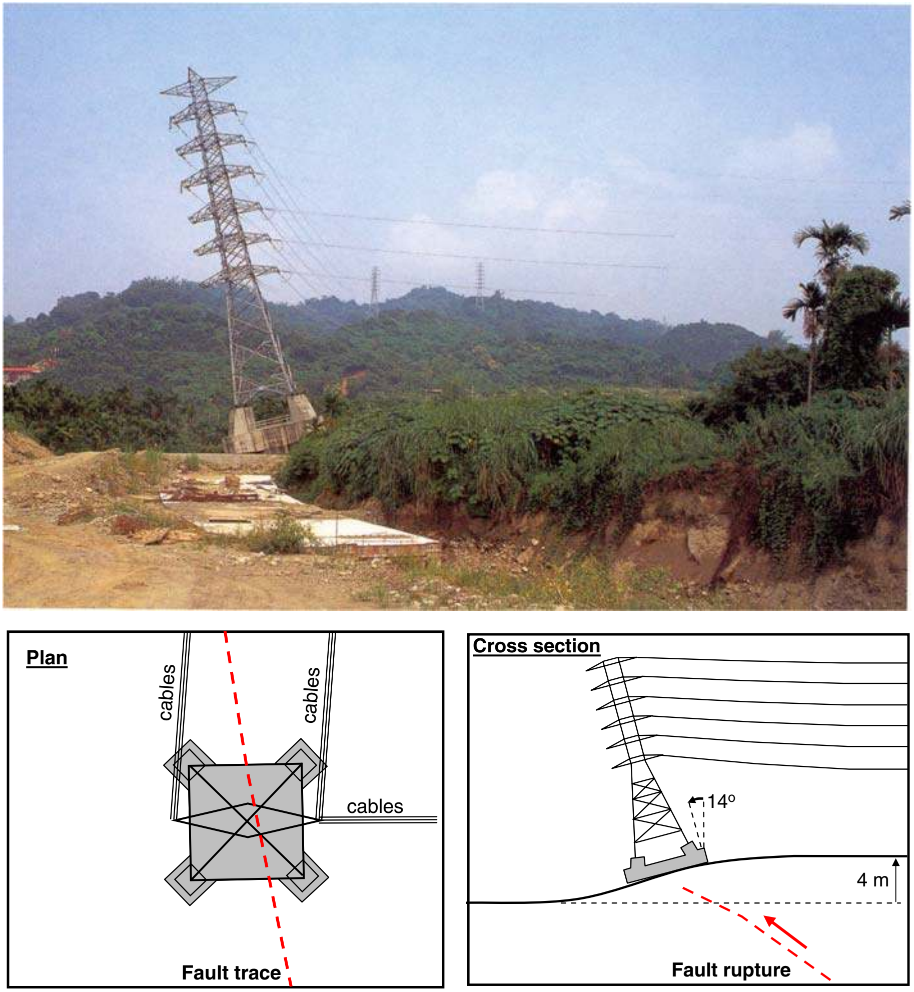

Fig. 11 Chelungpu thrust fault, Chi–Chi, Taiwan 1999 earthquake—Min-Chien City: Highvoltage electricity pylon resting on a continuous and rigid foundation (photo adapted from Hwang 2000). The pylon survived 4 m of upthrust without any visible structural damage, but subjected to approximately 14° of rigid-body rotation

the Mosque, in the form of a diffuse failure zone, causing the structure to tilt towards the hanging wall with a differential settlement $Dy = 1.4$ m. However, not all of the imposed deformation is converted to rigid-body rotation, and the Mosque was substantially distressed (computed $M_{max} = 945$ kN m). In general, the results of this analysis are in agreement with the observed performance.

A final example from the Chi–Chi 1999 earthquake is the failure of the Shih-Kang Dam. As illustrated in Fig. 17 (photos adapted from Hwang 2000), the Chelungpu fault passed through Fung-Yan City (see also Fig. 2b). With about 7 m of upthrust, the fault rupture caused complete collapse of one building (the details of which are unknown to us), substantial damage to three other buildings (shown in detail in Fig. 9), partial collapse of a light 1-storey structure, collapse of two spans of the Bei-Fung Bridge, and the failure of the Shih-Kang concrete gravity dam. As shown in Fig. 18, the fault rupture crossed the northern part of the dam with an upthrust of about 9 m, destroying its spillways and gates. Due to its length of about 700 m

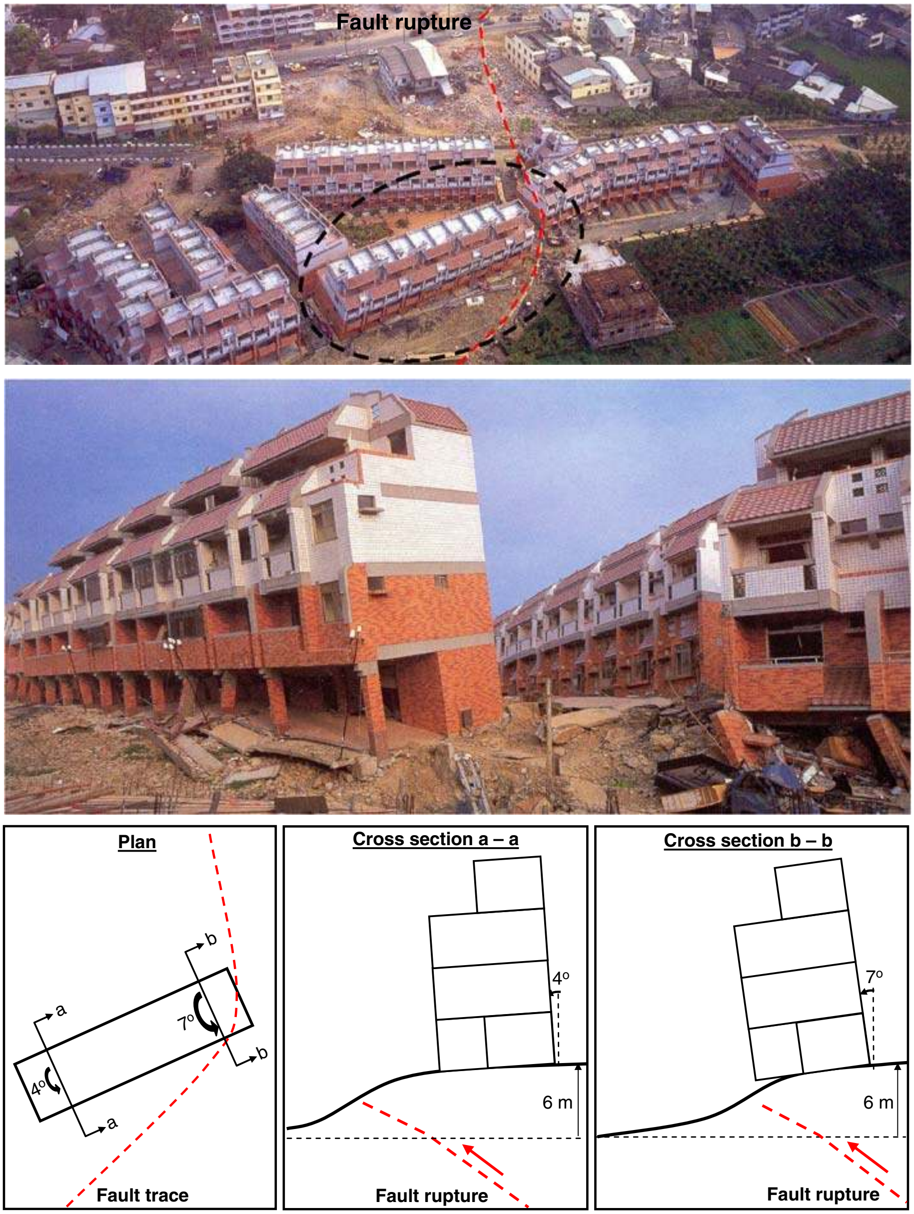

Fig. 12 Chelungpu thrust fault, Chi–Chi, Taiwan 1999 earthquake—Fung-Yan City: 4-story building resting on a relatively flexible foundation (photos adapted from Hwang 2000). The building survived 6 m of upthrust but with substantial structural damage. The rigid-body rotation ranged from 4° to 7°

(Chen-Shan et al. 2001; Sugimura et al. 2001), the dam seems to have behaved as a structure on flexible foundation and, as in the previous examples, practically followed the imposed deformation, sustaining substantial structural damage. Despite the obvious differences with the previous case-histories (the superstructure of this dam is certainly different from that of a building), from a behavioral point-of-view the response is rather similar.

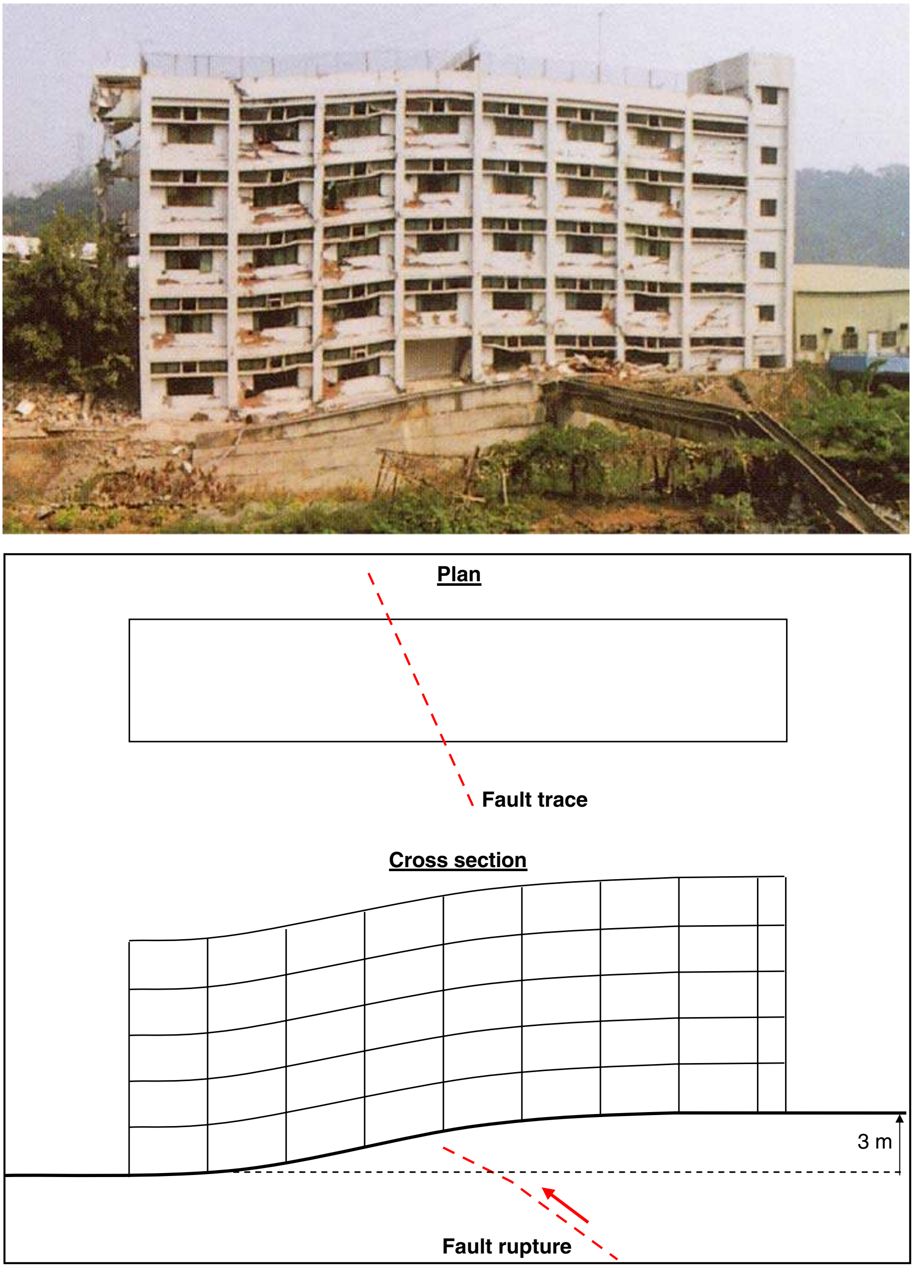

Fig. 13 Chelungpu thrust fault, Chi–Chi, Taiwan 1999 earthquake—Wu-Fung Hsiang, Tze-Min Commerce and Technical College: 5-story building resting on a relatively flexible foundation. The building survived about 3 m of upthrust, but with substantial structural damage

4.3 Structures on discrete supports

One of the main differences between buildings and bridges is that the latter are typically founded on discrete supports and, consequently, one would expect their response to be

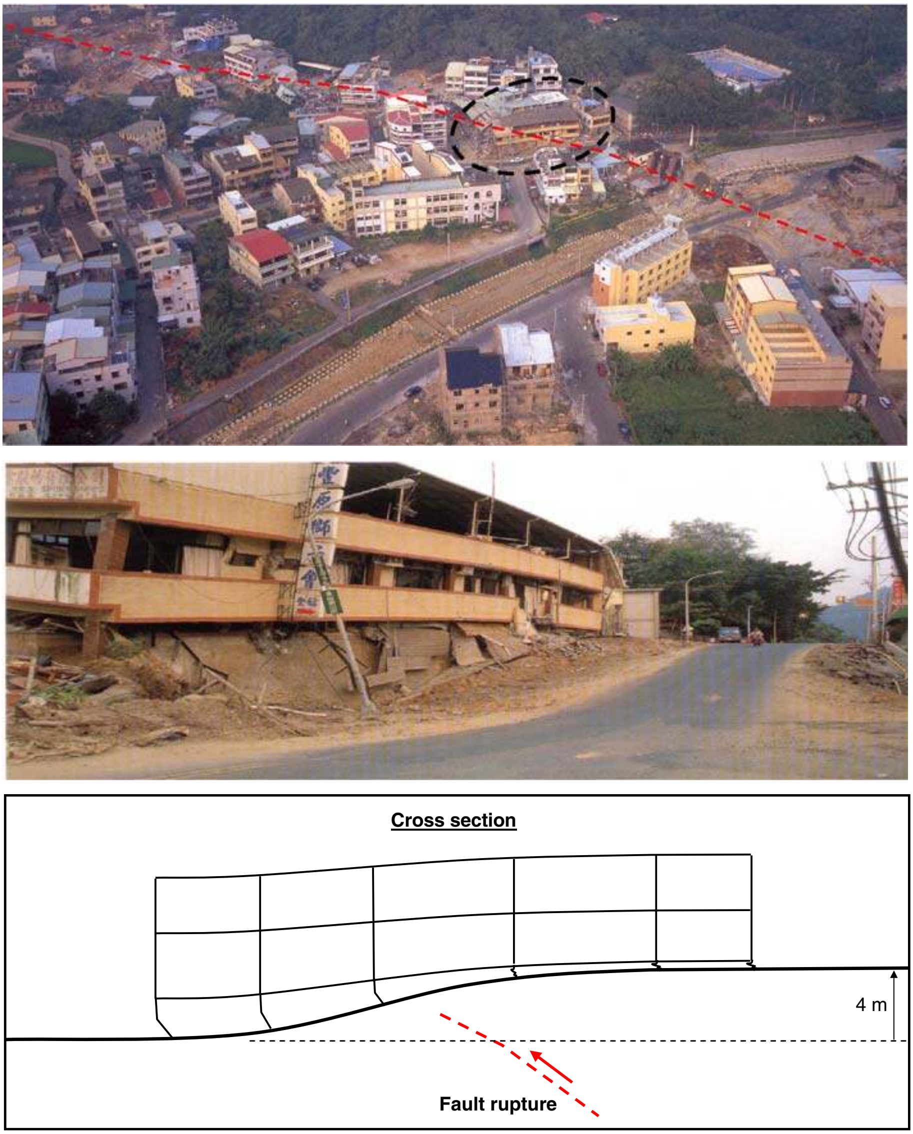

Fig. 14 Chelungpu thrust fault, Chi–Chi, Taiwan 1999 earthquake—Chung-Cheng Park, Fung-Yan City: 3-story building resting on flexible foundation (photos adapted from Hwang 2000). Subjected to 4 m of upthrust, the first floor of the building partially collapsed

substantially different from that of buildings. To illustrate the differences, this section provides two examples of seismic response of bridges from the earthquakes of Chi–Chi and Düzce.

The first example from the Chi–Chi 1999 earthquake refers to the Bei-Fung bridge, in Fung-Yan City (see also Figs. 2b, 17). As illustrated in Fig. 19 (photos adapted from Hwang 2000), the Chelungpu thrust fault crossed the south abutment of the Bei-Fung bridge with an upthrust of about 7 m. The deck of the bridge consisted of four pre-stressed concrete simply supported beams, with a reinforced concrete continuous slab on top. In addition to the

Fig. 15 Normal fault east of Gölcük, Kocaeli, Turkey 1999 earthquake—Denizevler: **a** Mosque resting on flexible foundation (isolated footings), and **b** 1-story cinder-block building (photo from Youd et al. 2000), directly founded on the ground (very flexible foundation). Both buildings were subjected to about 1.5 m differential displacement and partially collapsed

development of a small but impressive waterfall, the result of the faulting-induced deformation was the collapse of two spans of the bridge. It is evident that the differential displacement between the discrete supports (piers) of the structure (deck), was larger than the available seating. In fact, the same performance was also observed in similar bridges, such as the Shi-Wei bridge (Pamuk et al. 2005). Had the deck been continuous, it would still have collapsed, but not due to un-seating: the differential displacement would have generated dramatically large bending moments in the bridge deck.

Figure 20 shows the Kaynasli Viaduct of the Trans-European Motorway in Turkey. During the Düzce-Bolu 1999 earthquake, the seismically-isolated Viaduct was crossed by the North Anatolian fault and was subjected to a strike-slip offset of the order of 1.5 m. The Viaduct consisted of two separate decks, of 58 and 59 spans. With an average span of 40 m, the bridge was about 2.3 km in total length, and was supported on 10 m to 49 m high piers, founded on pile-groups consisting of 12 piles 1.8 m in diameter. Each deck consisted of seven pre-stressed concrete beams, connected together with a reinforced concrete slab on top. The decks were supported through pot bearings, with a capacity for multi-directional sliding. Joints were installed every 10 spans, to provide temperature deformation relief. At each joint, special energy dissipating units, viscous dampers, and stoppers were installed

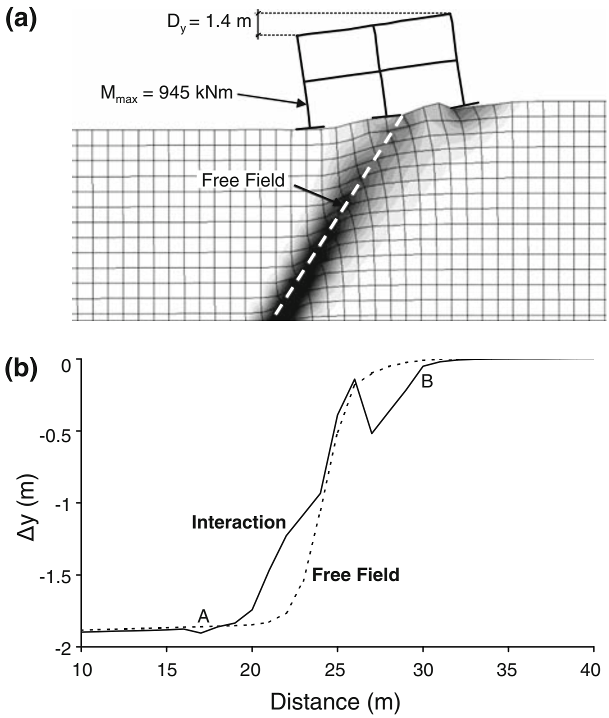

Fig. 16 Normal fault east of Gölcük, Kocaeli, Turkey 1999 earthquake—Denizevler—2-D finite element analysis of the Mosque, Fig. 14a ($h = 2$ m): **a** Deformed mesh and plastic strain, **b** Vertical displacement Δy at the ground surface. Due to the discontinuity and flexibility of its foundation, the superstructure of is subjected to excessive stressing, in accord with the observed performance

(Kawashima 2001). As illustrated in Fig. 20, the faulting-induced deformation was responsible for the development of substantial horizontal displacements and rotations of the piers (i.e., the discrete supports). The seismically-isolated deck experienced 1.2 m of differential displacement, barely avoiding collapse thanks to the restraint provided by the stoppers.

5 Conclusions

We have documented, analysed, and comparatively assessed selected case-histories of fault–foundation interaction from four different earthquake sites (Kocaeli, Düzce, Taiwan, and Mount Etna). To derive conclusions of general significance, different case-histories belonging to different sites were classified from a structural response point-of-view. The main conclusions of this study are as follows:

(1) The foundation system plays a key role in the response of structures subjected to faulting-induced ground deformation. Depending on the relative stiffness of the foundation, the superstructure will either rotate as a rigid-body without being substantially distressed, or will follow the faulting-induced deformation profile of the ground surface, usually sustaining substantial structural damage.
(2) Structures resting on rigid and continuous foundation systems (such as a raft, or a box-type foundation) demonstrated to be capable of achieving a very satisfactory performance, irrespective of the faulting type (normal, thrust, or strike-slip). When intersected by a surface rupturing fault, such structures undergo rigid-body rotation, without

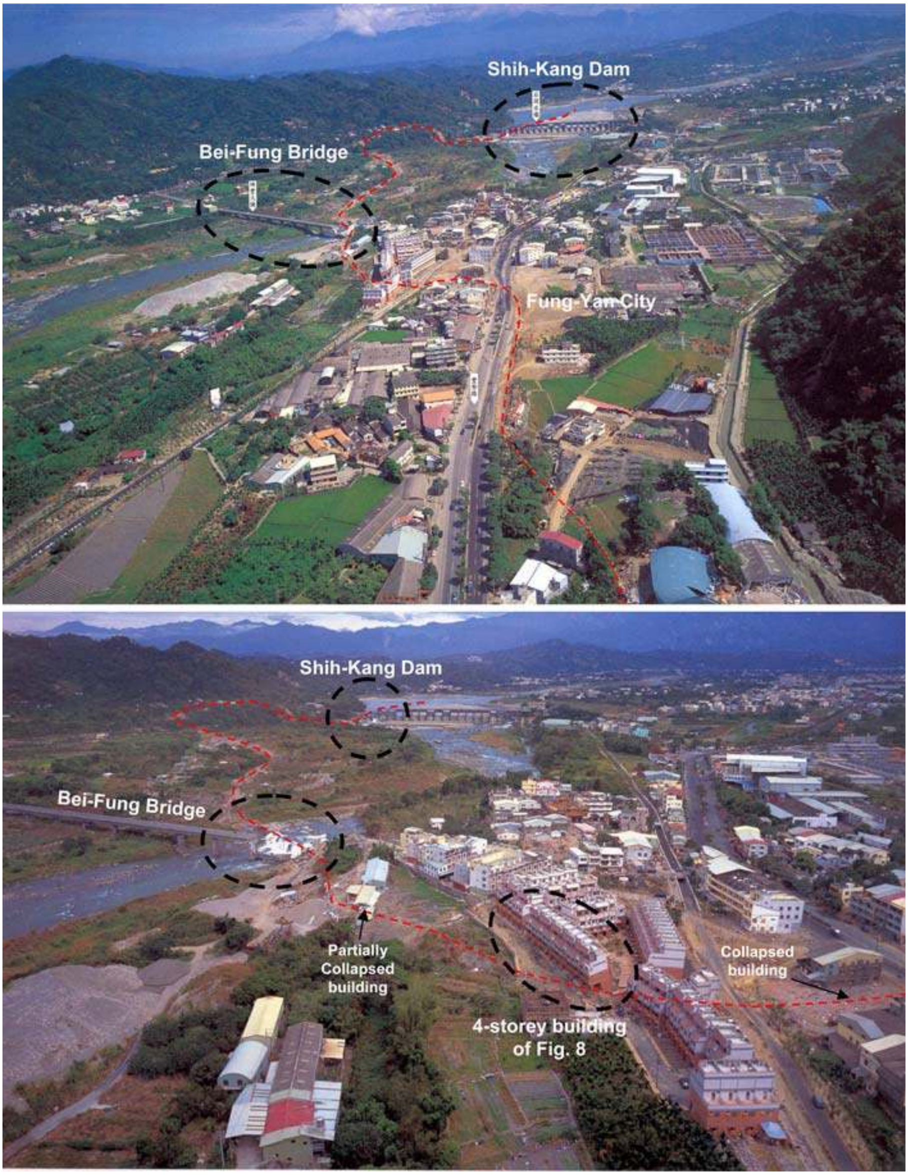

Fig. 17 Chelungpu thrust fault, Chi–Chi, Taiwan 1999 earthquake—Fung-Yan City. From bottomright to top-left: The fault rupture, of about 7 m of upthrust, passed through Fung-Yan City causing complete collapse of one building (the details of which are not known), substantial damage to three other buildings (shown in detail in Fig. 8), partial collapse of a light 1-story structure, collapse of two spans of the Bei-Fung Bridge, and failure of the Shih-Kang Dam (photos adapted from Hwang 2000)

significant distortion. Such rigid-body rotation is about the horizontal axis in the case of dip-slip (normal or thrust) faulting, and about the vertical axis (torsion) in the case of strike-slip faulting. A heavy structure lying on a rigid and continuous foundation system may force the surface fault rupture to divert, and may compress the surface asperities, thus leading to smaller differential displacements.

Fig. 18 Chelungpu thrust fault, Chi–Chi, Taiwan 1999 earthquake—Shih-Kang Dam. The fault rupture passed through the northern part of the dam with an upthrust of about 8 m, destroying spillways and gates. Due to its length of 700 m, the dam behaved as a flexible structure, practically following the imposed deformation (photos adapted from Hwang 2000)

(3) Structures resting on flexible foundation systems tend to follow the faulting-induced deformation of the ground surface, being subjected to substantial stressing and structural damage. Such structures are susceptible to partial or full collapse when subjected to severe fault dislocations. The flexibility of the foundation is not only a function of its absolute stiffness, but also of the length of the structure: the same foundation may be

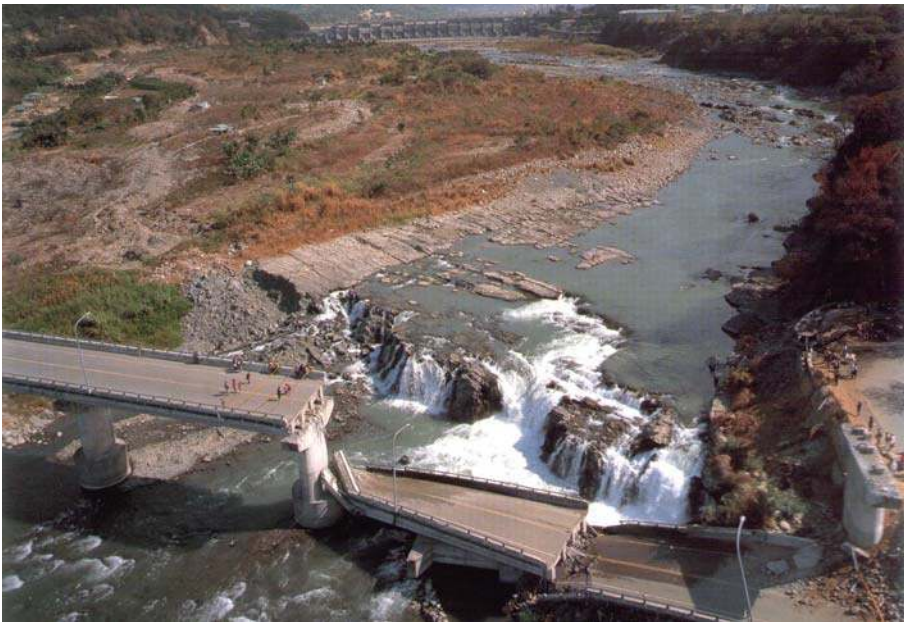

Fig. 19 Chelungpu thrust fault, Chi–Chi, Taiwan 1999 earthquake—Fung-Yan City. The fault rupture passed through the south abutment of the Bei-Fung bridge with an upthrust of about 7 m, causing the collapse of two spans and the development of a small, but impressive, waterfall (photos adapted from Hwang 2000)

stiff enough for a narrow building, but behave as flexible in a wide building. Moreover, the same structure may exhibit a totally different response, depending on the geometry of crossing.

(4) Structures, such as bridges, resting on discrete supports (piers) are practically forced to follow the imposed ground deformation. In such cases, and if the superstructure (deck) is simply supported, the main risk arises from the relative displacement between adjacent supports: if the seating of deck beams is not enough, one or more spans may collapse due to un-seating. With enough seating and adequate restraints, such as the stoppers in the Düzce-Bolu (Kaynasli) Viaduct, bridge structures can survive large dislocations.

(5) The conclusions derived herein are believed to be of rather general validity. The four earthquake sites (Kocaeli, Düzce, Taiwan, and Mount Etna) investigated herein provide the basis for this generalisation, because: (a) all faulting mechanisms (normal, thrust, and strike-slip) are adequately represented; (b) both co-seismic (Kocaeli, Düzce, and Taiwan) and aseismic-creep (Mount Etna) fault offsets are investigated; and (c) a variety of building styles and categories are adequately covered (Turkey, Taiwan, and Italy).

(6) Structures in the immediate vicinity of active faults proved to be capable of withstanding fault dislocations of several meters. The conclusions derived herein, in combination with the accompanying analytical studies (Anastasopoulos et al. 2007a) may form the basis for a proper design of structures against faulting.

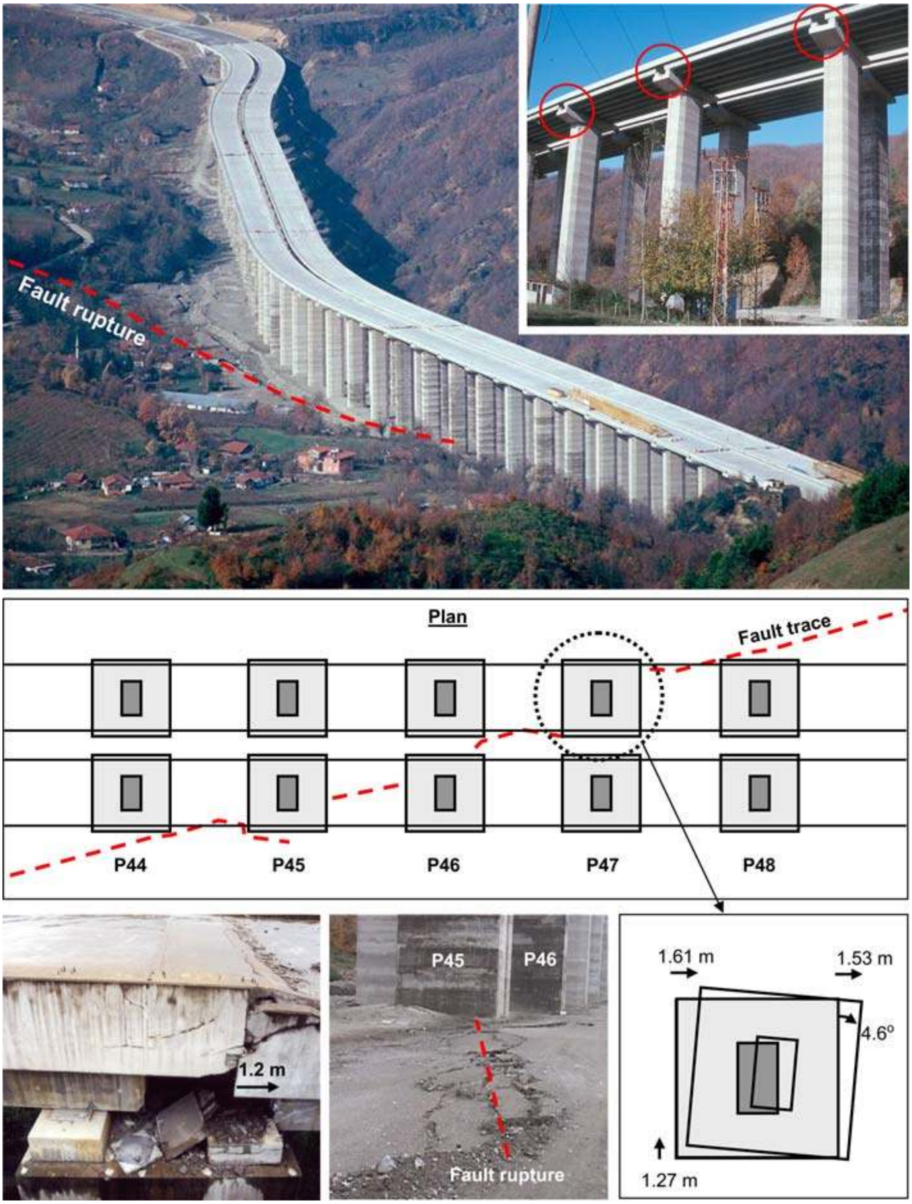

Fig. 20 The North-Anatolia strike-slip fault, Düzce, Turkey 1999 earthquake—Düzce-Bolu Viaduct: The fault rupture passed through the bridge generating substantial horizontal displacements and rotations of bridge piers. The seismic-isolated bridge deck was subjected to about 1.2 m of differential displacement, avoiding collapse at the last moment due to restrain provided by stoppers

Acknowledgements The cooperation by Andrea Masella, who performed the 3D FEM analysis of the Roccacampana case history in Fig. 6, is gratefully acknowledged. We also wish to express our gratitude to Raffaele Azzaro, invaluable field guide to the effects of fault rupture on the built environment in the Mt. Etna area.

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