Bull Earthquake Eng
DOI 10.1007/s10518-008-9082-5

ORIGINAL RESEARCH PAPER

Preliminary design recommendations for dip-slip fault–foundation interaction

G. Gazetas · A. Pecker · E. Faccioli · R. Paolucci · I. Anastasopoulos

Received: 26 November 2007 / Accepted: 14 July 2008

Abstract The article outlines the main findings and conclusions of the QUAKER research project and other related studies on the behaviour of foundations built on top of a rupturing dip-slip fault. Although emphasis is placed on normal faults, the derived conclusions are valid for reverse faults, as well. A key conclusion is that it is quite feasible to design a foundation to withstand an underneath rupturing fault. Practical design recommendations suitable for developing future Code requirements on the subject, are developed on the basis of the presented conclusions.

Keywords Fault rupture propagation · Soil–structure-interaction · Foundation design · Practical conclusions · Design recommendations

1 Introduction

Seismic codes and engineering practice had in the past invariably demanded that "*buildings of important classes . . . shall not be erected in the immediate vicinity of tectonic faults recognized as being seismically active*" (e.g.: EC8 1994). "Immediate vicinity" ranged in the various national codes from a few tens of meters to several hundred meters. However, such a strict prohibition is difficult (and sometimes meaningless) to obey for a number of reasons:

G. Gazetas (✉) · I. Anastasopoulos
National Technical University of Athens, Athens, Greece
e-mail: gazetas@ath.forthnet.gr

A. Pecker
Géodynamique et Structure, Bagneux, France

E. Faccioli
Studio Geotecnico Italiano, Milan, Italy

R. Paolucci
Politecnico di Milano, Milan, Italy

(a) It is difficult to reliably determine which faults are potentially *active* in the earthquake sense (i.e., are capable of generating a significant earthquake rupture). Even the definition of "active" is debatable.
(b) Along the ground surface, the "fault outcrop" neither is continuous, nor does it follow precisely pre-existing fault outcrops. Instead, faults follow planes of weakness within a rather broad shear zone. The presence of soil deposits further complicates the pattern of fault outcrop; the rupture path in the soil is not a simple extension of the base fault—phenomena such as "diffraction" and "bifurcation" change the direction of, and diffuse the rupture path. Secondary fault ruptures may occur outside a mapped fault zone. 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 examples of erratic and unpredictable path of a fault outcrop, see many sections of the Chelungpu fault rupture in the Chi-Chi 1999 earthquake in the companion paper (Faccioli et al. 2008).
(c) Large and spatially-extended structures (such as bridges, tunnels, pipelines, multiple-housing projects, embankments) cannot avoid crossing known (or unknown) seismically active faults.
(d) The hazard associated with a fault rupture reaching the ground surface has a low probability of occurrence in moderately seismic areas.

On the other hand, the Kocaeli and Düzce earthquakes revealed that several structures (simple buildings, bridges, pylons, bunkers) survived outcropping fault dislocations of the order of 2 m almost unscathed. In many of these cases, the surface rupture path deviated, and almost avoided rupturing directly underneath the structure. In other cases, however, the damage was substantial even though the fault rupture was "masked" by the near-surface soil and did not create a scarp. It became apparent that, in addition to the very important role of the depth and stiffness of the soil deposit under a particular structure, interplay takes place among the structure, the soil, and the propagating rupture. This interplay may be of critical importance for the performance of the structure.

All this motivated the joint research effort within the QUAKER project, aimed at clarifying the role of the soil–foundation–rupture interaction and developing proper design guidelines for building near suspected or actual active faults. Several papers in this issue of the journal have presented key findings of this research.

An integrated approach was followed in our research, comprising three interrelated steps: field studies, centrifugal experiments, and numerical/analytical modelling.

***Specifically*:**

- Field studies of documented case histories, which not only motivated our investigation but also offered material for calibration of the theoretical methods and analyses;
- carefully controlled centrifugal experiments helped in developing an improved understanding of the key mechanisms of the problem, and in acquiring a reliable experimental data base for validating the theoretical simulations; and
- theoretical methods (analytical or numerical), calibrated against the above field and experimental data, offered additional insight into the nature of the interaction, and were utilised in developing parametric results and design aids.

In the sequel we present a summary of our key conclusions and make some practical recommendations.

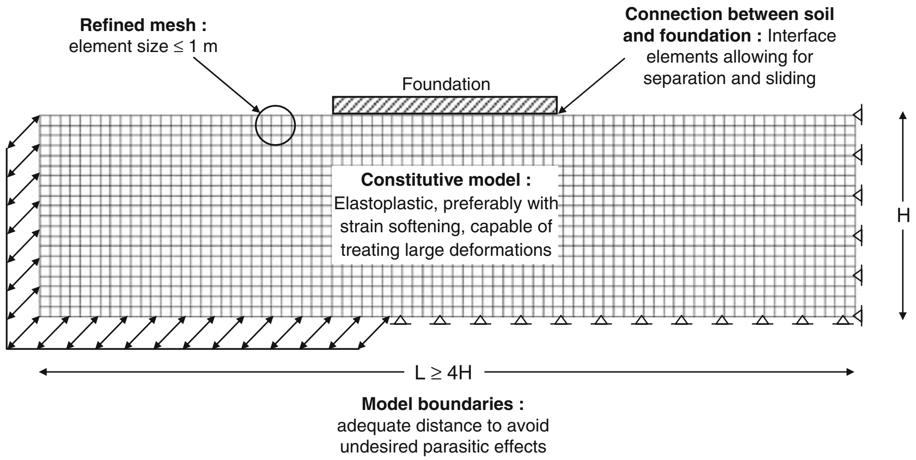

Fig. 1 Main prerequisites for successful numerical simulation of fault rupture propagation through soil, and its interaction with foundation–structure systems

2 Main conclusions of QUAKER and related studies

(a) The use of properly calibrated numerical methods of the complete system (soil, foundation, structure) under the action of a large imposed fault dislocation is indispensable. Such methods proved capable of explaining the observed behaviour (both successes and failures) of numerous structures in Turkey and Taiwan in the 1999 earthquakes, and led to reasonable interpretation of previously-published small-scale experimental results. Simple analytical approaches may also be desirable for estimating upper bounds of "safe" distances from a fault rupture.

(b) Several prerequisites for a successful numerical simulation were identified from a parametric investigation; they are illustrated in Fig. 1:

- the choice of a very refined mesh (element size of the order of 1 m or less), or a suitable slip-line tracing algorithm in the region of soil rupture and foundation loading;
- the consideration of a long region (total length L equal to four times the depth to rock H);
- the choice of a suitable elastoplastic constitutive model, such as a Mohr–Coulomb type model (preferably with strain softening), and being capable of treating large deformations;
- the use of suitable interface elements between foundation and soil, allowing for sliding and separation that may be caused by the emerging fault rupture.

(c) Centrifuge modelling of the propagation of a rupture through a soil deposit, and consequently of the interaction between the rupture and a rigid foundation on the ground surface on top of the emerging fault can be successfully accomplished.
The results of such modelling, performed at the University of Dundee (Bransby et al. 2008a, b), were in very good accord with genuine predictions using the numerical methodologies (Anastasopoulos et al. 2007, 2008a) for: (i) the diversion and bifurcation of the outcropping dislocation; (ii) the displacement profile at the ground surface;

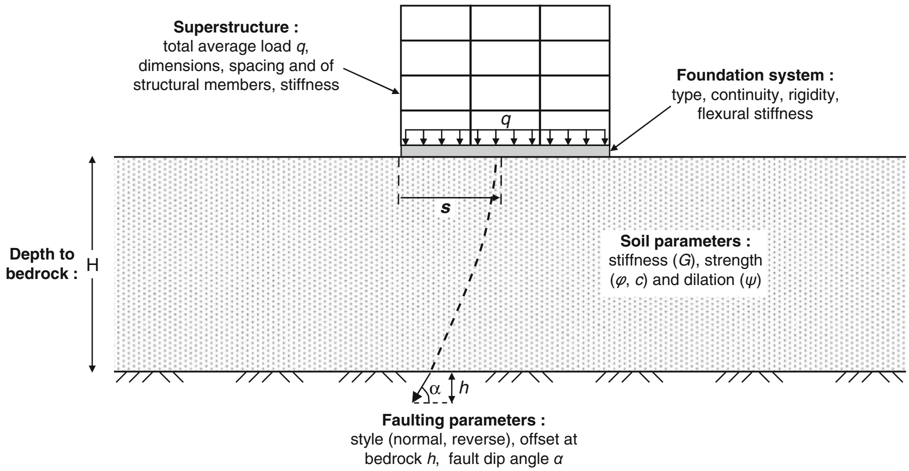

Fig. 2 The main factors influencing fault rupture–soil–foundation–structure interaction

and (iii) the rotation of the foundation. This gives confidence in the conclusions and recommendations of this study.

(d) The main factors influencing Fault Rupture–Soil–Foundation–Structure Interaction (FR-SFSI), as graphically outlined in Fig. 2, are:

- the style of faulting (normal, thrust, strike-slip), the angle of dip of the fault, and the offset (dislocation) at the basement rock;
- the total thickness (H) of the overlying soil deposit, the stiffness (G), the strength (φ, c) and dilation (ψ) characteristics of the soil along the depth;
- the type of the foundation system (for example, isolated footings, mat foundation, box-type foundation, piles, caissons);
- the flexural and axial rigidity of the foundation system (thickness of mat foundation, size and length of tie beams, etc.);
- the total load of the superstructure and the foundation;
- the (vertical) stiffness of the superstructure (number and dimensions of key structural members, spacing of columns, presence or not of shear walls, etc.);
- the distance ***s*** from the foundation corner to the free-field fault outcrop.

(e) The distress of the foundation stems to a large extent from the loss of support due to detachment of its base from the bearing soil. As schematically illustrated in Fig. 3, depending on the exact position of the foundation with respect to the outcropping fault rupture, loss of support may take place either at the two ends or at the middle. In the former case, the unsupported spans behave as cantilevers on a central elastic support (giving "hogging" deformation); in the latter case, as a single span on elastic end supports (giving "sagging" deformation).

(f) 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 perform 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.

(g) Even moderately reinforced buildings, may be capable of performing well as cantilevers, bridging locally-generated "gaps", if they are founded on rigid and continuous

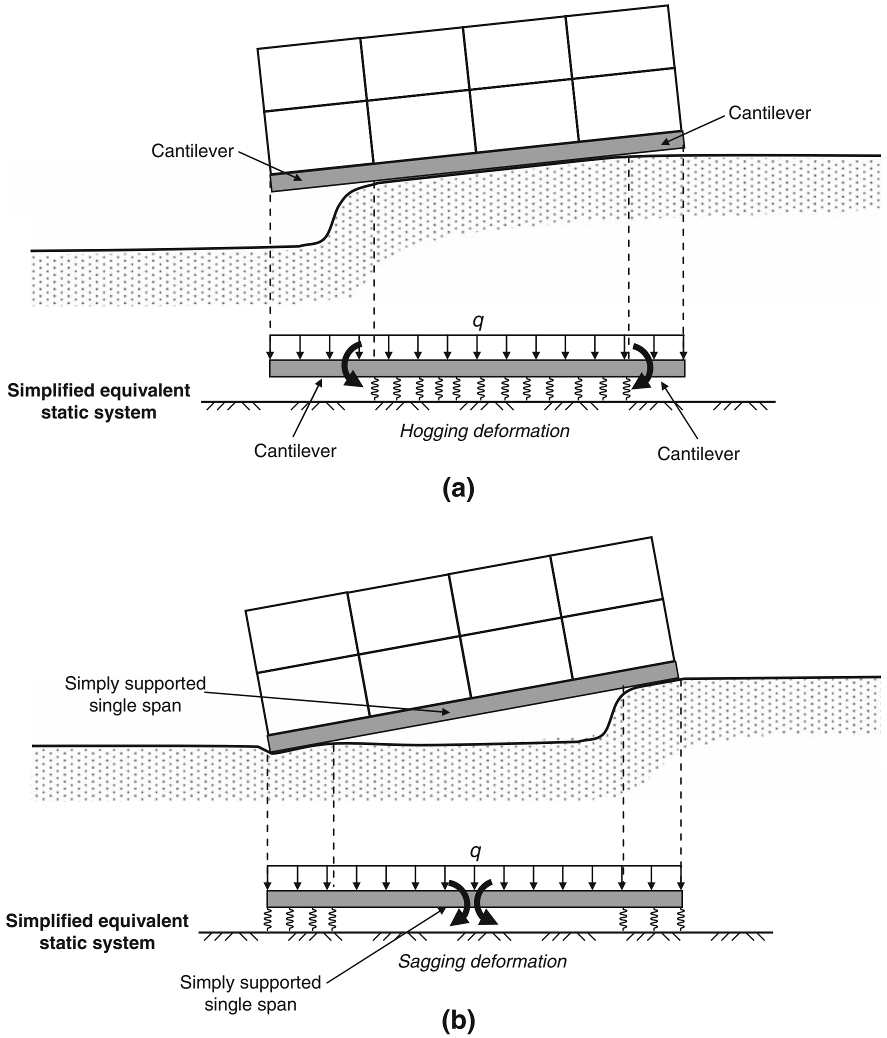

Fig. 3 Foundation distress arising from loss of support: depending on the position of the foundation relative to the outcropping fault rupture, loss of support may take place at either of the two ends (**a**) or at the middle (**b**)

foundation systems. Several simple buildings in the 1999 region of Denizevler, near Gölcük, offered real-world examples of such encouraging performance (Anastasopoulos and Gazetas 2007a, b; Faccioli et al. 2008).

(h) For each case, the total average pressure q transmitted onto the soil determines the width of the zone of separation. In general, increasing q decreases the width of separation; in some cases detachment from the soil may be completely avoided (Anastasopoulos et al. 2008a, b). Hence, the relative stressing of the foundation compared to the initial static loading decreases with increasing q. The beneficial role of q is dual in this respect: (i) by pushing the foundation it compresses the soil, and "flattens" any scarp or asperity that would have developed on the (free) ground surface; and (ii) it changes the stress field underneath the structure (e.g. increases the normal stresses under the centre), leading to diversion of the fault rupture. A "heavily" loaded foundation on soft/loose soil is capable of diverting the fault rupture and "flattening" the soil surface substantially.

(i) Structures *in the vicinity* of active faults *can be and should be designed* to withstand tectonic dislocations. This research, as outlined here and developed in the companion papers of this volume, provides combined numerical and experimental evidence indicating that fault rupture diversion is possible. However, even if the rupture is diverted, the foundation may still be subjected to significant stressing. The latter is quite sensitive to the exact position, $\boldsymbol{s}$, of the foundation with respect to the fault outcrop as it would have appeared in the free field. Since the latter cannot always be predicted with certainty, when designing a foundation against tectonic-induced deformation, its position should be varied parametrically as part of the design process.

(j) Buildings on isolated footings are unable to "avoid" a direct "hit" of an outcropping fault rupture. The dislocation emerges within the structure, causing significant differential vertical and horizontal displacements, and consequently deformation and distress in the structure (Anastasopoulos and Gazetas 2007a, b; Faccioli et al. 2008). Thus, such structures are susceptible to partial or full collapse when subjected to severe fault dislocations.

(k) Structures on piles may often perform worse than on rigid and continuous foundations. This is because piles tend to force the superstructure to follow the imposed deformation, thereby imposing severe horizontal and vertical differential displacements that may damage the structure. As an example, Fig. 4 illustrates the deformation of a 3×3 pile group (with a pile cap $10\,\text{m} \times 10\,\text{m}$ in plan) subjected to a 60° normal fault rupture that would have outcropped (in the free-field) at $s = 9\,\text{m}$, i.e. near the right edge of the group (Gazetas et al. 2007). The piles with their pressure and transmitted loads diffuse the rupture, but still suffer from unequal settlements and large non-uniform horizontal displacements. The lower parts of the front and central row of piles are pulled down- and out-ward, while the tips of the back row of piles remain nearly fixed inside the "footwall" block. As a result, the rotation and lateral displacement of the cap and the bending moments in the piles attain very large, perhaps unacceptable, values.

(l) Structures resting on discrete supports, such as bridges, are practically forced to follow the imposed ground deformation. Bridges with continuous superstructure (deck) will thus suffer from large, and most probably un-tolerable, stressing. Such an example of a three-span road bridge is illustrated in Fig. 5a. A practical solution can be the separation of the continuous superstructure in multiple simply-supported decks (Fig. 5b). In such a case, the main risk will arise from differential displacements and rotations between adjacent supports (piers). With enough seating of deck beams and adequate restraints (stoppers), bridge structures can be designed to survive even large tectonic dislocations.

3 Design recommendations

On the basis of all the analyses reported in this and the companion papers, as well as results from the literature (Duncan and Lefebvre 1973; Berill 1983; Youd et al. 2000; Bray 2001), the following recommendations are made for future seismic codes for structures on active faults:

(1) Building in the vicinity of active seismic faults could be allowed only after a special seismotectonic–geotechnical–structural study is performed. In such a study, the effects

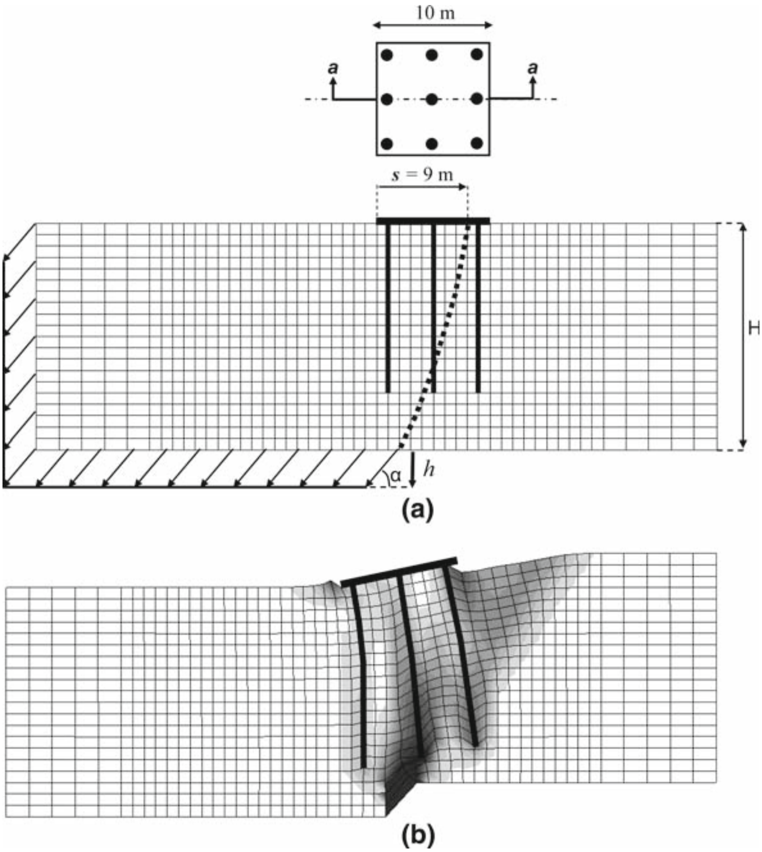

Fig. 4 Group of 3 × 3 piles founded in the path of a rupturing normal fault: (**a**) cross-section a–a of the 3-D finite element discretisation; (**b**) deformed mesh of the soil–pile–cap system with superimposed concentration of plastic octahedral shear strains, for $s = 9\,\text{m}$

of all known faults in the vicinity of the structure shall be investigated, and measures shall be taken to effectively face the consequences of their rupturing.

(2) The exact location of surface outcropping of a seismically active fault cannot be predicted with accuracy, even in cases of well-mapped faults. First of all, it relies on the location of the fault at bedrock, the estimation of which is not always straight-forward. Even if the fault line is accurately mapped, there is no practical guarantee that the same fault will outcrop at exactly the same location in a future earthquake. Since the location of the foundation relative to the outcropping fault rupture is critical for its stressing (Anastasopoulos et al. 2008a, b), foundation–superstructure design and analysis should be conducted for a range of postulated possible fault break positions. Furthermore, taking account that the magnitude of a future fault dislocation is also quite uncertain (e.g. Wells and Coppersmith 1994), it should also be investigated parametrically.

(3) The presence of a structure may lead to diversion of the rupture path, as well as to modification of the surface displacement profile caused by the emerging fault rupture (Anastasopoulos et al. 2008a, b). Depending on the rigidity, continuity, and weight of the foundation–structure system, even complete diversion of the fault path may take

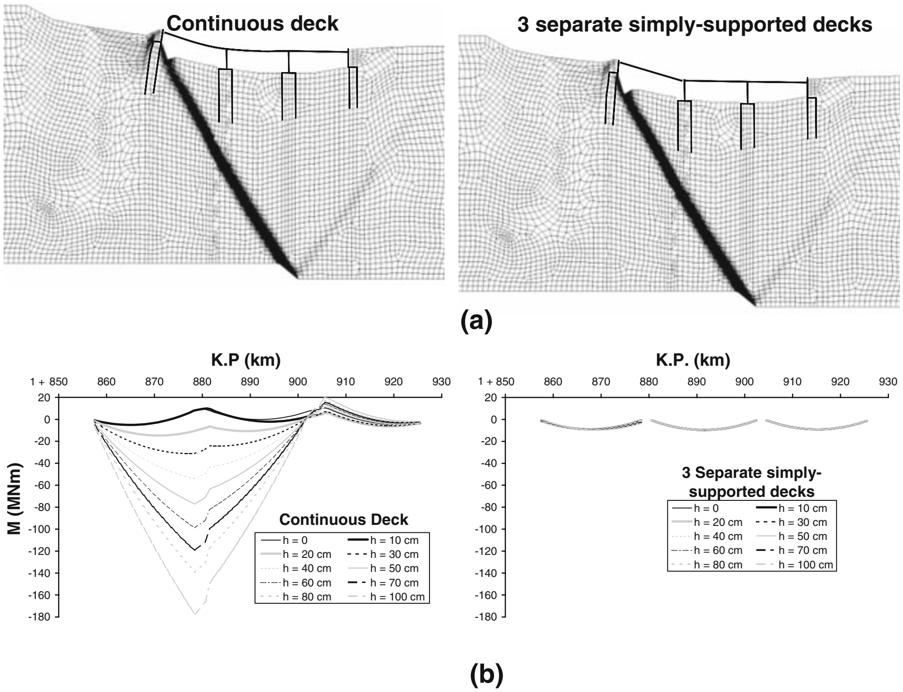

Fig. 5 Three-span road bridge subjected to faulting-induced deformation. Comparison of continuous deck versus three separate simply-supported decks: (**a**) deformed mesh with superimposed plastic octahedral shear strains; (**b**) evolution of faulting-induced bending moments M along the deck with parametrically increasing value of the imposed bedrock offset h

place. Additionally, depending on how soft/loose the soil is, a distinct (and steep) fault scarp may be diffused by the structure to a widespread differential settlement. Hence, soil–foundation interaction should be taken into account in the design of structures in the vicinity of active faults, and numerical methodologies such as those developed in the companion papers (Anastasopoulos et al. 2008b) can be used. Charts presented in Paolucci and Yilmaz (2007) may be advantageously used at a preliminary stage for shallow foundations to define the conditions for which, whatever the original location of the fault at the bedrock elevation, the ground surface rupture will not intersect the foundation.

(4) The foundation type plays a crucial role in the response of a structure to fault-induced displacement. Properly designed to act as partially unsupported, continuous and rigid foundation systems (Fig. 6a), such as rigid mat or box-type foundations, are advantageous and should be preferred. Isolated footings should in general be avoided. The lack of foundation continuity may lead to fault outcropping within the limits of a structure. If used, isolated footings should always be connected with rigid tie-beams (Fig. 6b).

(5) Piled foundations, if required, should be designed with special care. They tend to "force" the structure to follow the fault-induced displacement (Fig. 6c). To avoid or limit damage to the superstructure, piled foundations should be combined with a rigid and continuous pile cap, and possibly with weak pile/strong superstructure design (the opposite of conventional "capacity" design, as applied today). Such a combination may allow

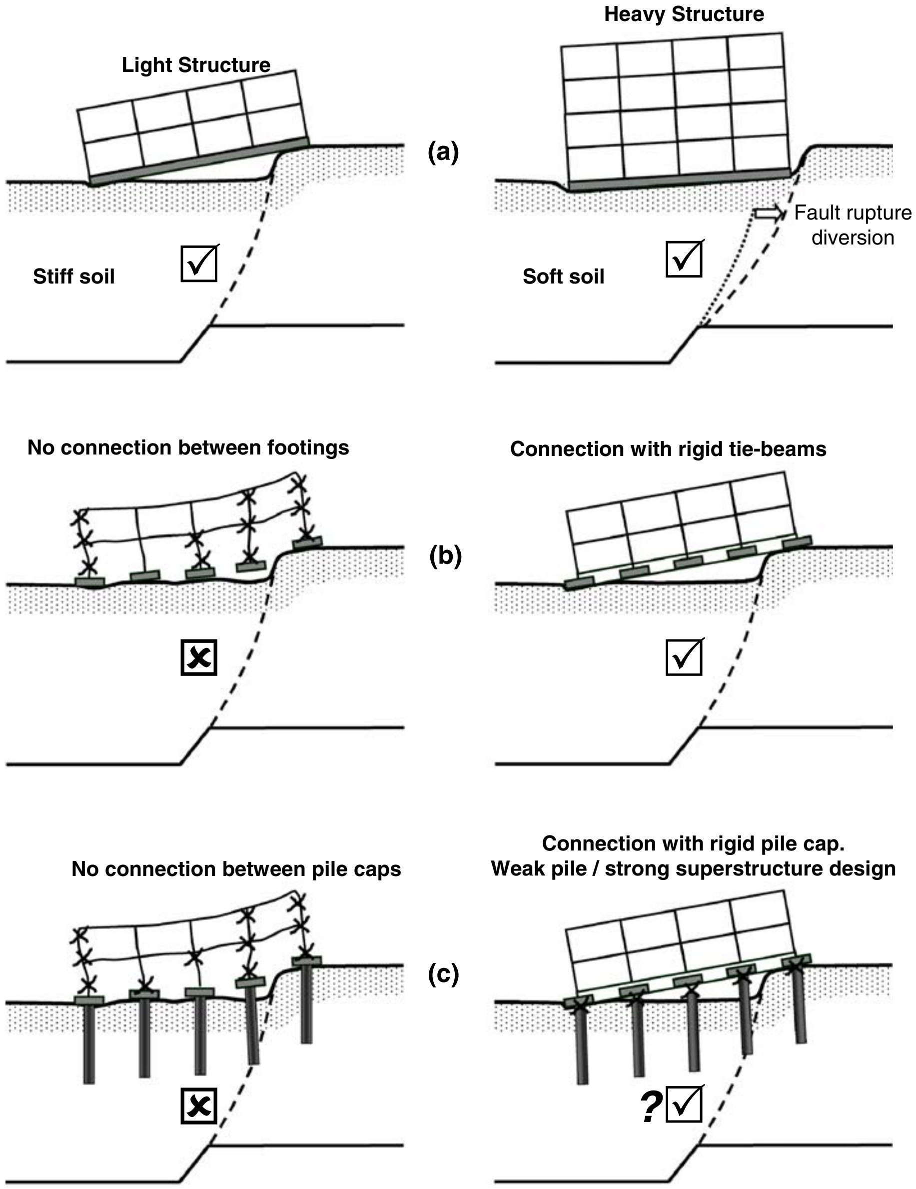

Fig. 6 Schematic summary of recommendations: (**a**) continuous and rigid foundation systems (mat or box-type); (**b**) discontinuous foundation systems (spread foundations); (**c**) piled foundations

the superstructure not to be subjected to the differential displacement experienced by the piles: since the piles will be weaker than the superstructure, they will be forced to fail, leaving the superstructure intact. The rigid and continuous pile cap is required: (i) to enforce pile failure, instead of failure of the superstructure; and (ii) to compensate for the loss of support due to pile failure (i.e., to bridge locally generated gaps). Such a design philosophy combines the advantages of a piled foundation (safe transmission of superstructure loads, when soil conditions are poor), with the advantage of rigid and continuous raft foundations (in terms of faulting-induced deformation). “Isolating” the pile from a potentially downward (or upward) moving soil block should also be explored. Such isolation may be achieved through use of special coating materials, such as low friction asphalt mixes, for example.

(6) For bridge structures, where foundation continuity is not possible (each pier is founded on a separate foundation), continuous superstructure systems are disadvantageous (the deck will be subjected to the imposed differential displacement) and simply supported superstructures are preferable: each deck may be displaced and/or rotated as a rigid body, without being subjected to stressing. Special care should be taken to avoid deck collapse due to excessive relative displacement of the deck relative to the pier. Large enough seating and adequate restraining devices, such as stoppers, are required to avoid such failures.

(7) In the case of underground structures, such as bored and cut-and-cover tunnels, “open” cross-sections should be avoided. Such cross-sections are equivalent to the case of isolated footings, and may allow fault outcropping within the limits of the tunnel, sustaining its superstructure to large differential displacements. In stark contrast, “closed” cross-sections provide adequate continuity and rigidity, helping the tunnel to convert the imposed deformation to rigid body rotation instead of distortion. In cut-and-cover tunnels, the weight of the fill (cover) plays a significant role and should be taken into account. Its effect may be seen as qualitatively similar to the effect of the surcharge load on a raft foundation.

4 Limitations

The numerical and experimental studies utilised to derive the conclusions and design recommendations of the present paper deal with the quasi-static offset due to dislocation of the seismogenic fault. The related shaking component is the result of the multitude of seismic waves emanating from different “points” of the rupturing fault, and is considered as an altogether different type of loading. The combination of the two phenomena (quasi-static offset, and oscillatory shaking) may be particularly severe for the superstructure (not specifically for the foundation). Such combined stressing has not been addressed in the present work, and further research is desirable.

5 Conclusions

The present article has outlined the main findings and conclusions of the EU-funded QUAKER research project, in combination with other related studies dealing with the interaction of foundation–structure systems with dip-slip fault ruptures. On the basis of numerical and experimental simulations, a set of practical design recommendations has been proposed. Although preliminary, these recommendations can form the basis for future Code requirements on the subject. The key conclusion is that it is quite feasible to design foundation–structure systems to withstand an outcropping dip-slip fault rupture. However, given the complexities of the problem, building in the vicinity of active seismic faults should be allowed only after a special seismotectonic-geotechnical-structural study is performed. In such a study, the effects of all known faults in the vicinity of the structure shall be investigated, and measures shall be taken to effectively face the consequences of their rupturing.

References

Anastasopoulos I, Gazetas G (2007a) Foundation–structure systems over a rupturing normal fault: part I. Observations after the Kocaeli 1999 earthquake. Bull Earthq Eng 5(3):253–275

Anastasopoulos I, Gazetas G (2007b) Behaviour of structure–foundation systems over a rupturing normal fault: part II. Analysis of the Kocaeli case histories. Bull Earthq Eng 5(3):277–301

Anastasopoulos I, Gazetas G, Bransby MF, Davies MCR, El Nahas A (2007) Fault rupture propagation through sand: finite element analysis and validation through centrifuge experiments. J Geotech Geoenviron Eng 133(8):943–958

Anastasopoulos I, Gazetas G, Bransby MF, Davies MCR, El Nahas A (2008a) Normal fault rupture interaction with strip foundations. J Geotech Geoenviron Eng, ASCE 134 (in print)

Anastasopoulos I, Callerio A, Bransby MF, Davies MCR, El Nahas A, Faccioli E, Gazetas G, Masella A, Paolucci R, Pecker A, Rossignol E (2008b) Numerical analyses of fault–foundation interaction. Bull Earthq Eng doi:10.1007/s10518-008-9078-1

Berill JB (1983) Two-dimensional analysis of the effect of fault rupture on buildings with shallow foundations. Soil Dyn Earthq Eng 2(3):156–160

Bransby MF, Davies MCR, El Nahas A (2008a) Centrifuge modelling of normal fault–foundation interaction. Bull Earthq Eng doi:10.1007/s10518-008-9079-0

Bransby MF, Davies MCR, El Nahas A (2008b) Centrifuge modelling of reverse fault–foundation interaction. Bull Earthq Eng doi:10.1007/s10518-008-9080-7

Bray JD (2001) Developing mitigation measures for the hazards associated with earthquake surface fault rupture. Workshop on seismic fault-induced failures—possible remedies for damage to urban facilities. University of Tokyo Press, pp 55–79

EC8 (1994) Eurocode 8—design of structures for earthquake resistance. Part 5: foundations, retaining structures and geotechnical aspects. prEN1998-5, Final draft August 2003. Comité Européen de Normalisation, Brussels

Duncan JM, Lefebvre G (1973) Earth pressure on structures due to fault movement. J Soil Mech Found Eng, ASCE 99:1153–1163

Faccioli E, Anastasopoulos I, Callerio A, Gazetas G (2008) Case histories of fault–foundation interaction. Bull Earthq Eng [Special issue: Integrated approach to fault rupture- and soil-foundation interaction, Companion paper (submitted for possible publication)]

Gazetas G, Anastasopoulos I, Apostolou M (2007) Shallow and deep foundations under fault rupture or strong seismic shaking. Geotech Earthq Eng, Springer, chap 9, pp 185–217

Paolucci R, Yilmaz T (2007) Limit analysis of fault–foundation interaction. Bull Earthq Eng [Special issue: Integrated approach to fault rupture- and soil-foundation interaction, Companion paper (submitted for possible publication)]

Wells DL, Coppersmith KJ (1994) New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. Bull Seismol Soc Am 84(4):974–1002

Youd TL, Bardet J-P, Bray JD (2000) Kocaeli, Turkey, earthquake of August 17, 1999 reconnaissance report. Earthq Spectra, Suppl A to vol 16, 456 pp