Geotechnical Mitigation Strategies for Earthquake Surface Fault Rupture

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Abstract: Surface fault rupture can be damaging to structures built on or near active faults if the hazard is not addressed properly. Fault-induced angular distortion and lateral ground strain can cause beams to yield and eventually lead to structural collapse. When avoidance is not possible, geotechnical mitigation strategies can be used. These strategies include spreading fault displacement over a large area, causing the structure to respond with rigid-body movement, and diverting the fault rupture around the structure. The effectiveness of these strategies can vary from protecting life safety to preventing significant damage and can be effective for a range of dip-slip fault displacements. Earth fills should be sufficiently thick and ductile to prevent the underlying fault dislocation from developing at the ground surface. Thick RC mat foundations proved to be especially effective in shielding the superstructure from the damaging effects of the underlying ground movements. Although more challenging to implement because they require excellent fault characterization, several fault diversion strategies have also proved effective at protecting structures from fault movement. **DOI: 10.1061/(ASCE)GT.1943-5606.0000933.**

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Introduction

Surface fault rupture is an important hazard that should be addressed when designing or evaluating structures built in areas with shallow active faults. Active fault traces at the ground surface exist in several urban areas, including Los Angeles, San Francisco, Salt Lake City, Seattle, and San Diego. Because surface fault traces typically reoccur at the same location, their location and characteristics can be discerned through a comprehensive geologic investigation. The movement at the ground surface is not always expressed along a single fault trace. Instead, the underlying fault movement is often expressed over a wide fault zone with secondary faults and distributed ground deformation. The resultant movement at the ground surface can damage infrastructure by breaking utilities, displacing bridge components, and inducing structural damage in buildings.

Surface faulting has interacted with several buildings during recent earthquakes (Bray 2001). The performance of buildings depends on site- and project-specific factors, including the fault characteristics (e.g., type, amount of offset, and its definition), the nature of the overlying soil (e.g., soil thickness and ductility), and the foundation and structural systems (Bray 2009). For example, the Attaturk Basketball Court in Turkey was significantly damaged and judged to be unrepairable in the part of the building overlying a displaced fault trace because its pile foundation locked the structure into each side of the fault (Anastasopoulos and Gazetas 2007). In 1972 in Nicaragua, the 15-story Banco Central Building was not damaged significantly because its thick basement walls, robust foundation, and weight caused the fault rupture to divert around the building (Niccum et al. 1976). A residential structure in the 1992 Landers Earthquake fault zone suffered relatively less damage because its mat foundation was isolated partially from the fault-induced ground strain through slippage along a plastic sheet that had been placed under the mat during construction (Murbach et al. 1999).

The prevailing strategy for mitigating the surface fault rupture hazard is to avoid building on or near active fault traces (Bryant 2010). However, in certain cases, this may be difficult to achieve, and sometimes when the amount of fault displacement is relatively minor, it may be unnecessary. Structures can be built safely on or near active faults when the hazard is well defined and manageable and the structure is designed appropriately (Cluff et al. 2003; Johansson and Konagai 2006; Gazetas et al. 2008; Bray 2009). In fact, several projects have been completed in active fault zones. A residential development in Southern California was designed utilizing numerical simulations to establish rational setback locations and mechanically stabilized soil in combination with posttensioned mats to mitigate damage from anticipated bedrock fault rupture offsets of 3 cm (Bray 2001). The California Memorial Stadium, which is situated on top of the Hayward Fault, was recently retrofitted using fault sliding blocks to accommodate a design strike-slip fault movement on the order of 2 m (Vignos et al. 2009).

There are several more cases where geologists and engineers have worked together to identify and characterize surface faulting and to apply sound engineering principles in developing robust designs that mitigate the hazards associated with surface faulting. Surface fault rupture is a ground deformation hazard that can be mitigated geotechnically and structurally using design strategies that are routinely applied to address other ground deformation hazards, such as mining subsidence, landslides, lateral spreading, and expansive soils. The objective of this paper is to investigate some of the

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most promising geotechnical mitigation strategies to develop insights that aid in the evaluation of the surface fault rupture hazard.

Previous Work

The characteristics of fault rupture through bedrock are controlled largely by the existing geologic structure and tectonic forces. However, the nature of the surficial earth materials and the built environment play an integral role in the development of the surface expression of the fault rupture at a particular location (Bray 2001, 2009). Brandsby et al. (2008a, b) investigated the response of fault rupture propagation through soil using a series of geotechnical centrifuge experiments. In these studies, both normal and reverse fault rupture through sand of varying relative density and thickness were investigated. Importantly, the effects of mat foundations were also investigated by including steel plates and flexible loads in some of the experiments.

The surface fault rupture phenomenon has been modeled successfully through numerical simulations using several soil constitutive models. Bray et al. (1994b) used the Duncan et al. (1980) hyperbolic model that incorporates stress-strain nonlinearity, stress dependency, and, importantly, a well-defined failure strain. However, it does not include dilation or strain softening. Anastasopoulos et al. (2007) and Loukidis et al. (2009) used Mohr-Coulomb models modified to include strain softening. Capturing the nonlinear stress-dependent response of soil is critical. It is also important to capture the soil's ductility through its failure strain (Bray et al. 1994b). Additionally, capturing localization requires the use of a soil constitutive model with strain softening. A finite-strain formulation provides improved performance for large fault offsets.

Recent studies have modeled directly the response of structures to fault rupture propagation through soil deposits. For example, using the same soil constitutive models that were used in the free-field analyses, Anastasopoulos et al. (2008) included structures by adding structural elements with a specified stiffness and surcharge pressure at the ground surface. Their simulations replicated reasonably well the results of the centrifuge tests conducted by Bransby et al. (2008a, b). These studies and previous studies have led to several recommendations regarding the design of structures near or on active faults. They include the use of nonarbitrary setbacks (Bray 2001), mechanically stabilized earth fills beneath structures (Bray et al. 1993), decoupling slip layers beneath foundation elements (Bray 2001), strong basement walls (Duncan and Lefebvre 1973), strong mat-type foundations (Bray 2001; Gazetas et al. 2008), building weight to divert or diffuse fault movement (Berrill 1983; Gazetas et al. 2008), and simply supported bridge spans (Gazetas et al. 2008). However, comprehensive investigations of the response of structures to surface fault rupture are limited, and additional work in this relatively novel field of study is warranted. Specifically, the effectiveness of geotechnical mitigation strategies has not yet been assessed comprehensively for realistic structures. This is the primary aim of this study.

Numerical Procedures and Validation

The two-dimensional, plane strain, explicit finite-difference program *FLAC* is used to assess various geotechnical mitigation strategies for surface fault rupture in the case of dip-slip faulting. The finite-difference code allows for incorporation of a nonlinear effective stress-soil model with postpeak strain softening and large-strain calculations with remeshing, among other features that are useful for analyzing earthquake fault rupture propagation. Information on the numerical procedures, in addition to that provided herein, is available in Oettle and Bray (2012, 2013).

UBCSAND (Byrne et al. 2004) is used to capture the nonlinear response of dry, uncemented sand. This is an elastoplastic constitutive model with nonlinear stress-strain response, contractive and dilative volumetric response, and response dependence on confining pressure. The version of UBCSAND used herein is based on code provided by Peter Byrne (personal communication, 2009). The UBCSAND model was modified to enhance its capabilities for simulating the surface fault rupture process. Importantly, postpeak strain softening, which was identified previously by several researchers as being essential, was added (Oettle and Bray 2013). This modification decreases the soil yield surface after a peak stress condition was reached over a given strain interval to the critical-state stress ratio.

As a result of including strain softening in the soil constitutive model, the numerical simulations became mesh dependent (Simo et al. 1993). Anastasopoulos et al. (2007) proposed a procedure to account approximately for mesh-dependency effects, which is adopted herein. This method allows the strain required to fully soften the shear band to be approximately scaled to the mesh size (Oettle and Bray 2013). The UBCSAND model parameters used are provided in Table 1.

The underlying fault movement was modeled as a single, distinct offset in rigid bedrock. The model's boundary conditions were implemented similar to other researchers (Bray et al. 1994b; Anastasopoulos et al. 2007). The stationary footwall lateral boundary was fixed in the horizontal direction; the footwall base boundary was fixed in both the horizontal and vertical directions. The displaced hanging wall has a specified velocity applied in the direction of fault movement at both the base and lateral boundary of the mesh. As conventionally done, the bedrock fault displacement was applied pseudostatically (i.e., transient ground motions were ignored). The structural demands of transient ground motions can be

Table 1. Representative UBCSAND Model Parameters Used in the Study

Parameter	Function	Value
D_r	Relative density	Varies
ρ	Dry mass density	$1.6\,\mathrm{Mg/m^3}$
$N_{1,60}$	Normalized, corrected standard penetration test blow count	$D_r^2 \times 60$
K_G^E	Elastic shear modulus multiplier	$21.7 \times 20 \times (N_{1,60})^{0.333}$
m_e	Elastic shear exponent	0.5
K_B	Elastic bulk modulus multiplier	$0.7 \times K_G^E$
n_e	Elastic bulk exponent	0.5
K_G^P	Plastic bulk modulus multiplier	$K_G^E \times (N_{1,60})^2 \times 0.003 + 100$
n_p	Plastic bulk exponent	0.4
ϕ_{cs}	Critical state friction angle	33°
ϕ_{peak}	Peak friction angle	$\phi_{cs} + N_{1,60}/10 + \max[0, (N_{1,60} - 15)/5]$
R_f	Failure ratio	0.95
m_hfac1	Model parameter	0.025
m_hfac2	Model parameter	1.0
m_hfac3	Model parameter	—
m_hfac4	Model parameter	—
anisofac	Model parameter	1.0
γ_{pp}	Shear strain from peak stress to critical state	0.06
$\Delta\phi$	Stress-dependent friction angle	4°

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added to the structural demands resulting from permanent ground deformation using procedures such as those developed in Goel and Chopra (2009). The effects of prior fault movement, if analyzed, were modeled with the methodology developed in Oettle and Bray (2013). The effects of groundwater and an undrained soil response were not analyzed herein. Johansson and Konagai (2006) described some of the potential effects of saturated sands during surface fault rupture.

Two steel moment-frame structures were analyzed to evaluate soil-foundation-structure interaction aspects further. A 3-story structure (Lee et al. 2004) and a 6-story structure (Kalkan and Kunnath 2006) were modeled with beam elements. Building loads were assumed to be 10 kPa per floor, including the roof, for the 3-story structure and 7 kPa for the 6-story structure. This mass was included in the beams. Full-moment capacity was assumed for both the beams and columns, and strength-limited compression and tension capacities were used. Properties for the structural elements were taken from the AISC (2005). Shear failure was not modeled directly; therefore, shear failure in the structural elements was checked manually. Analysis of these structures was limited to the elastic range with perfectly plastic response thereafter.

The steel frames of these two structural models were attached to RC mat foundations with full-moment connections. Properties of the mats were based on their thickness with typical detailing. The second moment of the area was taken as half of that calculated for a rectangular cross section to approximate the cracked second moment. Foundation elements were lined with interface elements with frictional properties similar to that of the underlying soil. The simulations with structural elements were analyzed in large-strain mode until just before the mesh was distorted beyond its ability to continue with large-strain calculations; fault movement was then continued with small-strain calculations because the program *FLAC* does not support remeshing of models with structural elements.

Validation of the numerical simulations for capturing free-field response is presented in Oettle and Bray (2013). Representative backanalyses of centrifuge tests conducted by Bransby et al. (2008a, b), which included model foundations, are shown in Figs. 1 and 2. In Fig. 1, the results of Test 14, consisting of a normal fault and a small steel strip footing and the corresponding numerical simulation, are compared. The primary shear band was formed in the same location as the centrifuge test, and the emergence of a second shear band in the centrifuge test was also captured in the simulation. In Fig. 2, comparisons of the measured angular distortion (herein defined as differential settlement over a horizontal length) and the calculated angular distortion for Tests 20 and 30 are presented. The observed trends of angular distortion along the ground surface were matched well by the simulations; variations between the centrifuge test results and the results of the numerical simulations are relatively minor. Based on these and similar comparisons, the finite-difference analyses using the modified UBCSAND model are judged to be reasonable.

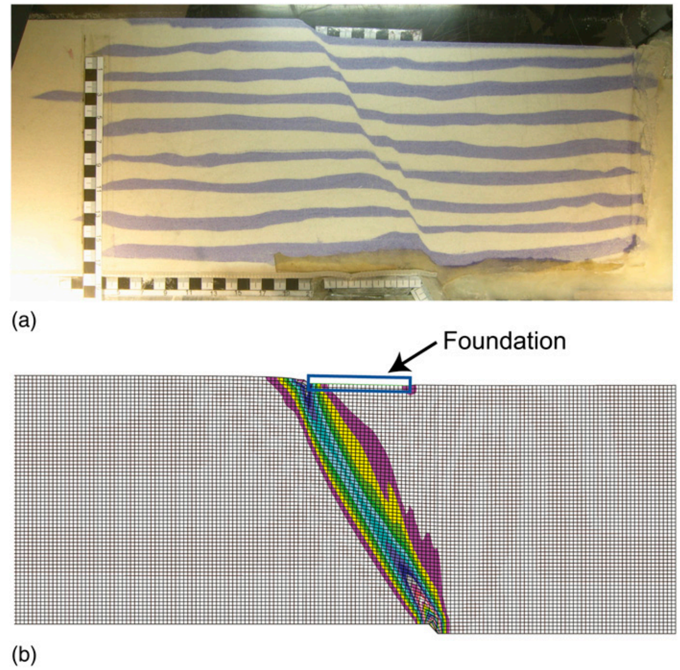

Fig. 1. Validation of the numerical model with centrifuge Test 14 from Bransby et al. (2008b): (a) photograph of the centrifuge experiment; (b) deformed mesh and shear strain contours for the numerical model (normal fault, 60° dip, 2.0 m of vertical fault movement, 24.5-m-thick soil deposit, $N_{1,60} = 23$, and $K_o = 0.45$); the lateral extent of the finite-element mesh on the left side has been cropped

Response of Structures to Surface Fault Rupture

The typical responses of structures to surface fault rupture when mitigation was not used are analyzed using the 3-story steel moment-frame building with a conventional 0.45-m-thick RC mat foundation. Representative results are presented in Fig. 3. Yielding in the structure was initiated typically through excessive bending in the second-floor beams at the beam-column joints. Yielding then progressed upward through the structural frame to the roof. Axial yielding of the beams and columns, either in tension or compression, did not occur typically. Shear failure in the beams and columns did not occur. Yielding in bending in the conventional mat foundation developed, whereas shear or axial failure did not occur. Similar results were obtained for the 6-story building with a conventional mat foundation.

The empirically based building damage evaluation procedure presented by Boscardin and Cording (1989) was used to evaluate the consequences of the fault-induced ground movements. This procedure uses angular distortion minus building tilt (which they simply call angular distortion or β) and lateral strain to estimate the level of damage to a structure. Fault-induced building damage was found to be caused largely by angular distortion rather than by lateral strain because even a thin mat foundation tied the structure's columns together laterally. When isolated spread footings were used, the structure was found to be damaged significantly because of the combination of lateral strain and angular distortion after minor vertical fault movement (0.1 m). In the case of the structure supported by isolated spread footings, column yielding in bending occurred in addition to the development of yielding in the rest of the structure.

Three categories of mitigation strategies were investigated to assess their effectiveness in limiting structural damage from dip-slip fault rupture: (1) diffusing the underlying fault rupture over a large area to limit angular distortion at the ground surface; (2) accommodating fault rupture through rigid-body movement of the structure; and (3) diverting the fault away from the structure. Specific design strategies that fall into each of these categories are discussed subsequently.

Diffusion of Fault Rupture

Ductile Engineered Fill

Ductile engineered fill placed on top of a bedrock fault is known to spread discrete fault slip over a broad zone, as schematically shown

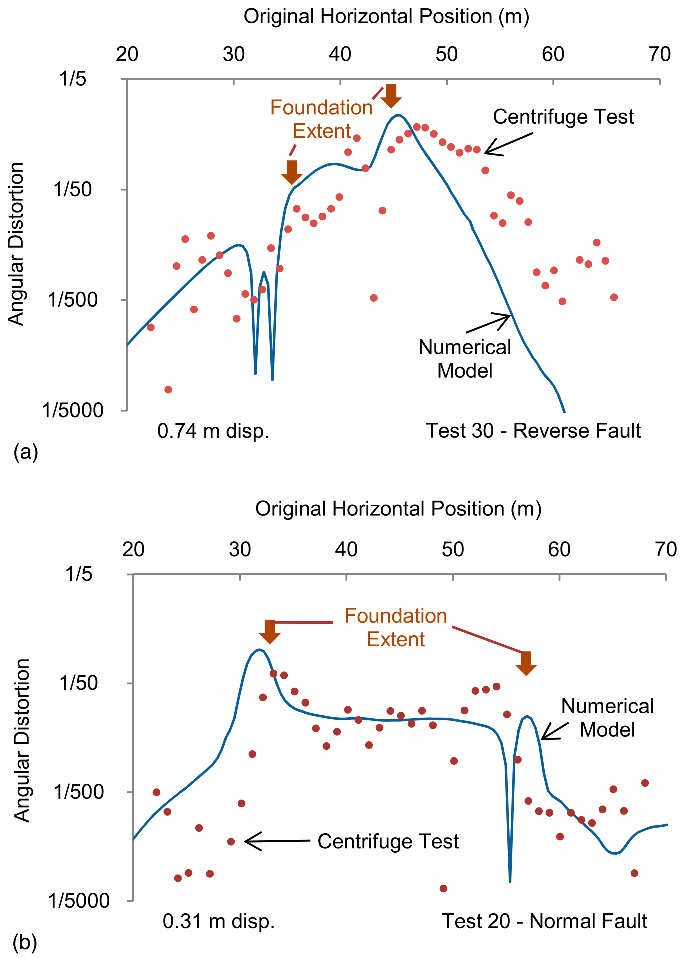

Fig. 2. Comparison between the centrifuge test (Bransby et al. 2008a, b) and numerical results for (a) centrifuge Test 30 (reverse fault, 60° dip, 15-m-thick soil deposit, 0.74 m of vertical fault movement, $N_{1,60} = 31$, $K_o = 0.45$, 10-m-wide mat, and 37-kPa mat load); (b) centrifuge Test 20 (normal fault, 60° dip, 25-m-thick soil deposit, 0.31 m of vertical fault movement, $N_{1,60} = 19$, $K_o = 0.45$, 25-m-wide mat, and 84-kPa mat load)

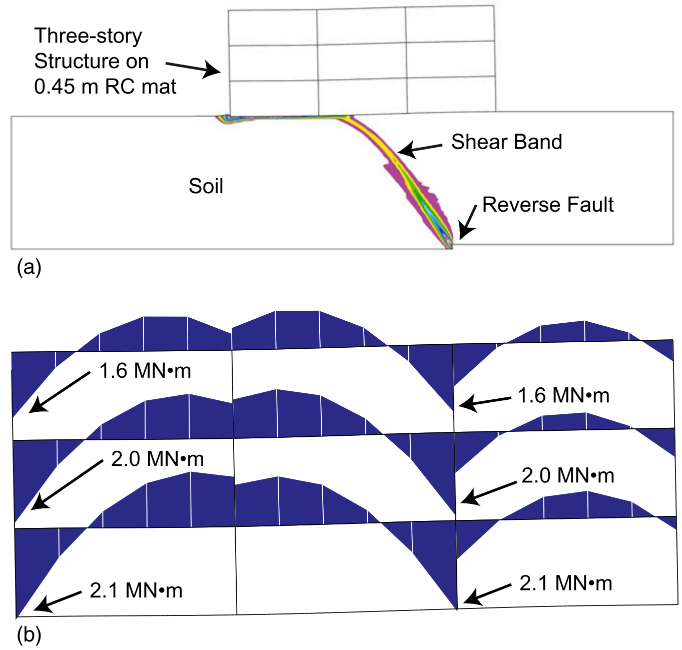

Fig. 3. (a) Representative soil response because of underlying reverse fault rupture of 0.6 m in the vertical direction (shear strain contours shown; 0.2- × 0.2-m mesh size used); (b) representative moments induced in the beams by fault rupture (the noted maximum values are where yielding is occurring)

in Fig. 4(a) (Bray 2001). This fill response can be used to improve building performance relative to the unmitigated scenario by replacing stiff, previously sheared soil with ductile compacted earth fill. The earth fill must be sufficiently deep and ductile to spread out the underlying fault deformation sufficiently. The width of the diffusion is roughly proportional to the fill thickness. Therefore, a greater fill depth will produce improved structural performance. Ductile fill (i.e., fill with a large failure strain) is also required to prevent a distinct shear failure offset from reaching the ground surface and to spread the underlying bedrock fault offset across a wider zone at the ground surface. The use of a thick, ductile compacted earth fill does not prevent fault movement from being expressed at the ground surface; rather, it causes the ground to warp in distributed shear in response to the underlying fault movement as opposed to rupturing along a distinct shear surface.

As an example of the effectiveness of this mitigation strategy, the case of a relatively stiff, brittle 10-m-thick native soil deposit ruptured previously during several past earthquakes was analyzed with the 3-story steel-frame structure described previously and a 0.45-m-thick mat foundation. For this case, yielding developed in the structure's beams after only about 0.2 m of vertical bedrock fault movement. However, if the previously sheared soil was replaced by 10-m-thick ductile engineered fill with 6% axial failure strain, the fault-induced ground deformation was diffused sufficiently; therefore, yielding in the structure's beams did not occur until about 0.6 m of vertical fault movement, as shown in Fig. 4(b). For the case where the 10-m-thick engineered earth fill was even more ductile (i.e., 10% failure strain), yielding did not occur for at least 1.5 m of vertical fault movement.

Bray et al. (1994a, b) demonstrated the dependence of the height of the propagation of the fault rupture into a soil deposit on the soil's failure strain (i.e., its ductility). In developing their relationship, they had examined primarily reverse faulting and had used the failure strain of the soil in triaxial compression as an index of soil ductility. An update to this relationship is developed herein. Fig. 5(a) was derived using the UBCSAND constitutive model by varying the soil's failure strain through several model parameters to provide a range of results. The relationships developed for reverse and normal faults differ because of the different stress paths that develop in the soil deposit for these two cases, which cause a difference in the soil's failure strain (Oettle and Bray 2013). Thus, the results presented in Fig. 5(a) rely on the constitutive model prediction for the soil's failure strain in a particular mode of shear. For the cases analyzed, the failure strain for a reverse fault displacement is approximately twice that for a normal fault displacement. Fig. 5(b) was developed wherein the more generalized stress-path dependent failure strain is plotted on the horizontal axis. Thus, normal and reverse fault results converge, which indicates that the soil's response to the base fault displacement is a function of the actual failure strain of the material for the resulting fault-induced stress path.

The angular distortion induced at the ground surface can be reduced by increasing the thickness of the fill until the spreading sufficiently accommodates structural requirements. As a rule of thumb, fault movement at the surface can be spread over a horizontal

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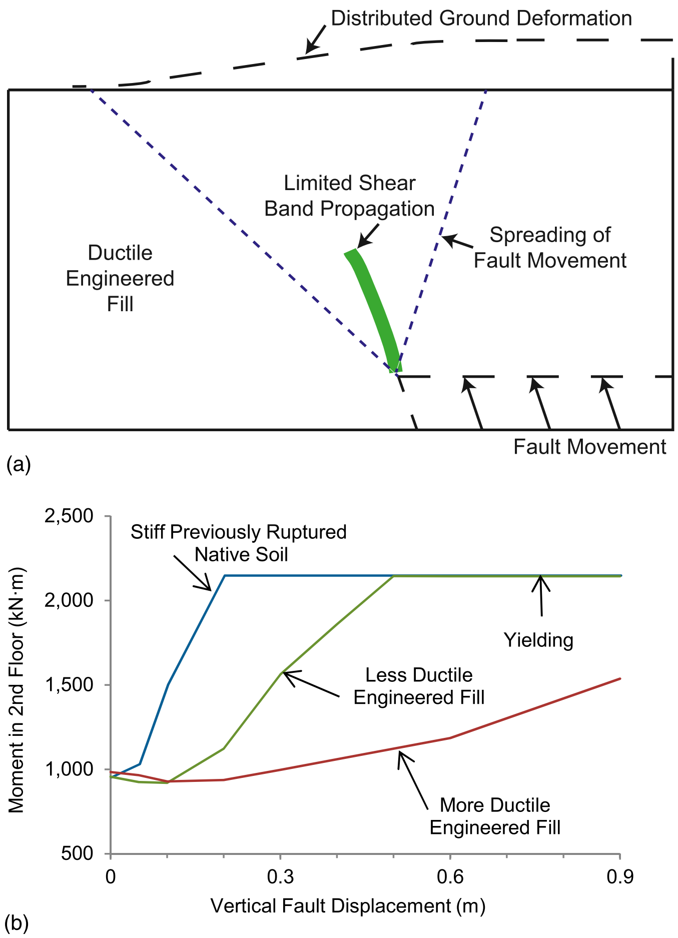

Fig. 4. (a) Characteristic diffusion of fault rupture through engineered fill (not to scale); (b) response of native soil and two ductile engineered fills (reverse fault, 45° dip, 10-m-thick soil deposit, 2.0 m of previous vertical fault movement, $N_{1,60} = 40$, $K_o = 0.45$, 3-story structure, 0.45-m-thick mat, right edge of building 5 m left of the bedrock fault, and plane-strain compression axial failure strains of 6 and 10% for less ductile and more ductile fills, respectively); the second floor is defined as the beam above the ground floor

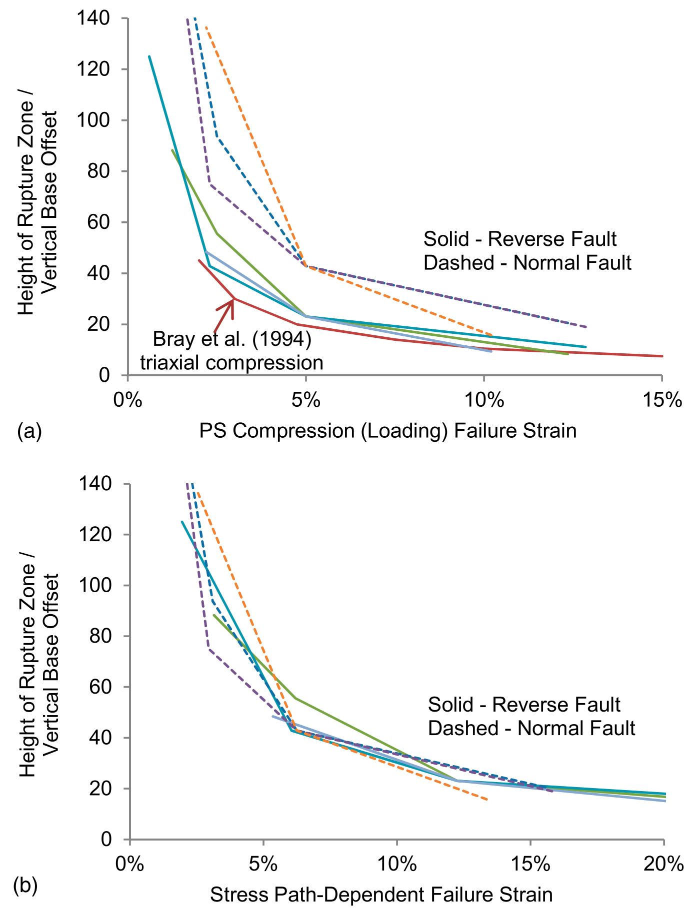

Fig. 5. (a) Height of the shear rupture zone in a previously unruptured soil deposit normalized by vertical bedrock fault displacement as a function of soil failure strain in plane-strain compression loading where the failure strain is varied by changing UBCSAND parameters $N_{1,60}$, R_f, and m_hfac1; (b) normalized height of the shear rupture zone as a function of the stress-path dependent failure strain (i.e., plane-strain compression unloading for a normal fault and plane-strain extension loading for a reverse fault)

zone approximately equal to 1–2 times the fill thickness. The required fill thickness is a function of the amount and type of fault movement and the ductility of the fill. The proposed numerical simulations can be utilized to evaluate an appropriate combination of these parameters to ensure satisfactory seismic performance of the structure.

Rigid-Body Movement

Thick Mat Foundation

A thick mat foundation can effectively resist the damaging effects of many types of ground movement (e.g., those because of expansive clay and liquefiable sand movements). Mat foundations improve structural performance by tying adjacent columns together, bridging gaps in soil support, and redistributing stresses beneath the mat.

Illustrative numerical analyses were performed to evaluate the effectiveness of thick mat foundations at mitigating the surface fault rupture hazard. In these analyses, the structure was placed at the center of the free-field outcrop of the fault. Mat thickness was varied between 0.2 and 3.0 m. A complex fault zone was also analyzed with the fault displacement split between two faults separated by 10 m because many fault zones are not comprised of a single idealized bedrock fault.

The results shown in Fig. 6 indicate that for the structural system analyzed, thick mat foundations can reduce significantly damage to the superstructure. For very thick mats, the fault movement-induced structural demands are well below the threshold of structural yielding, even for relatively large fault displacements of several meters. Failure in bending of the mat foundation only occurred for relatively thin mats (approximately < 0.8-m thick). Interpretation of the results using the Boscardin and Cording (1989) methodology is given in Table 2. The results indicate that structures with thicker mat foundations primarily responded by tilting. Thick mat foundations were effective for both reverse and normal faults and for varying fault outcropping locations. They worked well for both hogging- and sagging-type deformation modes and in complex fault zones, as shown in Fig. 7.

Thick mat foundations are a versatile design strategy for preventing damage from surface fault rupture. The performance of robust mat foundations can range from protecting life safety with relatively thin mats to preventing structural damage with very thick

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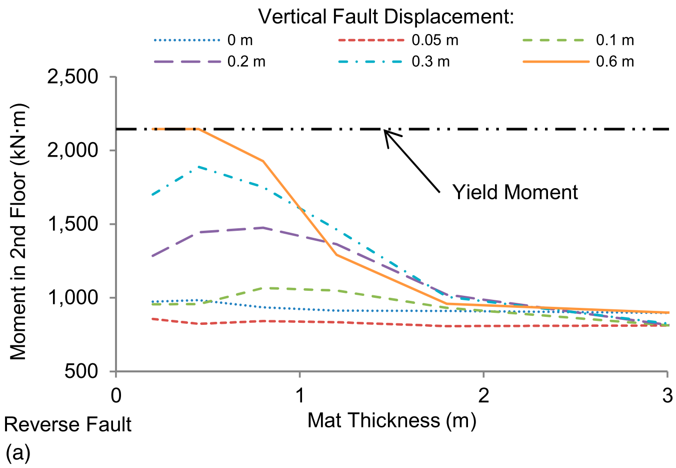
mats or with small fault movements. The structure may not be usable immediately after an earthquake because of excessive tilt. There are repair strategies available to relevel tilted mat foundations, such as the use of grouting or controlled excavations, that have been used successfully for structures a few stories in height. The implementation of these repair strategies becomes more challenging for taller, heavier buildings.



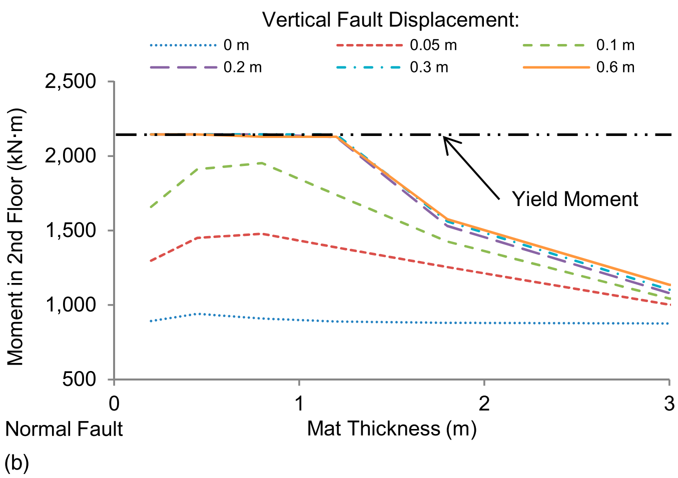


Fig. 6. Comparison of building performance with mat foundations of varying thickness: (a) reverse fault; (b) normal fault (60° dip, 15-m-thick soil deposit, 2.0 m of previous vertical fault movement, $N_{1,60} = 22$, and $K_o = 0.45$); the relevant problem geometry is provided in Fig. 3(a), and the maximum moment in the reverse fault case decreases for very small fault movements because the location of maximum moment is shifting

Decoupling of Foundation and Soil

Foundations can be decoupled from the potentially damaging ground strain induced by fault movements by reducing the friction between the foundation and the underlying soil (Bray 2001). This could reduce structural damage from surface fault rupture by decreasing the traction applied to the base of the foundation, as was observed for a strike-slip fault in Murbach et al. (1999). The decoupling layer beneath the building foundation acts as a fuse to limit the damaging effects of lateral ground strains. This mitigation strategy has been used successfully to mitigate structural damage because of mining subsidence (Kratzsch 1983). Decoupling can be achieved by installing two low-friction geosynthetic layers, with bedding sand below and above it, beneath the foundation of the structure. For example, two high-density polyethylene geomembranes were installed within the middle of a compacted sand layer as part of the retrofit of the California Memorial Stadium (Vignos et al. 2009). This limits the maximum force and strain applied from the ground to the base of the foundation of the structure.

Several numerical analyses were conducted to analyze the response of the 3-story building with and without a decoupling interface. The friction angle between the mat foundation and the underlying soil was assumed to be equal to the friction angle of the sand when no geosynthetics were used. The friction angle was assumed to be 11° (Koerner and Narejo 2005) when a geosynthetic decoupling interface was added. This analysis was performed for both reverse and normal faults and for several mat foundation thicknesses.

Representative results are presented in Fig. 8. The geosynthetic interface decreased the fault movement-induced deformation in the superstructure; however, the effect was not significant enough to substantially improve its structural performance. Hence, it had only a minor effect on reducing the moments induced in the superstructure for the cases analyzed. These analyses indicate that a mat foundation does an adequate job of laterally tying a structure's columns together without the assistance of a decoupling interface. Although placing geosynthetics underneath a mat foundation in a fault zone may be prudent, especially if a component of strike-slip movement is expected, it does not seem to have a significant enough impact on the damage induced by pure dip-slip fault deformation to serve as a substantial mitigation strategy for this particular case. If isolated spread footings were used, the decoupling layer would reduce the transmission of lateral ground strain to the structure.

Diversion of Fault Rupture

General

It is possible for an earthquake fault rupture to be diverted around a structure, as has been observed in several earthquakes (Niccum

Table 2. Comparison of Building Performance for Two Mat Foundation Thicknesses

Fault displacement (m)	0.45-m-thick mat foundation: Angular distortion	Tilt	β (angular distortion − tilt)	Damage	1.8-m-thick mat foundation: Angular distortion	Tilt	β (angular distortion − tilt)	Damage
0.05	−0.0002	0.0021	0.0023	Slight damage	0.0007	0.0024	0.0017	Slight damage
0.1	0.0000	0.0042	0.0042	Moderate to severe damage	0.0024	0.0048	0.0024	Slight damage
0.2	0.0006	0.0089	0.0083	Severe to very severe damage	0.0063	0.0092	0.0029	Slight damage
0.3	0.0011	0.0140	0.0129	Severe to very severe damage	0.0110	0.0140	0.0030	Slight damage

Note: Data is from the geometry shown in Fig. 3 (normal fault, 60° dip, 15-m-deep soil deposit, 2.0 m of previous vertical fault movement, $N_{1,60} = 22$, and $K_o = 0.45$). Damage definitions are according to Boscardin and Cording (1989). Boscardin and Cording (1989) use the values of β and lateral strain to estimate building damage. Induced-lateral strain was negligible for all instances.

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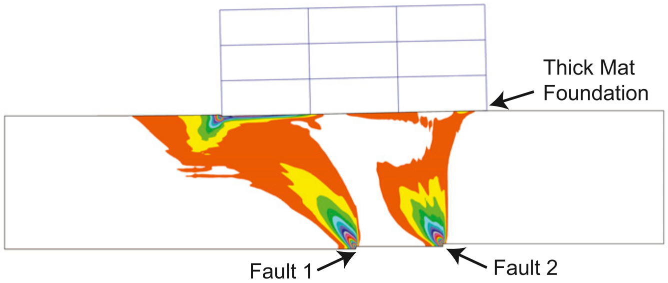

Fig. 7. Complex fault ruptures (as an example, two fault breaks 10 m apart are shown) can be mitigated by versatile mitigation strategies, such as thick mat foundations (shown) or engineered fill; for this example, very slight damage was calculated for a 1.2-m-thick mat foundation and moderate to severe damage was calculated for a 0.45-m-thick mat foundation, according to the Boscardin and Cording (1989) method; contours of shear strain are shown (60° dip, 15-m-thick soil deposit, 0.6 m of vertical fault movement, no previous fault movement, $N_{1,60} = 22$, and $K_o = 0.45$)

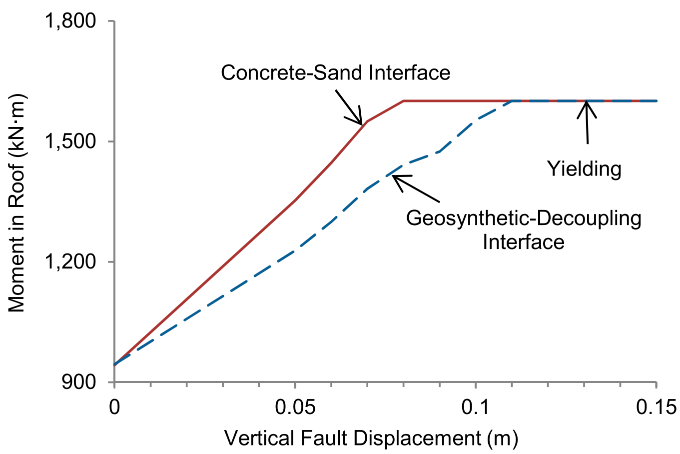

Fig. 8. Comparison of building performance with and without a decoupling geosynthetic slip layer (normal fault, 30° dip, 15-m-thick soil deposit, no previous fault movement, $N_{1,60} = 22$, $K_o = 0.45$, 0.45-m-thick mat foundation, and 11° interface friction compared with the full friction angle of the sand)

et al. 1976; Lettis et al. 2000). Fault diversion strategies investigated herein include ground improvement beneath a structure, a diaphragm wall between a fault and structure, the addition of a basement, tying a building down with ground anchors, and installing a seismic gap between the fault and structure. The inherent weight of a structure is also known to divert fault rupture (Berrill 1983). This effect has been implicitly included in the scenarios analyzed herein.

A diversion strategy is useful when a structure is located on a single side of a bedrock fault or at the edge of a bedrock fault zone with sufficient soil or engineered fill overlying bedrock to divert the fault. It is necessary when relying on fault diversion to have a well-characterized fault zone to ensure that the fault can be adequately diverted from the structure. A more versatile design strategy is prudent in areas where the fault zone cannot be well characterized. A relatively small setback can often achieve similar performance to fault diversion because fault diversion can only occur at the edge of a fault zone. However, in areas with constrained siting requirements, or for existing buildings, diversion strategies may be useful. The diversion strategy warrants caution, however, because the hanging wall of the bedrock fault often undergoes distributed shearing. As stated previously, often the underlying fault-induced movement does not just displace along a distinct fault; instead, the primary fault offset is accompanied by significant warping of the hanging wall block. In these cases, diversion by deflecting the primary fault rupture, but not the associated ground warping of the hanging wall, may prove to be ineffective. Thus, the diversion strategy should be considered primarily for cases when the structure is situated on the footwall of a dip-slip fault (or with strike-slip faulting).

Gazetas et al. (2008) suggested that it may be appropriate to assume the worst case position of a structure relative to a fault. However, this may be unnecessarily conservative in cases where fault trenching clearly identifies the extent of a fault and a reasonably wide zone in which the fault can be expected to rupture can be established. Combinations of mitigation strategies can be used with fault diversion strategies to provide higher levels of reliability where potential bedrock fault ruptures are not well located.

Ground Improvement

Increasing the strength and stiffness of soil beneath a structure could divert a fault rupture away from the building and limit damaging foundation deformation. With this approach, the structure and improved ground must be entirely on one side of the bedrock fault. If the ground were improved directly on top of the fault, the fault would be forced to propagate through the improved ground, and no fault diversion would take place. Several ground improvement techniques can be used to increase the strength and stiffness of the soil, including vibratory compaction, jet grouting, and deep soil mixing.

The effectiveness of ground improvement as a mitigation strategy is analyzed herein. An increase in the foundation soil relative density was modeled using the constitutive model by adjusting $N_{1,60}$, which causes an appropriate scaling of strength and stiffness. Cement treating was modeled by replacing the foundation soil with Mohr-Coulomb material with properties appropriate to cement-treated sand [e.g., $\varepsilon_{af} = 0.2\%$, $\mu = 0.167$, $\phi = 30°$, and $c = 490$ kPa from Namikawa and Mihira (2007)]. Ground improvement was applied over a 6-m-wide zone under the building on the side closest to the bedrock fault, as shown in Fig. 9. The results indicate that ground improvement can significantly improve building performance. Structural performance was improved from moderate to severe damage to slight damage [using the criteria of Boscardin and Cording (1989)] when the soil's relative density was increased because of soil densification ground improvement technique applied on the footwall side of a reverse fault. Ground improvement through cement treatment resulted in a very slight damage state being developed in the overlying structure.

Diaphragm Wall

Fault diversion can be achieved by installing a diaphragm wall between the bedrock fault and the structure. In the case of a normal fault, the diaphragm wall will act like an excavation support system where the fault can be thought of as excavating the adjacent soil. The diaphragm wall can be designed to support the structure and prevent the structure from being undermined by fault movement. In the case of a reverse fault, the diaphragm wall can shield the structure from the fault rupture propagation.

Several numerical analyses were performed for normal and reverse fault movements to evaluate the effectiveness of this mitigation strategy. A 1.2-m-thick RC diaphragm wall (Nikolinakou et al. 2011) was installed 2 m from the otherwise unmitigated 3-story building with a 0.45-m-thick mat foundation. A tieback was installed

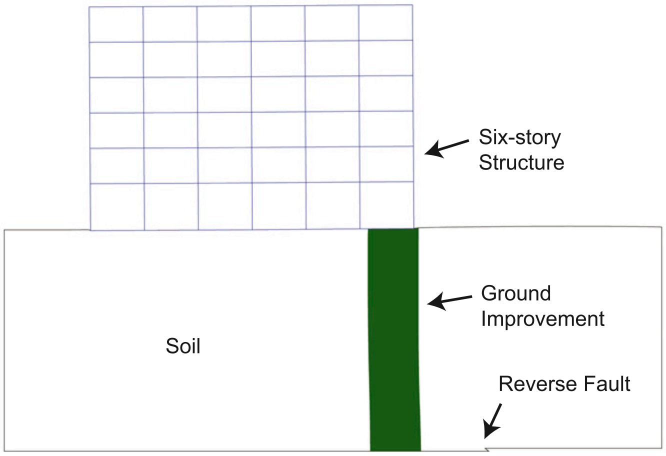

Fig. 9. Ground improvement by densification of the soil beneath a structure results in estimated slight damage compared with moderate to severe damage according to the definitions in Boscardin and Cording (1989) for this representative situation [reverse fault, 60° dip, 25-m-thick soil deposit, 0.6 m of vertical fault movement, no previous fault movement, $N_{1,60} = 12$ ($N_{1,60} = 36$ in densified zone), $K_o = 0.45$, and 0.45-m-thick mat foundation]

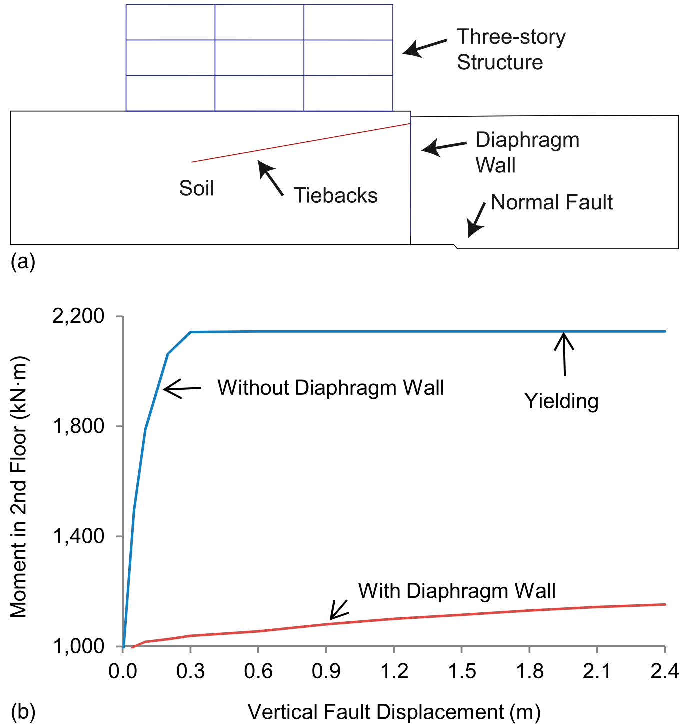

Fig. 10. Comparison of building performance with and without a diaphragm wall: (a) model geometry; (b) loads induced in the building are significantly decreased with the diaphragm wall (normal fault, 60° dip, 15-m-thick soil deposit, 2.0 m of previous vertical fault movement, $N_{1,60} = 22$, $K_o = 0.45$, 0.45-m-thick mat foundation, 1.2-m-thick diaphragm wall, 1,500-kN anchor capacity, 800-kN pretensioning, and 3.0-m anchor spacing)

at approximately 1.5 m below the ground surface for the normal fault case. Tiebacks were not used for the reverse fault because the wall was being loaded by the fault and the tiebacks would not be engaged. The analysis was performed for cases wherein the structure was located on the footwall side of the fault, as shown in Fig. 10(a).

These analyses indicate that diaphragm walls can significantly reduce building damage. Results presented in Fig. 10(b) show that the bending moments in the structure are minimal when a diaphragm wall is installed. Without the diaphragm wall, the structure would have yielded significantly after only a moderate amount of vertical fault movement (<0.3 m). This strategy was effective for substantial normal fault movements. The robust diaphragm wall diverted the fault rupture from the structure and provided the required support. By varying the location and characteristics of the diaphragm wall, this mitigation strategy was generally more effective when the wall was closer to the structure and installed to greater depths.

Basement

As discussed previously, a strong basement can divert fault movement away from the structure. A basement can lower the foundation level below the expected fault propagation plane and cause the fault plane to intersect the basement perimeter walls rather than the bottom of the foundation. If the basement walls are sufficiently strong, the fault rupture can be diverted along the basement walls, reducing damage to the building. As suggested in Duncan and Lefebvre (1973), the passive soil pressure is the maximum pressure that soil can exert on a basement wall. A stiff basement can also increase the rigidity of the foundation similar to a thick mat foundation.

Several numerical analyses were performed to evaluate the performance of basements in active fault zones. The unmitigated 3-story building with a 0.45-m-thick RC mat foundation, shown in Fig. 3, was modified by adding one level of RC basement walls. The interior columns of the building were assumed to extend to the foundation, and the same beams used for the second floor were used for the ground floor. The structure was not modified otherwise. The results of these analyses indicate that a basement, under the described circumstances, can be beneficial for mitigating the surface fault rupture hazard. The addition of a strong basement improved the structure's performance from a moderate to severe damage state to a negligible damage state, as defined in Boscardin and Cording (1989).

Ground Anchors

Tying a structure down with stiff ground anchors can also cause the fault rupture to divert around a structure. This approach can be a viable option for structures located on the footwall of a reverse fault. As long as the bonded portion of the ground anchors is well below the expected fault rupture plane and sufficiently strong, the anchors will act to hold the building foundation at a constant elevation, causing the fault to be diverted around the structure.

Several analyses were performed to evaluate the effectiveness of using ground anchors as a mitigation strategy. In these examples, the ground anchors were extended to 1 m above the base of the model and had a bonded length of 4 m. The 3-story unmitigated structure with a 0.45-m-thick RC mat foundation was used as the structural model. The ground anchors were placed at each column. The results shown in Fig. 11 indicate that structural damage can be significantly reduced with ground anchors. This strategy was effective even at large fault movements. However, the installation of ground anchors can be deleterious to the performance of the structure if the location of the fault, or the edge of the fault zone, is mischaracterized. This is the case in the example shown in Fig. 12. Poor performance will also occur if the ground anchors are shorter than necessary, as was observed in Anastasopoulos and Gazetas (2007).

Robust, well-designed drilled shaft or pile foundations may be used similarly in some cases to divert an underlying fault rupture

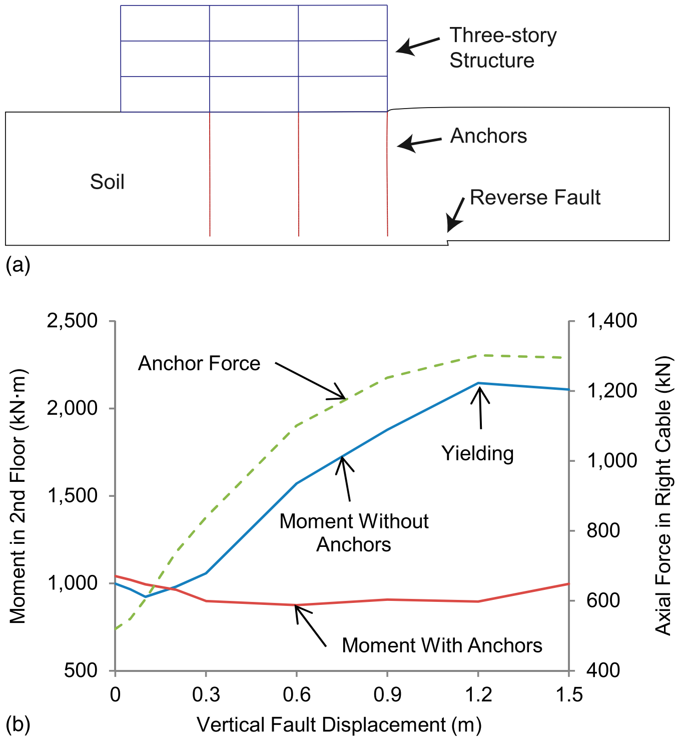

Fig. 11. Comparison of building response with and without ground anchors: (a) model geometry with anchors; (b) loads induced in the structure are significantly decreased when the anchors are used (reverse fault, 60° dip, 15-m-thick soil deposit, 2.0 m of previous vertical fault movement, $N_{1,60} = 22$, $K_o = 0.45$, 0.45-m-thick mat foundation, 1,500-kN anchor capacity, 500-kN pretensioning, and 5-m anchor spacing)

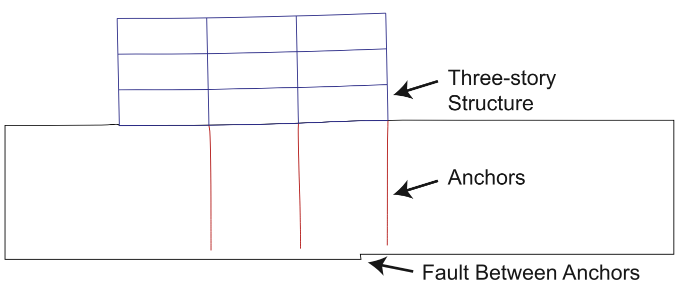

Fig. 12. Structure can be more damaged with anchors installed than if no anchors were present if the fault ruptures between anchors, thus only tying part of the building down

around a building. However, because of the complexities of modeling pile foundations in a fault zone (e.g., three-dimensional effects), this case was not analyzed. If used, it is critical that the fault movement be characterized adequately, because if differential ground movement occurs within the drilled shaft or pile foundation, the shafts/piles will be essentially locked into both sides of the fault and the differential ground movement will be transferred into the superstructure with disastrous consequences. Bray and Kelson (2006) use the example of a tree that is ripped apart because it is rooted into the ground on both sides of a strike-slip fault offset to illustrate the potentially adverse effects of locking a structure into the ground. Therefore, this strategy must only lock the structure into one side of the ground adjacent to the fault, which should be the footwall for a dip-slip fault displacement scenario.

Seismic Gap

It may be difficult to use the fault diversion mitigation strategies described herein at sites with rock near the surface. Therefore, a strategy was developed, which should perform well at rock sites. By placing a seismic gap between a reverse fault and a structure, the anticipated reverse fault movement can be accommodated by allowing the fault-induced ground movement to displace into the seismic gap. The excavation support system used during construction can be left in place with sufficient consideration of durability issues to provide a seismic gap between it and the embedded building. A compressible cover is required over the gap. The seismic gap could also be filled with very compressible material.

Conclusions

Surface fault rupture can be damaging to structures built on or near active faults. For the baseline structure examined, which underwent dip-slip fault displacements without geotechnical mitigation, the fault-induced ground deformations typically produced yielding of the structure's floor beams, starting from the second floor toward the roof, in bending at the beam-column joints and failure in bending in relatively thin mat foundations (approximately <0.8 m). For structures with RC mat foundations, this damage was predominately caused by angular distortion of the ground and not by lateral ground strain. For structures with spread footings, both angular distortion and lateral spreading significantly damaged the structures. Several geotechnical mitigation strategies were then examined. These strategies are categorized as (1) diffusing fault displacement over a large area, (2) causing the structure to respond with rigid-body movement, and (3) diverting the fault rupture. The effectiveness of these strategies can vary from protecting life safety to preventing significant damage and can be effective for a range of dip-slip fault displacements. Ultimately, the structural demands resulting from permanent ground deformation should be added to the demands from transient ground motions and compared against the project design criteria.

Structural response was significantly improved using the fault movement diffusion strategy when the previously ruptured soil was replaced by ductile compacted earth fill, because the fault movement was spread over a wide zone in distributed shear. Earth fills should be sufficiently thick and ductile to prevent the underlying fault dislocation from developing at the ground surface again.

RC mat foundations effectively mitigated the surface fault rupture hazard. This strategy was effective for both reverse and normal faults for many site and structural conditions. Specifying a mat of at least minimal thickness may be prudent in areas where a fault zone is known to exist but is concealed or poorly defined and cannot be located with confidence. Thicker mat foundations provide superior performance and are recommended in areas where shallow active faults are known to exist. Mat foundations will also improve structural performance in combination with other mitigation strategies.

Several fault diversion strategies proved effective at protecting structures from bedrock fault movement. These strategies are limited, however, to structures placed on one side of a bedrock fault, which should in most cases be the footwall side of a dip-slip fault. These strategies are not as versatile as using a thick RC mat foundation or ductile compacted earth fills. The fault diversion mitigation strategies are also more tenuous than the other strategies, because mischaracterization of the fault zone could lead to poor system performance. Therefore, it is recommended that a mat foundation be used in conjunction with a fault diversion strategy, when possible, for additional resiliency.

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Ground improvement beneath the structure proved to be an effective fault diversion strategy in some cases. This approach caused shear strains to concentrate in the adjacent unimproved ground. Diaphragm walls can be installed between faults and structures to shield ground deformation from the structure. Basements can be placed to deflect fault movement so the shear rupture propagates along the side of the strengthened basement walls. Similarly, seismic gaps can be placed on the fault side of a structure to accommodate fault movement. Finally, ground anchors can hold structures down on the footwall side of reverse faults when the ground anchors are bonded well below the expected fault rupture plane.

The development of effective geotechnical mitigation strategies of the surface fault rupture hazard demands an interdisciplinary approach that includes a comprehensive geologic characterization of the potential fault displacements, including secondary faults, a thorough geotechnical investigation of site conditions and evaluation of foundation design strategies and foundation movements, and an appropriate structural design that ensures the structural system and its components will withstand the anticipated movements of the foundation. Additionally, the implementation of the proposed geotechnical mitigation strategies requires a rational legal and regulatory environment. The proposed geotechnical mitigation strategies provide rational means for addressing the hazards associated with surface fault rupture.

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