Designing Buildings to Accommodate Earthquake Surface Fault Rupture

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ABSTRACT

Recent earthquakes have provided several examples of the devastating effects of earthquake surface fault rupture on buildings. Numerous examples of satisfactory performance of buildings have also been observed. These examples of satisfactory performance indicate that similar to other forms of ground movement, effective design strategies can be developed to address the hazards associated with surface fault rupture. Advancements in surface fault rupture hazard mitigation lag behind those for other forms of ground failure, because of the overreliance on avoidance. However, not all faults can be avoided, and not all faults require avoidance if engineering design techniques can be shown to be effective in mitigating the ground deformation resulting from fault movements. Potentially effective design measures include establishing non-arbitrary setbacks based on fault characteristics and site conditions; constructing reinforced earth fills to absorb partially underlying ground movements; using slip layers to decouple ground movements from foundation elements; and designing strong, ductile foundation elements that can resist imposed earth pressures.

INTRODUCTION

Surface fault rupture has severely damaged numerous buildings and bridges during major earthquakes that produce significant ground deformations associated with differential movement along the ruptured fault (e.g., Bray 2001). While documentation of these cases of poor engineering performance is important, it is noteworthy that many other structures that were never designed for surface faulting did not fail when subjected to significant faulting. Unsatisfactory and satisfactory performances of buildings have been observed during these events.

Although avoidance of the trace of an active fault might be one’s preference, it is not always a viable option. There are times when lifelines or structures must cross active faults. There are cases where the traces of active faults are not discovered until after the building has been constructed. In other cases, the amount of potential fault movement is relatively small. Well engineered structures can be designed to accommodate the ground movements, so avoidance is not necessary. Rational design guidance is required for those cases when buildings need to be evaluated and designed to accommodate the hazards associated with surface fault rupture. In this paper, some important lessons from observations of surface faulting are summarized, and some earthquake surface fault rupture design considerations are discussed.
EARTHQUAKE SURFACE FAULT RUPTURE

The phenomenon of earthquake surface fault rupture is described in several publications, including Bonilla (1970), Sherard et al. (1974), Cole and Lade (1984), Bray (1990), Bray et al. (1994a-b), Lazarte et al. (1994), Bray (2001), Bray and Kelson (2006), and Bray (2009). A brief summary of the phenomenon is presented in this paper. The reader is referred to these and other publications for additional information on surface fault rupture.

The principal hazards of earthquake surface fault rupture are: (a) propagation of the distinct shear rupture plane to the ground surface, (b) differential movement or angular distortion of the ground surface, and (c) extensional or compressive horizontal strains at the ground surface. Ground deformations resulting from surface fault rupturing have the potential to damage structures. However, similar to how engineers design structures to accommodate other forms of ground movements, such as expansive soils, mining subsidence, and differential settlement at soft soil sites, the hazards of surface fault rupture can be accommodated for in design.

The factors that largely control the characteristics of surface faulting in the free-field are (Bray 2001): (a) the type of fault movement (reverse, normal, or strike-slip), (b) the inclination of the fault plane, (c) the amount of displacement on the fault, (d) the depth and geometry of the earth materials overlying the bedrock fault, (d) the nature of the overlying earth materials, and (e) the definition of the fault (i.e., well-established or more recently developed). Structures interact with the development of surface fault features and thus can alter the ground deformations associated with surface faulting.

Reverse faults tend to gradually decrease in dip near the ground surface (Bray et al. 1994a). Normal faults tend to refract at the soil-bedrock contact and increase in dip as they approach the ground surface. This refraction and variation of the dip of the normal fault plane may produce gravity grabens. Strike-slip faults tend to follow the almost vertical orientation of the underlying bedrock fault, although the rupture zone may spread or "flower" near the ground surface.

Differential movement across an underlying distinct bedrock fault dissipates as the shear rupture plane propagates through previously unfractured overlying soils. A deep, ductile earth mass can absorb a relatively minor amount of offset across an underlying bedrock fault. In these cases, a distinct surface rupture does not reach the ground surface; instead, the base movement is "spread out" over a wider zone. Thus, ductile earth materials may accommodate significant fault movement by warping without actually developing distinct shear surfaces. Ground warping and secondary ground ruptures are most significant over the hanging wall of dip-slip faults (i.e., over the upthrown block for reverse faults and over the downthrown block for normal faults). Once shear failure develops in the overlying warped earth mass, differential movement is localized primarily to thin, distinct failure planes within the earth. However, additional ground deformation will continue to occur adjacent to the fault primarily in the hanging wall of dip-slip faults and in ductile ground adjacent to a strike-slip fault.

The distance that a distinct bedrock rupture propagates up through overlying earth materials that were previously unfractured is primarily a function of the ductility
of the overlying materials and the amount of relative displacement across the bedrock fault. Numerical simulations validated by the results of carefully performed physical model experiments and the trends found in documented field studies indicate that at a specified amount of bedrock fault displacement, the height that the shear rupture will propagate up into the overlying soil can be related to the failure strain of the soil as shown in Figure 1 (Bray et al. 1994b).

The angular distortion and lateral ground strain that would likely develop at the ground surface can be estimated through the use of calibrated numerical simulations. These calculations with the application of engineering judgment may be used to evaluate fault setback criteria when the ground deformation is significant and to evaluate mitigation measures when the level of ground deformation can be made to be tolerable. For example, the ductility of the soil that overlies the bedrock fault has been found to be an important soil response characteristic. More ductile soils spread the distinct offset in the bedrock over a wider area, which limits differential ground movements and ground strain. Thus, geosynthetic reinforcement that increases the ductility of a compacted earth fill can be used to minimize the depth of over-excavation and the amount of earth fill required to mitigate the surficial hazards of earthquake fault rupture at a project site (Bray et al. 1993).

Figure 1. Normalized height of shear rupture zone in earth overlying base rock fault as a function of its failure strain (Bray et al. 1994b).

SURFACE FAULT RUPTURE-STRUCTURE INTERACTION

The manner in which surface faulting interacts with structures is illustrated through several well-documented case histories. Recent earthquake surface fault rupture events in highly urbanized areas have provided exceptionally insightful observations that can be used to develop engineering design guidance (Bray 2009).

Several cases that illustrate the effects of faulting on structures were documented at the northern end of the Chelungpu fault in Taiwan. For example, the four-story reinforced concrete structure shown in Figure 2 was uplifted approximately 4.5 m across its width, which rendered the building unserviceable. Everyone in the building was able to evacuate, however, so the building code’s life safety objective was not compromised.

The reinforced concrete shear walls of the building worked in combination with a reportedly well-reinforced 0.6 m-thick reinforced concrete mat foundation to...
allow the building to tilt excessively in a nearly rigid body mode. The tilting led to some internal deformation of the building, but the occupants were able to walk down the stairs of the building without incident following the event. Thus, a robust structural system with stiff, high-strength shear walls and a thick reinforced concrete foundation can undergo significant ground deformation associated with surface fault rupture without collapsing.

Figure 2. Reinforced concrete building tilted by about 4.5 m of reverse fault displacement without collapsing during 1999 Chi-Chi earthquake.

The two-story building with a robust foundation (i.e., a 30 cm-thick mat overlain with 1 m deep grade beams in a grid layout) that is shown in Figure 3 was subjected to significant differential horizontal ground displacement, but it was largely undamaged (Lettis et al. 2000). The North Anatolian strike-slip fault displaced 3 to 3.5 m horizontally underneath this building during the 1999 (Mw = 7.5) Kocaeli, Turkey earthquake. The fault rupture movements displaced the building, but there was no observable damage to the building. The building’s structural frame was essentially undamaged, although its structural system is relatively weak and brittle (i.e., reinforced concrete frame with in-filled walls).

Figure 3. House with robust foundation is not damaged significantly as a result of over 3 m of right-lateral fault displacement (Lettis et al. 2000).

In another area affected by the 1999 Kocaeli earthquake, another two-story building, which is shown in Figure 4, has no discernable damage (i.e., the glass windows are not even broken), although it is situated less than 1 m off the primary
trace of the normal fault rupture that occurred in this area. Ground deformation is not uniformly distributed on each side of a dip-slip fault. Significantly more ground deformation occurs over the hanging wall, which in this case is the downthrown block in the foreground of the photograph. Thus, setback distance from the primary trace of a dip-slip fault should not be arbitrarily the same amount on each side of the fault.

Figure 4. Lack of secondary ground deformation on the footwall of the normal fault movement near Golcuk during the 1999 Kocaeli earthquake.

If significant differential ground movements are produced by surface faulting under a building, its foundation should not be “rooted” into the ground. The heavily reinforced concrete bunkers shown in Figure 5a are internally very strong, but they are not fixed into the ground. The shear rupture in this case is more likely to move around the relatively stiff and strong bunkers than to break through them. Conversely, the pile-supported wharf structure shown in Figure 5c is fixed into the ground surrounding the primary trace of the fault. As the ground on each side of the fault displaces relative to each other, the piles go with the ground, and nearly all of the differential ground movement from the surface faulting is transferred up into the wharf’s deck. The deck is not sufficiently strong to withstand the large forces induced through the fault movement, so it is severely damaged.

Useful analogies to these different structural responses are the telephone pole and tree responses shown in Figures 5b and 5d, respectively. The telephone pole is not rooted into the ground on each side of the fault, but the tree is rooted into the ground on each side of the fault. The telephone pole, not being anchored into the surrounding ground, may displace as a rigid body, but it does not undergo internal deformation. The tree trunk is split, because its foundation of many strong roots on each side of the fault forces all of the differential ground deformation to be concentrated within it.

Therefore, a building’s foundation influences significantly its structural response to surface faulting. Structures that are tied to the ground (i.e., pile foundations) will undergo nearly the full relative displacement of the ground movements; whereas structures that are allowed to move relative to the ground (i.e., a shallow well-reinforced concrete mat) will undergo rigid body movement, but the structure will be isolated from much of the damaging effects of the differential ground movements.
Figure 5. Different responses to surface fault rupture: (a) heavily reinforced concrete bunkers that underwent over 4 m of strike-slip offset without cracking (Lettis et al. 2000); (b) telephone pole undamaged by surface faulting (Ulusay et al. 2001), (c) pile-supported wharf damaged by 2.4 m of strike-slip offset; and (d) tree trunk split by surface faulting through roots of tree (Ulusay et al. 2001).

A side-by-side comparison of two different structural systems undergoing similar ground deformation resulting from surface fault rupture with different performances is shown in Figure 6. The 8 m-diameter, 0.3 m-thick unreinforced brick forebay was heavily damaged by the distributed ground deformation between the main-trace of the San Andreas fault and an auxiliary fault to the west of it (Lawson et al. 1908). It was deformed into a 9 m by 6.5 m oval. This response can be contrasted to that exhibited by a rectangular-shaped concrete forebay that was constructed of three compartments, each 0.76 m by 0.76 m in plan. The relatively stiff and strong concrete structure was undamaged, even though it was located about the same distance off of the primary fault trace and was intersected by a secondary fault trace.

If a long structure or lifeline must traverse a fault that could undergo surface rupture, it should be designed to respond flexibly to the differential ground movement. For example, the relative ground displacement that occurs along a line oriented perpendicular to the strike of a strike-slip fault must be transferred to a long structure that is aligned along this line if it is eventually locked into the ground at two distant points from the fault trace. In these cases, the structure cannot accommodate the ground deformation through a rigid body mode of deformation and it should be able to deform internally without collapse. As an example, the Trans-Alaskan pipeline was designed to accommodate movement from an active strike-slip fault (Cluff et al. 2003). The pipeline was moved out of the ground as it approached the
fault and placed on Teflon-coated supports with sufficient slack to accommodate the anticipated surface fault displacement. During the 2002 Denali earthquake, the system was sufficiently flexible to withstand the ground movements associated with surface fault rupture without compromising the performance of the pipeline.

Figure 6. Interaction of two structures situated astride the San Andreas fault (Lawson et al. 1908).

DESIGN CONCEPTS FOR THE SURFACE FAULT RUPTURE HAZARD

Principal Measures. There are four principal measures for addressing the potential hazards associated with earthquake surface fault rupture: (a) land use planning, (b) engineering geology, (c) geotechnical engineering, and (d) structural engineering. Some of the primary elements of these measures are provided in Table 1. Discussions of each of these measures are presented in the following sections of this paper.

Land Use Planning. The most straightforward approach for addressing the surface fault rupture hazard is avoidance through land use planning. The California Alquist-Priolo Earthquake Fault Studies (A-P) Act of 1972 often serves as a model of this approach. It has been effective in restricting development atop of active faults in the State of California. Other states have also adopted land use planning regulations to address this hazard through avoidance.

The original intent of A-P Act, however, was to “provide policies and criteria to assist cities, counties, and state agencies in the exercise of their responsibility for the public safety in hazardous fault zones.” The original intent was to not locate a “structure within a delineated special studies zone if an undue hazard would be created …” Later in 1973, the California State Mining and Geology Board introduced the language of prohibiting structures with human occupancy “to be placed across the trace of an active fault.” There was a shift from “hazardous” fault to “active” fault, and a move from protecting the public from an “undue hazard” to not placing a structure “across the trace of an active fault.” Not all active faults are hazardous.

To provide some level of conservatism, the often misunderstood 50 feet (15 m) setback criterion was also added. It required that an area within 50 ft of a trace of an active fault “shall be presumed to be underlain by active branches of that fault unless proven otherwise ...” If an appropriate geologic investigation demonstrates that the
ground adjacent to an active trace does not contain active branches of that fault trace then a structure may be sited directly adjacent to the primary trace.

One of the primary deficiencies of the current version of the A-P Act is that it places all active faults in the same category. It is not reasonable to treat the primary trace of the San Andreas fault, which could have meters of movement across it, the same as an unnamed minor bending moment fault that may have moved once in the last 11,000 years a few centimeters. If land-use regulators allow engineers to mitigate major landslides, mining subsidence, and liquefaction-induced lateral spreads, they should also allow engineering mitigation of minor active faults. Also, it is sometimes impossible or too costly to avoid active faults.

Table 1. Defensive measures for accommodating surface fault rupture

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<thead>
<tr>
<th>LAND USE PLANNING</th>
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<td>Avoid areas with the potential for surface fault rupture</td>
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<tr>
<th>ENGINEERING GEOLOGY</th>
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<tr>
<td>Identify and avoid primary faults</td>
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<tr>
<td>Establish non-arbitrary setbacks based on fault and ground conditions</td>
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<tr>
<td>Estimate amount and type of potential fault displacement</td>
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<th>GEOTEchnical ENGINEERING</th>
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<tr>
<td>Construct ductile earth fills to spread out fault displacement</td>
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<tr>
<td>Install soil reinforcement</td>
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<td>Use slip layers to decouple ground movements from foundation</td>
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<td>Keep the base of all foundation elements at the same elevation</td>
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<tr>
<td>Avoid protrusions that would act like cleats to lock the building into the ground</td>
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<td>Place compressible materials adjacent to walls and utilities</td>
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<th>STRUCTURAL ENGINEERING</th>
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<td>Design strong, ductile foundations, such as thickened reinforced mat foundations, waffle slabs, and post-tensioned slabs</td>
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<tr>
<td>Do not use piles or piers that tie structure into the ground</td>
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<tr>
<td>Design structure to be flexible and with isolation joints</td>
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<td>Install “catcher bents” or ties for bridge spans that must cross over faults</td>
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**Engineering Geology.** The success of the every mitigation approaches depends on a sound engineering interpretation of the regional and local geology. A comprehensive geologic study by a well-trained and highly experienced team of engineering geologists is critically important. The results of the geologic study provide the key fault parameters such as fault type, fault geometry, and the amount, sense, and distribution of potential ground movement associated surface fault rupture. Best estimates of each should be provided with upper and lower estimates at about the 16% and 84% probability levels to capture the significant uncertainty of this complex phenomenon. Surface faulting, however, is generally no more complex than other earthquake hazards, such as ground shaking, liquefaction, and landsliding. These
other hazards are often currently characterized through a probabilistic seismic hazard assessment that provides some assessment of the variability in the seismic demand parameter. Correspondingly, the surface fault rupture hazard should not be characterized only through a “worst” case deterministic assessment.

Ground deformations associated with surface faulting are not equally distributed on each side of the fault. Hence, the engineering geologist should work toward interpreting the geologic information to establish non-arbitrary setbacks based on specific site, fault, and soil characteristics. Although the profession requires continual enhancement of its understanding of the surface faulting, sound judgment, coupled with reasonable interpretations of surficial geology and crack propagation theory, can be applied to develop earthquake-resistant designs without relying strictly on avoidance. In most cases, an accurate record of the likely characteristics of a future fault displacement is captured in the geology record. Through mapping, trenching, and other tools, the engineering geologist can provide a reasonable description of the amount and type of potential fault displacement at the project site.

**Geotechnical Engineering.** The geotechnical engineer plays an integral role in what should be a multi-disciplinary team of experienced engineers and scientists that evaluates the surface fault rupture hazard and develops effective design measures.

One geotechnical engineering approach is to use the inherent capability of soil to “locally absorb” the distinct offset across a bedrock fault. Differential movement across a distinct bedrock fault dissipates as the shear rupture plane rises through an overlying compacted earth fill, especially if it is reinforced with geosynthetics (Bray et al. 1993, 1994a-b). The relative displacement across the bedrock fault is spread across a wider zone of shearing in the reinforced earth fill. This spreading of the localized bedrock fault displacement over a wider zone at the ground surface reduces angular distortion and lateral ground strain at the foundation level. Hence, ductile compacted earth fills or reinforced earth fills may be used to mitigate earthquake fault rupture hazards.

An alternate approach is to construct a weak soil element, such as a bentonite slurry wall built above a fault trace, to localize most of the differential fault movement across a narrow zone. By narrowing setback distances from the primary fault trace, more land would become available for development. The bedrock fault movement and the associated warping of the adjacent rock will eventually be expressed at the ground surface. The geotechnical engineer can help evaluate the amount and distribution of ground movement and either attempt to spread it out over a wider area or to localize it to a narrower zone.

Reinforced concrete mat foundations and interconnected spread footings, which should all have the same base elevation, can be constructed atop a double layer of smoothly laid-out polyethylene sheets sandwiched between layers of clean coarse sand to fine gravel to “decouple” anticipated ground deformation from the foundation elements. This defensive design measure will minimize the transfer of horizontal strains in the ground below the foundation to the structure. Trenches excavated to construct grade beams and underground utilities can be backfilled with loose soil or styrofoam to reduce lateral earth pressures that can develop on these elements.
Many of these geotechnical design measures have been used successfully in areas subject to ground deformations associated with mining subsidence. Several of these approaches are described in Kratzch (1983). Potential ground deformation beneath a structure from mining subsidence or expansive soils, for example, are routinely accommodated in foundation engineering. Most of these approaches can be employed to address the earthquake surface fault rupture hazard as well.

**Structural Engineering.** A building can be designed by an experienced structural engineer to undergo some limited amount of ground deformation without significant structural damage or collapse. The design of structures subjected to ground deformation resulting from other forms of ground deformation is generally applicable. Foundation elements should be heavily reinforced to improve ductility and their bases should be at the same elevation. The use of foundation elements that tie the structure into the ground should be avoided. Pile or pier foundations force the superstructure to undergo a large amount of differential ground displacement across the building’s footprint. Likewise, a two-level foundation design would likely “lock” the building into the ground. The foundation elements should be designed to minimize the transfer of ground strain into the superstructure.

The maximum allowable angular distortion to limit architectural damage for many buildings, which includes a factor of safety of about 1.5, is 1/500. However, well-designed buildings can undergo significantly more angular distortion before structural damage occurs (i.e., approximately 1/150). Specially designed and built structures can tolerate even more ground distortion without posing a life safety risk to the building’s occupants. The maximum allowable horizontal tensile ground strain below buildings is on the order of 0.3%. The combination of angular distortion and lateral strain of the ground, after considering that portion that will be transmitted into the building’s foundation, should be considered in design.

There is likely no mitigation method (other than avoidance) that is more important than the use of a well-reinforced thickened mat foundation. There are countless examples of thick reinforced concrete foundations that undergo significant ground deformation without collapse. The use of waffle slabs or an integrated foundation of footings interconnected with substantial grade beams may also provide the foundation stiffness desired to bridge over gaps and span warped ground. Post-tensioning the floor slab will improve its ability to bridge over irregular ground deformation of limited extent.

In designing the structure, care should be also given to the selection of its structural system. A redundant, robust structural system can work with the building’s foundation elements to reduce internal distortions and enable the structure to respond to ground deformations in primarily a rigid body mode. In those cases, where the structure and its foundation cannot be designed to withstand the anticipated ground deformation, isolation joints can be employed to control deformation within the structure. Flexible structures are also inherently more stable than stiff long structures that must accommodate differential ground movements across a wide zone. Lastly, if large ground movements are possible, then systems can be installed to keep system components from falling, such as “catcher bents” and “ties.”
CONCLUSIONS

Observations of surface fault rupture after major earthquakes provide insight into how differing ground conditions alter the surface expression of faulting and how surface fault rupture affects buildings. These observations provide clear paths forward toward the development of a robust framework for evaluating the hazards associated with earthquake surface fault rupture. Mitigation through the application of sound engineering design practices can be achieved in those cases when avoidance is not possible or practical.

In addressing the surface fault rupture hazard, the potential patterns of ground deformation should be developed through the use of a comprehensive investigation and detailed mapping. Measured patterns of surface fault-induced ground deformation from similar types of faulting from past events offer useful insights to complement site-specific studies. With the likely patterns of expected ground deformation characterized by engineering geologists, civil engineers can design structures to accommodate fault-induced ground movements, when necessary. Building strong, ductile structural foundation elements that can accommodate some level of ground deformation and isolating the superstructure from much of the underlying ground movement are effective design measures. Structures should not be tied into the ground with piles or piers. Other mitigation measures include establishing non-arbitrary setbacks based on fault geometry, fault displacement, and the overlying soil; constructing reinforced earth fills to partially absorb and spread out the underlying ground movements; using slip layers to decouple ground movements from foundation elements; and using compressible materials or voids to reduce ground-movement induced lateral earth pressures.

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