Bray, J.D. (2009) "Earthquake Surface Fault Rupture Design Considerations," Proc. Sixth Inter. Conf. on Urban Earthquake Engineering, Center for Urban EQ Engineering, Tokyo Institute of Tech., Tokyo, Japan, Mar 3-4, pp. 37-45.

EARTHQUAKE SURFACE FAULT RUPTURE DESIGN CONSIDERATIONS

Jonathan D. Bray

Professor, Dept. of Civil & Environmental Engineering, University of California, Berkeley, CA, USA
bray@ce.berkeley.edu

Abstract: Buildings, facilities, and lifelines that will be sited across or adjacent to active faults should be designed considering the hazards associated with earthquake surface fault rupture. Observations of surface faulting during earthquakes show how the resulting ground movements affect engineered systems. Lessons learned from these case histories can be extended to provide insight on a particular project through the use of numerical analyses that have been calibrated by field observations and experimental data. Similar to other forms of ground failure, such as mining subsidence, landslides, and lateral spreading, effective design strategies can be employed to address the hazards associated with surface faulting. These design measures include establishing non-arbitrary setbacks based on fault geometry, fault displacement, and site conditions; constructing reinforced earth fills to partially absorb underlying ground movements; using slip layers to decouple ground movements from foundation elements; and designing strong, ductile foundation elements that can resist the resulting earth pressures.

1. INTRODUCTION

Surface fault rupture has severely damaged numerous structures during shallow earthquakes that produce significant ground deformations associated with differential movement along the ruptured fault. The spectacular damage of the Shihkang Dam in Taiwan as a result of nearly 9 m of reverse fault movement through the dam during the 1999 M_w=7.6 Chi-Chi earthquake is just one example. While documentation of these dramatic cases is important, it is noteworthy that many other structures that were never designed for surface faulting did not fail when subjected to significant faulting. Both satisfactory and unsatisfactory performances of engineered systems have been observed during these events.

Avoidance of the trace of an active fault is not always a viable option. There are times when engineered systems either currently overlie active faults or must cross active faults. Sometimes the amount of fault movement is relatively minor so avoidance is not necessary. It is imperative that we develop rational design guidance for those cases when a structure needs to be evaluated and designed to accommodate the hazards associated with surface fault rupture. In this paper, key observations of surface faulting are summarized and earthquake surface fault rupture design considerations are discussed.

2. SURFACE FAULT RUPTURE HAZARDS

2.1 Principal Hazards

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.

The first hazard is obvious and one that should be avoided if possible. However, engineered systems can be designed to deflect or accommodate the extreme differential ground movement that occurs across a displaced fault. If the shear rupture does not reach the ground surface, the ground will still be warped due to the underlying rock fault displacement. In these cases, the engineer should assess the amount of angular ground distortion ($\beta = \delta/L$) and lateral ground strain (ε_L) produced beneath the structure's foundation due to the underlying fault displacement. Similar to other forms of ground movement-induced structural damage (e.g., from mining subsidence or excavations), these engineering parameters can be estimated and the structure can be evaluated with regards to its capacity to accommodate the estimated levels of ground distortion and strain. Son and Cording (2005) provide rational criteria for evaluating damage potential due to the combination of angular distortion and lateral strain (Figure 1).

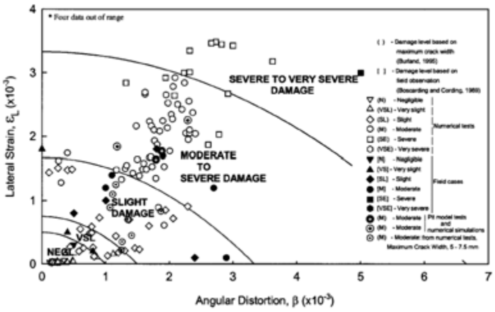

Figure 1 Relationship of Damage to Angular Distortion and Horizontal Extension Strain (Son and Cording 2005)

2.2 Important Factors

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). Engineered systems can alter the ground deformations associated with surface faulting. Detailed descriptions of surface fault rupture are provided in Bray (1990) and Lazarte (1996), and in papers such as Bray et al. (1994a,b) and Bray (2001).

In summary, 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.

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.

Differential movement across an underlying distinct bedrock fault dissipates as the shear rupture plane propagates through previously unfractured overlying soils (e.g., Bonilla 1970, Cole and Lade 1984, Bray et al. 1994a, Lazarte et al. 1994, Lazarte and Bray 1996). A deep, ductile earth mass can “absorb” a relatively minor amount of offset across the 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.

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 2 (Bray et al. 1994b).

Using boundary deformation analyses, the angular distortion and lateral ground strain developed at the ground surface can be estimated. The results of these analyses 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. As the ductility of the soil that overlies the bedrock fault has been found to be an important soil response characteristic, fill-reinforcement materials can be used to optimize 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).

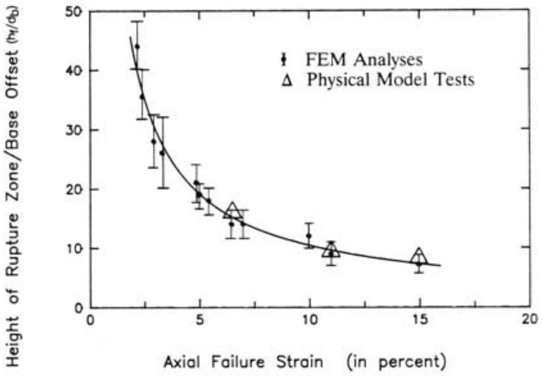

Figure 2 Normalized Height of Shear Rupture Zone in Earth Overlying Base Rock Fault as a Function of its Failure Strain (Bray et al. 1994b)

3. OBSERVATIONS FROM CASE HISTORIES

3.1 General

Specific observations of surface fault rupture serve to illustrate some of the key points that were summarized in the previous section. First, it is insightful to examine field case histories that describe free-field ground deformation resulting from earthquake faulting. Later, the interaction of surface faulting with structures will be examined.

3.2 Free-Field Ground Deformation

Differential ground movement is often concentrated within a relatively narrow zone above the bedrock fault. In many other cases, it is not. Instead, it is spread over a wide zone of distributed shearing.

Careful measurements of ground deformation associated with faulting were made as early as 1906 in the Lawson et al. (1908) report of the 1906 San Francisco earthquake. For example, a detailed survey by H. Schussler of an originally linear fence that was offset by the San Andreas fault rupture provides important insights regarding the characteristics of strike-slip faulting. At this location, Fence “C” exhibited a total lateral offset of 5.2 m over a zone about 370 m wide (Lawson et al. 1908). The survey data were used to construct Figure 3 by Bray and Kelson (2006). The primary fault strand offset Fence “C” approximately 2.2 m, or only about 43% of the total horizontal movement, within a zone less than 12 m wide. The remaining offset was accommodated as “secondary” faulting or ground warping over a distance of about 100 m on both sides of the primary fault zone. These types of measurements illustrates the characteristics of the free-field ground deformation associated with a significant strike-slip fault movement. They can be used to assess whether engineered systems, such as pipelines, can withstand a fault rupture event.

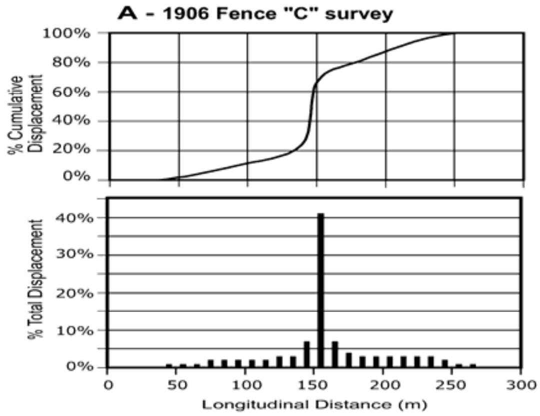

Figure 3 Ground Deformation across the San Andreas fault movement in 1906 as interpreted from the detailed survey of Fence “C” by Schussler in Lawson et al. (1908) (Bray and Kelson 2006)

A more recent example is the surface fault rupture zone produced by the 1992 (M_w = 7.3) Landers, California earthquake. It was often expressed as a broad shear zone, hundreds of meters wide with numerous individual fractures (Lazarte et al. 1994). Although the majority of relative fault displacement often occurred within a zone only 10 m wide or less, significant fractures and ground movements (on the order of a few centimeters, which is sufficient to be of engineering interest for many projects) were observed over a zone 100 m wide or more.

The stress-deformation response of the soil that overlies a ruptured fault was shown to be important. For example, the loose, compressible, wind-blown sand dune shown in Figure 4 spread the distinct bedrock displacement of several meters across a much wider and diffused zone of shearing.

Figure 4 1992 Landers Earthquake Fault Rupture through a Sand Dune (photo by E. Gath).

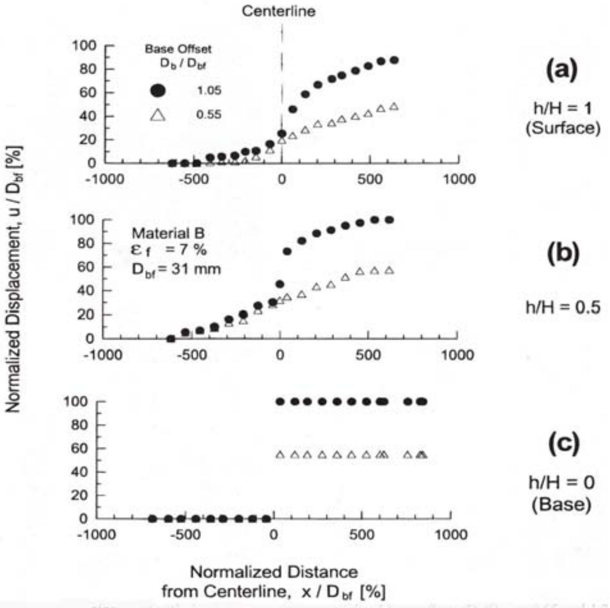

Figure 5 Distribution of Horizontal Displacement with Depth for Increasing Normalized Base Offsets: (a) Surface, (b) Mid-Height, and (c) Base of Model

The development of the shear rupture zone in a ductile, saturated clay deposit overlying a distinct bedrock fault rupture is illustrated in the experiments performed by Lazarte and Bray (1996). In this experiment, a soft mixture of kaolinite and bentonite (3:1) was placed atop a split rigid base, and the right side of the base was displaced horizontally while the left side was kept stationary. Relative displacement was measured at the base of the model and observed at the top of the model. A string-line device at mid-height within the clay allowed the deformation pattern within the clay to be tracked.

As shown in Figure 5, at a base offset of 55% of that required to shear through the height of the clay, the ground deformed in a simple shear mode in the upper half of the clay deposit, even though the distinct shear rupture was imposed at the base of the model. At a larger base offset a distinct shear rupture developed in the middle of the clay. Once this shear developed, the rate of additional warping of the surrounding clay was greatly reduced. A sufficient amount of base deformation was induced so that the distinct shear rupture emerged eventually at the surface of the clay.

The widespread warping of the ground overlying the upthrown block of the Chelungpu reverse fault offset during the 1999 Chi-Chi earthquake is another example of the significant amount of deformation that can occur off the primary trace of a major fault. The warped rice paddies shown in Figure 6 were originally relatively level. Although significant differential movement occurred across the primary trace it can be seen that considerably more vertical ground movement developed in the soil above the hanging wall of this reverse fault. Whereas a setback distance of 15 m might have been adequate on the undeformed ground on the footwall side of this shallow reverse (thrust) fault, it would not have been adequate on the hanging wall. Thus, setback criteria should be based on geologic principals rather than be based on arbitrary, standardized regulations.

Figure 6 Ground Warping Associated with the 1999 Chi-Chi Earthquake (photo by N. Sitar)

Figure 7 Lack of Secondary Ground Deformation on the Footwall of the Normal Fault Movement near Golcuk during the 1999 Kocaeli Earthquake

The two-story building shown in Figure 7 has no discernable damage (even the glass windows are not broken), although it is situated less than 1 m off the primary trace of the normal fault rupture that occurred in this area during the 1999 (M_w = 7.5) Kocaeli, Turkey earthquake. Again, the ground deformation is not uniformly distributed on each side of a dip-slip fault, so setback criteria should not be the same on each side of a dip-slip fault.

3.2 Effects on Structures

The manner in which surface faulting interacts with structures is illustrated through numerous well-documented case histories. Recent earthquake surface fault rupture events in highly urbanized areas have provided exceptionally insightful observations. For example, at the northern end of the Chelungpu fault in Taiwan, several cases that illustrate the effects of faulting on structures were documented. The four-story reinforced concrete structure shown in Figure 8 was uplifted approximately 4.5 m across its width, which rendered the building unserviceable. However, everyone in the building was able to evacuate. Thus, the life safety objective of most building codes was achieved.

Figure 8 Reinforced Concrete Building Tilted by about 4.5 m of Reverse Fault Displacement without Collapsing

In this case, 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. At the time that this picture was taken, which is several weeks after the event, the author was still able to walk up the stairs and within the building. 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.

The two-story building described in Figure 9 by Lettis et al. (2000) is an example of a structure with a robust foundation (i.e., a 30 cm-thick mat overlain with 1 m deep grade beams in a grid layout), which was subjected to significant differential ground displacement, that was largely undamaged. The North Anatolian fault displaced 3 to 3.5 m underneath this structure. It moved the structure some, but there was no observable damage in the building, although its structural system is relatively weak and brittle (i.e., reinforced concrete frame with in-filled walls).

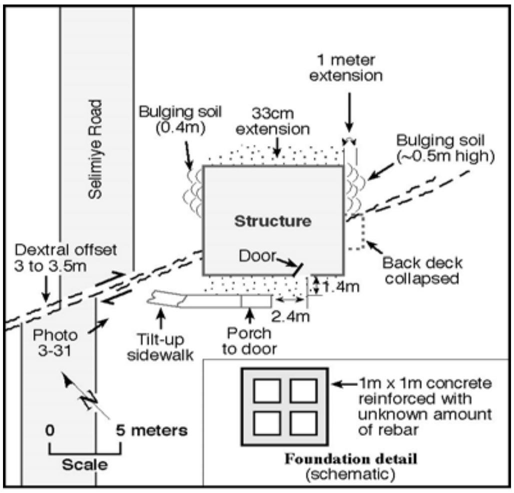

Figure 9 House with Robust Foundation is Not Damaged Significantly as a Result of over 3 m of Right-Lateral Fault Displacement (Lettis et al. 2000)

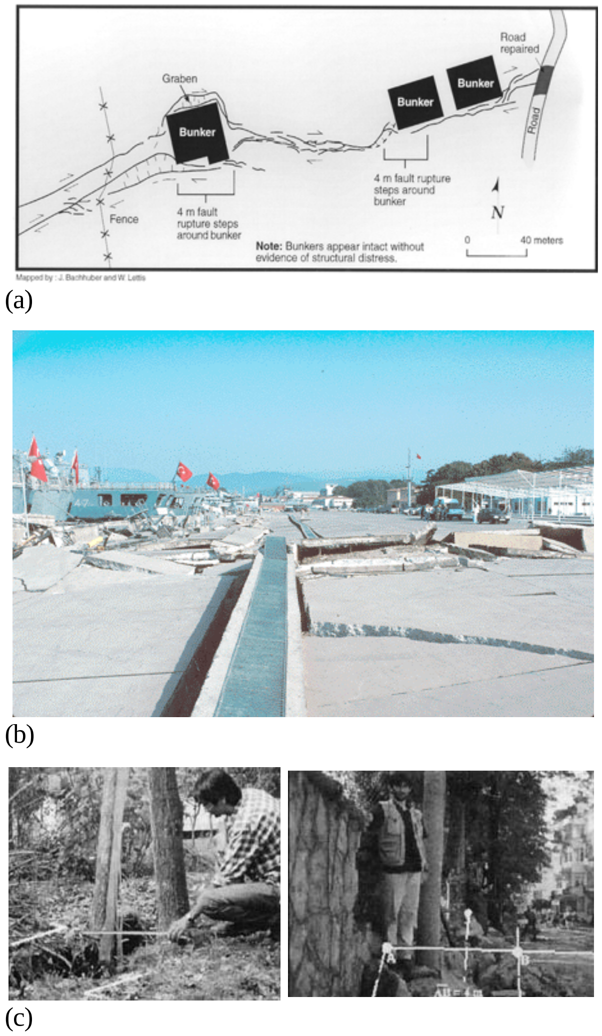

Figure 10 Different Responses to Surface Fault Rupture: (a) Heavily Reinforced Concrete Bunkers that Underwent over 4 m of Strike-Slip Offset without Cracking (Lettis et al. 2008); (b) Pile-Supported Wharf Damaged by 2.4 m of Strike-Slip Offset; and (c) Tree Trunk Split and Telephone Pole Undamaged by Surface Faulting (Ulusay et al. 2001)

If significant differential ground movements are produced by surface faulting under a structure, it is preferred that the structure not be "rooted" into the ground. The heavily reinforced concrete bunkers shown in Figure 10a 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 inclusion of these bunkers than to break them. Conversely, the pile-supported wharf structure shown in Figure 10b is fixed into the ground surrounding the primary trace of the fault. As the ground on each side of the trace of the fault displaces relative to each other, the piles go with the ground, and nearly all of the differential ground movement is transferred up into the deck of the wharf. The deck is not sufficiently strong to withstand the large forces induced through the fault movement, so it is heavily damaged as a result of surface fault rupture.

Useful analogies to these different structural responses are the tree and telephone pole responses shown in Figure 10c. The tree in the left photograph is rooted into the ground on each side of the fault. The telephone pole in the right photograph is not rooted into the ground on each side of the fault. Whereas there are numerous observations in the literature of trees that are well rooted on both sides of a displaced fault splitting up their trunk, there are no cases of telephone poles splitting due to surface faulting. 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 force all of the differential ground deformation to be concentrated within it.

Therefore, the foundation of a building has a large influence on its structural response to surface faulting. Structures that are tied to the ground (i.e., pile foundations) will undergo the full relative displacement of the ground movements; whereas structures that are allowed to move relative to the ground (i.e., a shallow 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.

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 11. 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 forebay was undamaged, even though it was located about the same distance off of the main-trace and was intersected by the auxiliary fault located to the west of the main-trace.

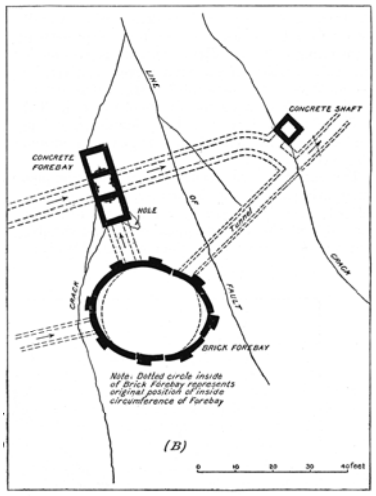

Figure 11 Interaction of Two Structures Situated Astride the San Andreas Fault (Lawson et al. 1908)

Figure 12 Suspension Walkway Bridge Undergoing Relative Movement of its Abutments due to Fault Movement (photo by C. Roblee)

If a long structure or lifeline must traverse a fault that could undergo surface rupture, it may be prudent to design the system to respond flexibly to the differential ground movement. The relative ground displacement that occurs along a line oriented perpendicular to the strike of a strike-slip fault, for example, as shown in Figure 3, 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 must be able to deform internally without collapse. The performance of the suspension bridge shown in Figure 12 is an excellent example of a flexible system that can deform internally between its two anchorages without falling. The Trans-Alaskan pipeline was thoughtfully designed when it crossed a major fault (Cluff et al. 2003). The pipeline was moved out of the ground and placed on Teflon-coated supports with sufficient slack to accommodate the anticipated surface fault displacement. It performed exceptional well during the 2002 Denali earthquake. The design was sufficiently flexible to allow the system to withstand the ground movements associated with surface fault rupture without collapsing.

4. DESIGN CONSIDERATIONS

4.1 General

There are four principal means of mitigating the potential hazards associated with earthquake fault rupture: (a) land use planning, (b) engineering geology, (c) geotechnical engineering, and (d) structural engineering. The California Alquist-Priolo Earthquake Fault Studies Act has served as a model for mitigation of this hazard through avoidance. Although it took damage from surface faulting resulting from the 1971 San Fernando earthquake to motivate politicians to enact it, the A-P Act's underpinnings result from the post-1906 San Francisco earthquake mindset (Bray and Kelson 2006). Echoing the sentiments of many scientists and engineers, Humphrey states: *"It is a generally accepted fact that no structure could have withstood the stresses produced by the movement of the earth at the 'fault trace' …"* (Gilbert et al. 1907). The author prefers the more reasonable approach delineated by Derleth: *"If fortunately located … a structure on or near a fault line may not be seriously crippled … Where structures must be built upon treacherous ground or near fault lines, no expense should be spared for good materials, high grade workmanship, and intelligent design."* (Jordan 1907). Through field observations, physical model studies, numerical analyses, and the application of engineering judgment, the mitigation measures summarized in Table 1 are offered as a rational means for achieving "intelligent design."

Table 1 Mitigation Measures for Engineered Systems

LAND USE PLANNING
· Avoid areas with the potential for surface fault rupture
ENGINEERNG GEOLOGY
· Identify and avoid primary faults · Establish non-arbitrary setbacks based on fault and ground conditions · Estimate amount and type of potential fault displacement
GEOTECHNICAL ENGINEERING
· Construct ductile earth fills to spread out fault displacement · Install soil reinforcement · Use slip layers to decouple ground movements from foundation · Keep the base of all foundation elements at the same elevation · Avoid protrusions that would act like cleats to lock the building into the ground · Place compressible materials adjacent to walls and utilities · For dams, use thick, ductile clay cores, thick upstream "crack-stopper" zones, thick downstream filters zones, thick chimney drains, and rockfill zone at the downstream face · Increase freeboard, minimize reservoir height, and enlarge crest width · Site outlet works and spillway off the fault trace
STRUCTURAL ENGINEERING
· Design strong, ductile foundations, such as thickened reinforced mat foundations, waffle slabs, and post-tensioned slabs · Do not use piles or piers that tie structure into the ground · Design structure to be flexible and with isolation joints · Install "catcher bents" or ties for bridge spans that must cross over faults

4.2 Land Use Planning

The intent of the Alquist-Priolo Act of 1972 was to avoid the surface fault rupture hazard by prohibiting the building of structures with human occupancy across the trace of an active fault. To provide some level of conservatism, the Act established the “infamous” 50 ft (15 m) setback criterion. The Act required that an area within this distance of an active fault shall be presumed to be underlain by active branches of that fault unless proven otherwise. Many scientists, engineers, and regulators forget the last part of this sentence (i.e., “unless proven otherwise”). If a comprehensive geologic study 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. However, most engineers and scientists prefer to setback at least a couple of meters from the trace of a major active fault.

One of the primary deficiencies of the Alquist-Priolo Act is that it treats all active faults the same. Is it reasonable to place the primary trace of the San Andreas fault, which could have meters of movement across it, in the same category as an unnamed minor bending moment fault that may have moved once in the last 11,000 years an amount on the order of a centimeter or two? If land-use regulators allow engineers to mitigate major landslides, mining subsidence, and large liquefaction-induced lateral spreads, why would they not also allow engineering mitigation of the minor ground deformations resulting from movements along a minor fault? Moreover, it is sometimes impossible to avoid all active faults in all cases. It is time to employ a more rational, consistent approach when addressing the earthquake surface fault rupture hazard.

4.3 Engineering Geology

The success of the remaining mitigation approaches depends primarily on a sound interpretation of the geology on regional and project level scales. The importance of a comprehensive geologic study by a well-trained and highly experienced team of engineering geologists cannot be overstated. 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 84% and 16% levels of probability to capture the inherent 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 currently characterized through a probabilistic seismic hazard assessment or at least through a pseudo-probabilistic approach 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.

As discussed previously, countless observations of surface faulting prove that the ground deformations associated with surface faulting are not equally distributed on each side of the fault. Thus, 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 complex fault rupture phenomenon, sound judgment, coupled with reasonable interpretations of surficial geology and crack propagation theory, can be applied to develop earthquake-resistant designs without resorting to arbitrary setback criteria. In most cases, an accurate record of the likely characteristics of a future fault displacement is written into the local geology. Through sound mapping, trenching, and other tools, the engineering geologist can provide a reasonable description of the amount and type of potential fault displacement at the site.

4.4 Geotechnical Engineering

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

One of the geotechnical engineer’s first approaches is typically to use the inherent capability of soil to “locally absorb” and distribute distinct bedrock fault movements. Previous field, physical model, and numerical studies (e.g. Bray et al. 1994a,b) have found that differential movement across distinct bedrock faults dissipates as the shear rupture plane rises through overlying fills, especially if the fills are reinforced with geosynthetics (Bray et al. 1993). The relative displacement across a distinct bedrock fault is spread across a wider zone in the overlying 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 fill or reinforced fill may be used at a site to mitigate the hazards associated with earthquake fault rupture.

There may be times, however, when the geotechnical engineer may consider using 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. This would enable the developer to possibly utilize more land by requiring narrower setbacks. The distinct base rock shear dislocation and the associated warping of the adjacent rock will eventually be expressed at the ground surface. The geotechnical engineer can help access the amount and distribution of ground movement and either spread it out over a wider area or localize it to a narrow, more confined zone. This should be part of the design process.

Mat foundations and interconnected spread footings, which should all be at the same elevation, can be constructed atop a double layer of smoothly laid-out polyethylene (plastic) 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 structural foundation elements. 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. There are many good references that describe these approaches (e.g., Kratzch 1983). Potential ground deformation beneath a structure from mining subsidence, excavations, 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.

Geotechnical engineering plays an integral role in developing prudent design measures in earth dams that are built atop or near active faults. Some of these measures are listed in Table 1. The reader is referred to papers such as Sherard et al. (1974) and Bray et al. (1992) for a thorough discussion of these issues.

4.5 Structural Engineering

The constructed facility can be designed by an experienced structural engineer to undergo some limited amount of ground deformation without collapse or significant structural damage. Again, the design of structures subjected to ground deformation resulting from mining subsidence (e.g., Kratzsch 1983) or other forms of ground deformation are generally applicable. Similar to observations of foundation performance undergoing fault rupture, mining subsidence studies indicate that foundation elements should be heavily reinforced to improve ductility. The maximum allowable angular distortion for conventional structures is approximately 1/400, however, specially designed and built structures can tolerate significantly 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%, but as discussed previously (e.g., Figure 1), it is the combination of angular distortion and lateral strain of the ground, after considering that portion that will be transmitted up into the building's foundation, that is important.

The use of foundation elements that tie the structure into the ground should be avoided. Pile or pier foundations would likely force the superstructure to undergo the full 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.

Post-tensioning the floor slab will improve its ability to bridge over irregular ground deformation of limited extent. However, 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 numerous 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.

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."

5. CONCLUSIONS

Earthquake surface fault rupture is an important hazard that must be addressed in areas where major faults may break the ground surface or underlying bedrock faults may produce significant ground warping. Recent major earthquakes have reminded the profession and the public of the potentially devastating effects of surface fault rupture on structures and lifelines. Conversely, the fact that relatively simple structures located across major fault movements were able to survive ground fracturing in terms of life safety suggests that we can design structures to withstand ground deformations associated with surface rupture.

Field observations, experiments, and analysis can be employed to evaluate the hazards associated with surface faulting and to develop effective mitigation measures. Numerous illustrative cases show how differing ground conditions alter the surface expression of faulting and how surface fault rupture affects engineered systems, such as pipelines, earth dams, and buildings. Case histories have shown that the response of engineered systems can be devastating or acceptable, depending on geologic relations and engineering design. Engineering geology in concert with sound engineering practice can be employed to evaluate the hazards associated with surface faulting and to develop reasonable mitigation measures.

These 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; employing foundation systems that do not force the underlying ground movements up into the superstructure; and designing strong, ductile foundation elements that can accommodate some level of deformation without compromising the functionality of the structure.

In addressing the surface fault rupture hazard, the potential pattern of ground deformation should be developed through the use of detailed mapping and trenching at the site.

Measured patterns of surface fault-induced ground deformation from similar types of faulting from past events offer useful insights to complement site-specific studies. Having characterized the likely patterns of expected ground deformation, engineers can site systems across the fault in an optimal manner and design it to accommodate fault-induced ground movements. 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 prudent design measures. It is not prudent to tie structures into the ground with foundation elements such as piers and piles.

Acknowledgements:

Partial support for the research efforts presented in this paper was provided over the years by the David and Lucile Packard Foundation and the National Science Foundation. Many students and colleagues have contributed to the author’s understanding of earthquake surface fault rupture, and the sharing of their expertise and insights is greatly appreciated. I would also like to thank the Japan Ministry of Education, Culture, Sport, Science, and Technology (MEXT) for establishing the Center for Urban Earthquake Engineering (CUEE) in the Tokyo Institute of Technology, which is providing support for this conference.

References:

Bonilla, M. G. (1970) “Surface Faulting and Related Effects,” in Earthquake Engineering, Weigel, R. L., ed., New Jersey, Prentice-Hall, 47-74.

Bray, Jonathan D. (1990) “The Effects of Tectonic Movements on Stresses and Deformations in Earth Embankments,” Dissertation, PhD, UC Berkeley, 414.

Bray, J. D., R. B. Seed and H. B. Seed (1992) “On the Response of Earth Dams Subjected to Fault Rupture,” *Proceedings of Stability and Performance of Slopes and Embankments - II*, 608-624.

Bray, J. D., A. Ashmawy, G. Mukhopadhyay and E. M. Gath (1993) “Use of Geosynthetics to Mitigate Earthquake Fault Rupture Propagation Through Compacted Fill,” *Proceedings of the Geosynthetics '93 Conference*, 1, 379-392.

Bray, J. D., R. B. Seed, L. S. Cluff and H. B. Seed (1994a) “Earthquake Fault Rupture Propagation through Soil,” *Journal of Geotechnical Engineering*, ASCE, 120(3), 543-561.

Bray, J. D., R. B. Seed and H. B. Seed (1994b) “Analysis of Earthquake Fault Rupture Propagation through Cohesive Soil,” *Journal of Geotechnical Engineering*, ASCE, 120(3), 562-580.

Bray, J. D. (2001) “Developing Mitigation Measures for the Hazards Associated with Earthquake Surface Fault Rupture,” in *Seismic Fault-Induced Failures – Possible Remedies for Damage to Urban Facilities*, Japan Soc. Prom. Sci., K. Konagai, Ed., Univ. of Tokyo, Japan, pp. 55-79.

Bray, J. D. and Kelson, K. I.. (2006) “Observations of Surface Fault Rupture from the 1906 Earthquake in the Context of Current Practice,” *Earthquake Spectra*, Earthquake Engineering Research Institute, Vol. 22, No. S2, pp. S69-S89.

Cluff, L.S., R.A. Page, D.B. Slemmons, and C.B. Crouse (2003) “Seismic Hazard Exposure for Trans-Alaska Pipeline,” Proc. 6th U.S. Conf. on Lifeline Earthquake Engineering, Long Beach, CA, TCLEE, ASCE.

Cole, D. A., Jr. and Lade, P. V. (1984) “Influence Zones in Alluvium Over Dip-Slip Faults,” *Journal of Geotechnical Engineering*, ASCE, 110(5), 599-615.

Gilbert, G. K., Humphrey, R. L., Sewell, J. S. and Soule, F. (1907) “The San Francisco Earthquake and Fire of April 18, 1906 and their effects on structures and structural materials,” U.S. Geological Survey Bulletin 324, Washington D.C.

Jordan, D.S., Ed. (1907) “The California Earthquake of 1906,” A.M. Robertson, San Francisco, CA.

Kelson, K., Bray, J., Cluff, L., Harder, L., Kieffer, S., Page, W., Perkins, W., Rix, G., Roblee, C., Sitar, N., Wells, D., Wright, R., and Yashinsky, M. (2001) “Fault-Related Surface Deformation,” Chapter 3 of the Chi-Chi, Taiwan, Earthquake of September 21, 1999 Reconnaissance Report, in *Earthquake Spectra* Journal, Suppl. A to Vol. 17, EERI, 2001, pp. 19-36.

Kratzsch, H. (1983) “Mining Subsidence Engineering, Springer Verlag,” Berlin, 543.

Lawson, A.C., et al. (1908) “The California Earthquake of April 18, 1906,” *Report of the State Earthquake Investigation Commission*, Carnegie Institution of Washington, Vols. I & II, Washington D.C.

Lazarte, C. A. (1996) “The Response of Earth Structures to Surface Fault Rupture,” Ph.D. Thesis, UC Berkeley.

Lazarte, C. A, Bray J. D., Johnson A. M. and R. E. Lemmer (1994) “Surface Breakage of the 1992 Landers Earthquake and Its Effects on Structures,” *Bulletin of the Seismological Society of America*, 84(3), 547-561.

Lazarte, C. A. and Bray, J. D. (1996) “A Study of Strike-Slip Faulting Using Small-Scale Models,” *Geotechnical Testing Journal*, American Society for Testing and Materials, 19(2), 118-129.

Lettis, W., Bachhuber, J, and Witter, R., with Barka, A., Bray, J., Page, W., and Swan, F., “Surface Fault Rupture,” Chapter 2 of the Kocaeli, Turkey Earthquake of August 17, 1999 Reconnaissance Report, in *Earthquake Spectra* Journal, Suppl. A to Vol. 16, EERI, 2000, pp. 11-53.

Sherard, J. L., Cluff, L. S., and Allen, C. R. (1974) “Potentially active faults in dam foundations,” *Geotechnique*, **24**, 367-427.

Son, M. and Cording, E. J. (2005). “Estimation of Building Damage Due to Excavation-Induced Ground Movements.” *ASCE Journal of Geotechnical and Geoenvironmental Engineering*. 131(2): 162-177.

Ulusay, R., Aydan, O., and Hamada, M. (2001) “The behaviour of structures built on active fault zones: examples from the recent earthquakes of Turkey,” in *Seismic Fault-Induced Failures – Possible Remedies for Damage to Urban Facilities*, Japan Soc. Prom. Sci., K. Konagai, Ed., Univ. of Tokyo, Japan, pp. 1-26.