Recent Developments in Post-Earthquake Investigations

A Geotechnical Perspective

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Odds are, geotechnical effects of earthquakes will be one of the most important engineering issues in the next 50 years. According to the USGS, the probability of a magnitude 7 or greater earthquake by the year 2024 in Southern California is as high as 80 to 90% (USGS Fact Sheet FS-225-95). And, the risk of a major earthquake is not exclusively a west coast phenomenon. Scientists estimate that the probability of a magnitude 6 to 7 earthquake occurring in the Mississippi Valley within the next 50 years is higher than 90%, and will likely damage an area significantly larger than a California earthquake of similar magnitude (USGS Fact Sheet FS-168-95) (*Figure 1*). Recent developments in research and investigative guidelines have advanced the state of geotechnical earthquake engineering practice, and hopefully improved the objectivity and consistency of what unfortunately may become a frequent task of assessing post-earthquake damage of structures.

Where we have been as a profession

Recent experience has exposed dramatic weaknesses, as a society and as an engineering profession, in our response to recent natural disasters. Take the January 17, 1994 Northridge earthquake (M6.7) as an example. Many engineers performing post-earthquake investigations lacked appropriate education and experience to perform these investigations. Consensus engineering guidelines for the investigation, assessment, and repair of earthquake damage did not exist. Engineering literature was silent on the technical issues routinely faced by engineers. Could soil be "damaged" by an earthquake? If so, how do you repair "damaged" soil? Were cracks in concrete foundations, driveways, sidewalks, and patios caused by the earthquake or by normal concrete shrinkage? Remarkably, questions such as these consumed considerable effort by engineers, owners, contractors, building officials, and insurance adjusters.

An immediate consequence of the Northridge earthquake was an overwhelmed engineering profession. For the reasons listed above, huge variations emerged regarding the adequacy of engineering inspections, accuracy of the damage assessments, and nature and scope of the repair recommendations. One of the Northridge earthquake's enduring legacies has become the inevitable controversy from vastly divergent engineering assessments of the same property. Even today, over a decade after the earthquake, disputes about Northridge earthquake damage are still being litigated.

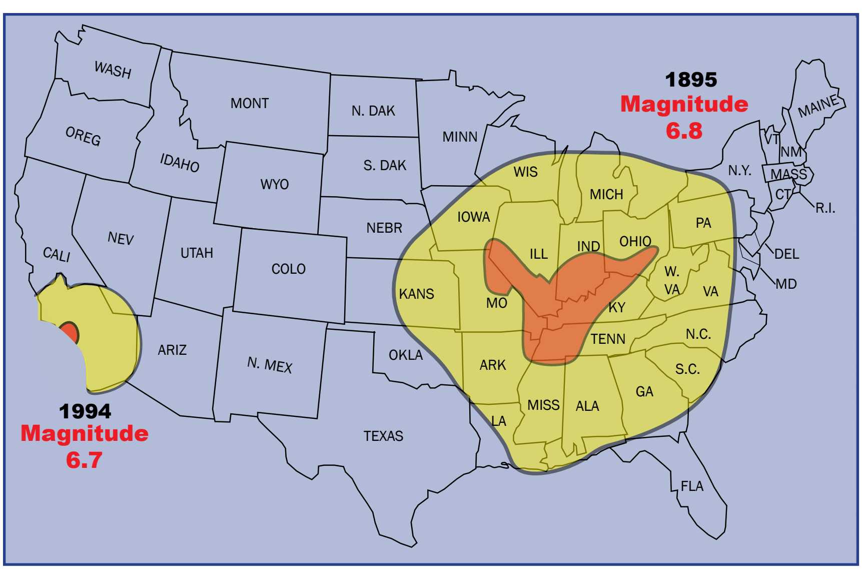

Figure 1: Areas affected by two major earthquakes of similar magnitude – 1895 Charleston, Missouri, earthquake and 1994 Northridge, California, earthquake. Red area indicates minor to major damage to buildings and their contents. Yellow area indicates shaking felt, but little or no damage to objects, such as dishes. Source: USGS Fact Sheet: The Mississippi Valley –"Whole Lotta Shakin' Goin' On"

Recent developments

During this same post-Northridge period, the Consortium of Universities for Research in Earthquake Engineering (CUREE) commenced the Earthquake Damage Assessment and Repair Project to address gaps in our understanding of seismic response of structures and geotechnical effects of earthquakes. The on-going project has focused on research into the seismic structural response and repair of woodframed construction, and on selected seismic geotechnical engineering issues such as seismic induced settlement of fills. A primary project objective is to publish consensus-engineering guidelines that distill this research for practitioners, and document the best engineering practices for assessing and repairing earthquake damaged woodframe construction. The research and completed portions of the guidelines are available for download at the CUREE website (***www.curee.org***).

These engineering guidelines are published as CUREE Publication No. EDA-06 *Engineering Guidelines for the Assessment and Repair of Earthquake Damage in Residential Woodframe Buildings*. Chapter 4 of these guidelines contains the current understanding and latest developments regarding geotechnical effects of earthquakes. The chapter was written by Professor Jonathon Stewart, at the University of California Los Angeles (UCLA) and this author. This work focused on damage to structures caused by earthquake-induced permanent ground deformations. The remainder of this article provides synapses of several salient features extracted from the publication. While the aforementioned CUREE publication is specific to residential woodframe buildings, the discussion of the geotechnical effects of earthquakes contained therein is more general and not structure specific. The principles and guidelines may be applied to any site that experienced an earthquake.

Geotechnical effects of earthquakes

During earthquakes, buildings and other improvements can be damaged directly by strong shaking or from geotechnical effects of the earthquake. These effects cause seismically-induced permanent displacements of the ground which is defined

Figure 2: House damaged by surface fault rupture from the M 6.6 1971 San Fernando Earthquake. Source: Applied Technology Council, ATC (1994).

as any earthquake-generated process that leads to deformations within a soil medium, which in turn results in permanent horizontal or vertical displacements of the ground surface. There are five modes of seismically-induced permanent ground deformations documented in past earthquakes:

- Fault rupture
- Liquefaction
- Landslides
- Seismic Compression
- Retaining Wall Deformation

Permanent earthquake-induced ground deformations and associated damage cannot occur at a site without one or more of these mechanisms occurring.

No discussion of earthquake induced geotechnical phenomena would be complete without also discussing the non-seismic geotechnical mechanisms that may affect a site. If all sites were pristine and stable before the earthquake, identification of seismically-induced permanent ground deformation after an earthquake would be straightforward. However, a number of non-seismic geotechnical mechanisms may result in permanent ground displacement that likewise may damage structures. These mechanisms are:

Consolidation settlement: Volume change due to dissipation of excess pore pressure resulting in expulsion of water from the soil matrix and increased effective stress. (*Excess pore pressure* is defined as pore pressures beyond the hydrostatic pore pressure.) The excess pore pressures responsible for consolidation may result from changes in overburden pressure (i.e., fill placement, addition of structural loads) or changes in ground water levels.

Hydro-compression settlement: Volume reduction of unsaturated soils upon wetting, which is associated with collapse of the soil fabric. Soils subject to collapse can include wind-deposited sands and silts, alluvial fan and mudflow sediments, and some man-made fills. Volume reductions are rapid upon introduction of water; however, settlements will occur over time until all the collapse potential is achieved through wetting. The rate of settlement depends on the rate of water infiltration into the soil.

Immediate settlement: Settlement caused by small-strain shear and/or volumetric deformations in soil that are not associated with consolidation or hydro-compression. These deformations are sometimes referred to as elastic settlements.

Expansive soil movement: Shrink/swell of plastic clays when the water content is reduced (drying) or increased (wetting). Cycles of shrinking and swelling typically occur in near-surface soil layers subjected to water content fluctuations. The water content variation can be seasonal (e.g., summer to winter) or can follow a long-term trend (e.g., from changes in landscaping and vegetation or installation of pavements that change surface drainage patterns) or may be more transient such as from irrigation or utility line leaks.

Landsliding: The movement of a mass of rock, debris or earth down a slope from seismic and non-seismic causes. The term "landslide" encompasses a wide range of ground movements, such as shallow rock falls, deep-seated slope failures and flow slides such as earth or debris flows. Other than from earthquakes, landslides can be triggered by changes in slope geometry (i.e., excavation near slope toe), loading of the top of slope and increased water pressure within the slope.

Slope creep: Slow downslope movement of plastic rock and soil. The rate of creep is dependent on factors such as material type, slope inclination and water content fluctuations within the slope.

Retaining wall deformation and failure: Tilt, sliding, deterioration and failure of retaining walls from seismic and non-seismic causes. Excessive movements of retaining walls can result in soil deformations and ground cracking behind the walls.

During post-earthquake investigations of flat sites, care should be exercised to distinguish ground settlements and/or heave that are typical of non-seismic ground settlement from ground settlements associated with liquefaction or seismic compression. Similarly, post-earthquake investigations of sloping sites must distinguish long-term slope instability (landslides), creep, or retaining wall movements from ground deformations associated with seismically-induced landsliding.

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Figure 3: Bridge approach settlement due to liquefaction during the M 6.5 San Simeon earthquake of December 22, 2003. Source: EERI (2004).

Figure 4: Street and house damaged by several inches of landslide displacement during the M 6.6 1971 San Fernando Earthquake. Displacement is readily visible as street crack in photograph. Source: Applied Technology Council, ATC (1994).

Fault rupture

Earthquakes result from sudden slip across a fault surface (*Figure 2*). Earthquakes on faults are generated in rock deep within the earth's crust, with typical focal depths (i.e., the depth at which slip originates) in California being on the order of 5 to 20 kilometers. Earthquake depths in the midwestern portion of the country are considerably deeper. The slip of a fault during an earthquake results in large-scale relative displacements of the earth on opposite sides of the fault. These relative displacements can be as large as 10 meters. When fault slip extends to the ground surface, the resulting ground displacements are termed "surface fault rupture." Examples of California earthquakes with surface fault rupture include 1906 San Francisco, 1971 San Fernando, 1992 Landers, and 1999 Hector Mine.

Fault rupture involves relative displacements (i.e., *slip*) of blocks of rock on opposite sides of the fault surface. Principal faulting and distributed faulting are two types of ground displacement resulting from faulting.

Principal faulting is slip along the main plane (or planes) responsible for the release of seismic energy during the earthquake. In order for principal faulting to occur, a site must be in direct proximity to the fault that produced the earthquake.

Distributed faulting is displacement that occurs in response to the principal faulting on discontinuities such as other faults, shears, or fractures in the vicinity of the principal rupture. Distributed faulting is discontinuous in nature and occurs over a zone that can extend up to several kilometers from the principal rupture. Like principal faulting, in order for distributed faulting to occur, a site must be in proximity to the fault that produced the earthquake. However, "proximate" distances in this case may be much larger (on the order of hundreds of meters to kilometers) than in the case of principal faulting (on the order of meters to tens of meters). The term *distributed faulting* can also involve ground warping that does not involve distinct displacements across discontinuities.

Liquefaction

Liquefaction is defined as the transforma tion of a granular soil from a solid state to a liquefied state as a consequence of increased pore pressure and reduced effective stress (Committee on Soil Dynamics of the Geotechnical Engineering Division, 1978) (*Figure 3,26*). Soil softening and loss of shear strength from liquefaction allows large cyclic and perhaps permanent ground deformations to occur, both of which can be damaging to structures and at-grade improvements. Consequences of liquefaction can be grouped into the general categories of flow failure and cyclic mobility.

Flow failure occurs when the post-liquefaction shear strength of the liquefied soil is less than the shear stress required for static equilibrium of the system. Resulting shear deformations are typically large (i.e., large translational or rotational failures) and often occur shortly after the conclusion of earthquake shaking.

Cyclic mobility occurs when the post-liquefaction shear strength is greater than the static shear stress required for equilibrium of the system. Accordingly, deformations develop incrementally during earthquake shaking in the direction of the driving static shear stress; or, in the absence of static shear stresses, large transient ground oscillations may occur.

Landslides

Seismically-induced landslides involve permanent shear deformations within geologic materials (*Figure 4*). Landslides can be subdivided into several generalized categories:

1. Masses of disrupted slide material, such as rock falls or avalanches. Disrupted slides and falls occur in areas of high topographic relief (slopes steeper than 35-40 degrees) and tend to involve closely jointed or weakly cemented materials.
   Rock avalanches are a particularly damaging type of disrupted slide, involving slide masses that originate in steep terrain and disintegrate into streams of rock that travel large distances (on the order of kilometers) at high velocities.
2. Relatively coherent slide masses whose displacement is accommodated along well-defined slip surfaces or across relatively broad, distributed shear zones. Coherent slides can occur in rock or soil materials, and at slope angles much lower than those for disrupted slides and falls.
3. Lateral spreads and flows associated with soil strength loss due to pore pressure increase. Lateral spreads and flows can occur in soil on very mild slopes or behind a free-face if the soil is geologically young, has a granular texture, and the groundwater table) occurs at shallow depths.

Local geologic, hydrologic, and topographic conditions provide the principal means of evaluating which type of landslide mechanism is most likely for a given site. This is a crucial step in engineering analyses of slope stability, because different analysis procedures are appropriate for different landslide mechanisms.

Figure 5: Retaining wall damage from the M 6.5 San Simeon earthquake of December 22, 2003. Granular backfill spilling from new crack in retaining wall.

Seismic Compression

Seismic compression is defined as the accrual of contractive volumetric strains in unsaturated soil during strong shaking from earthquakes. Characteristic fill deformation features include cracks at cut/fill contacts due to differential settlement, ground cracks due to differential settlement across the surface of fill pads, and ground cracks due to lateral extension of fill pads towards the slope face. The requisite conditions for seismic compression are simply the presence of unsaturated soil and large amplitude earthquake ground motions.

An analysis of seismic compression for a site begins with an assessment of susceptibility. Susceptible soils include granular soils, silts, and low-plasticity clays. Highly plastic clays (Plasticity Index > approximately 30) tend to have a low susceptibility to seismic compression. Plasticity index is a measure of the range of water contents within which the soil behaves plastically.

Two simplified procedures for estimating ground displacements from seismic compression have recently been developed. The procedures share three common steps: (1) estimation of shear strain amplitude within the soil mass from the peak acceleration at the ground surface and from other seismological and site parameters; (2) estimation of volumetric strains within the soil based on soil density/water content, the shear strain amplitude, and the equivalent number of uniform strain cycles; and (3) integration of volumetric strains across the soil section to estimate settlement. One of the procedures presented is that published by Tokimatsu and Seed (*Evaluation of Settlements in Sands Due to Earthquake Shaking*, Journal of Geotechnical Engineering, ASCE, 113(8), 861-878, 1987), which is strictly applicable only to clean sands (natural soil or fill). The second procedure was developed as part of research funded by the CUREE and is applicable to compacted fill soils. The procedure for compacted fills applies for a variety of soil fines contents and fines plasticities and is published in CUREE Publication No. EDA-05, *Seismic Compression of As-Compacted Fill Soils with Variable Levels of Fines Content and Fines Plasticity.*

Retaining Wall Deformation

The function of retaining walls is to safely support the retained material and any structures constructed behind the wall (e.g., soil slope, building, roadway, etc.) without excessive deformation. In service, most retaining walls deform to some degree. When retaining wall deformations, whether seismically-induced or otherwise, become excessive, the retaining wall is said to have "failed." However, with the exception of obvious collapse or imminent collapse, the magnitude of retaining wall deformations that constitutes failure, or even damage, has not been well defined.

Post-earthquake evaluation of retaining walls requires evaluation of the stability, serviceability, and appearance with respect to the nature and extent of wall deformations (*Figure 5*). Post earthquake serviceability of retaining walls is closely related to the total permanent deformations that the wall has experienced from seismic movements and otherwise. Retaining wall damage is defined as conditions that 1) reduce the wall's stability below minimum requirements under reasonable future loading conditions, 2) materially alter its serviceability, or 3) materially affect its appearance. Retaining wall analyses typically recognize that, in some instances, large permanent wall deformations may be acceptable while in others, smaller deformations may not be acceptable, deeming the wall damaged or even "failed" at these smaller deformations. Reasonable assumptions regarding future loading and performance expectations for the wall are essential for these analyses.

Future Developments

Future research and completion of the engineering guidelines are planned for the future. Examples of geotechnical related research incl-udes diversifying the types of materials considered for the study of the seismic compression of fills and studying the effects of transient ground surface strains on at-grade improvements. As future draft documents are prepared, they are posted by the CUREE project manager for review, with comments from the review process addressed prior to public posting of the documents on the CUREE website. Individuals interested in being included on the reviewer e-mail list are encouraged to contact the author of this paper.▪

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