Geotechnical Earthquake Engineering
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illustrated essays by Robert Retherman

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Cover photo: The September 21, 1999 Chi-Chi, Taiwan earthquake created a fault rupture in the river bed near the Bei-feng Bridge creating a waterfall estimated to be 9-10 meters high. (Stephen Mahin, Taiwan Collection, NISEE-PEER, University of California, Berkeley.)
Spacecraft in orbit far from Earth or floating structures like boats do not
rest on earth -- on soil and rock—but all of our terrestrial buildings,
bridges, utility facilities, roads, pipelines, and other construction must
be supported by the geologic materials at or near Earth’s surface. It is
often said that there are four basic structural materials—steel, concrete,
wood, and masonry—but we should not overlook the fifth, the soil and
rock supporting the foundation and superstructure. By the last decades of
the twentieth century, what was once called soil engineering had evolved
into a discipline called geotechnical engineering that treated soil and
rock materials in ways parallel with the quantitative descriptions that
structural engineers used in analyzing a steel beam or concrete column,
with analogous concepts of stress, strain, types and durations of loads,
and especially with regard to earthquakes dynamic properties. As noted
by Terzaghi and Peck (1948, p. xvii), however, this fifth class of structural
materials is unique: “In all other fields, the engineer is concerned with
the effect of forces on structures made of manufactured products such as
steel and concrete or carefully selected natural materials such as timber
or stone.”

A fundamental concept in the application of mechanics to the analysis of
a building or other construction is that the loads must be carried through
the elements of the structure all the way through the foundation to the
ground. Equilibrium requires that the gravitational or other loads be
balanced with resisting forces, and the end of the load path is always where
the resisting forces of earth come into play. Many examples of structural
analysis that one finds in textbooks focus on the forces transmitted through
the superstructure, for example, from the dead loads and vehicular loads
in a truss bridge, but the analysis stops when the forces reach where the
truss meets its foundation. The illustration of the analysis problem in the
typical structures textbook shows a bridge in some detail and the analysis
of each of its members to determine the forces exerted on them and their
resulting internal forces. But the foundation and earth around and under
the foundation are represented only by little triangles representing pinned
supports, circles for roller supports, hatched lines for a fixed condition, and
so on. Until a civil engineering student takes a geotechnical engineering
course, most of his or her other experience has been with “floating
structures” that sit on those little symbols, symbols that magically absorb
the loads. After that first course in geotechnical engineering, the civil
engineering student learns that the way the soil resists the weight of the
structure is a complex aspect of the load path, and they also realize that
when an earthquake occurs, the loading works in reverse and begins with
the soil and the way it dynamically behaves. Today’s civil engineering
curriculum typically includes at least one geotechnical engineering course
for undergraduates. Among CUREE’s two dozen Member Universities,
a master’s course devoted to geotechnical earthquake engineering is also
offered, because it is an important topic but one that does not fit into the
undergraduate curriculum.
The Development of Geotechnical Engineering in the 1800s

Geotechnical earthquake engineering has so rapidly developed that we must remind ourselves that not until fifty years ago was liquefaction understood and studied. In fact, fifty years ago, “liquefaction” was a word that had just barely entered the earthquake engineering literature.

Geotechnical engineering knowledge and technology had to develop first before they could be applied to earthquake problems, quite similarly to the historic process whereby structural engineering for static loads was first developed and then decades later applied to the dynamic context of earthquakes. Gravity is a type of geotechnical loading, including the weight of the structure and foundation bearing on and in the soil and the self-weight of the soil. Gravity applies to all geotechnical engineering research or design projects, whereas earthquake geotechnical engineering is a subdiscipline that applies more narrowly to seismic regions around the world. That is one reason for the late development of geotechnical earthquake engineering. Given also the fact that the dynamic aspects of earthquakes had to be understood to evolve geotechnical engineering into earthquake geotechnical engineering, it is not surprising that geotechnical earthquake engineering only arrived on the scene mostly in the second half or even last quarter of the twentieth century.

Two of earthquake engineering’s nineteenth century founders, Robert Mallet and John Milne, both realized how important the response of soil to earthquake shaking was, though it was too early to achieve breakthroughs to predict such phenomenon. Mallet (1810-1881) had experience with explosives and cannons. During the Crimean War, three years before his historic study of the 1857 Neapolitan Earthquake, he designed for the British Army a cannon shooting what was the world’s largest shell (2940 pounds, 1,334 kilograms). Realizing that the velocity of waves varies through various soil materials, Mallet used his experience with artillery to set off underground explosives to study the velocity of waves traveling through different soils, a technique somewhat similar to geophysical investigations of today.

Milne (1850-1913) describes a geotechnical field investigation technique that also has a parallel with today’s in-situ techniques, though using a strange type of instrument to do so. Milne used a two-ton (3.67 metric ton) iron ball dropped from heights up to 35 feet (10.7 meters) to do simple tests on soil vibrations.

These two earthquake engineering pioneers, Mallet and Milne, were trying to study soil dynamics for earthquake purposes, but being limited by the technology of the day, such as the absence of any strong motion seismographs (introduced in 1932), their search for answers about how the soil responded in earthquakes was inconclusive.

The nature of the little particles of earth, and of the spaces in between, were not studied in detail in the 1800s, given the macroscopic focus of soils engineers, who tended to conceptualize soil as a large lump of dirt, a local type of soil given a picturesque name such as Bootlegger Cove Clay, Saddlebunch, or Agbogbocha. By far the most common type of soil mapping and soil analysis then, as is still the case, was for agricultural purposes, not for construction, and relatively simple definitions of the soil at and very near the surface are often sufficient for that purpose. The engineers who needed to “put a number” on the soil to design an appropriate foundation often used only one quantitative value—allowable bearing pressure. “Allowable bearing values in handbooks in the 1800s provided values such as 1,000 lb/ft² (48 kPa) for soft alluvial soil, 4,000 lb/ft² for clay, and 8,000 lb/ft² for gravel.” (Colliery Engineer Co. 1899, cited in Reitherman 2012 p. 535). Field investigation often consisted of digging pits and examining the soil, sometimes putting weights on the ground and measuring short-term settlement, whereas later on, technological development would produce equipment that could probe deeply to remove samples to be tested in the laboratory or load the soil in-situ to make strata thirty or more meters deep reveal their properties.

Two of the most important researchers and consultants in geotechnical engineering in the twentieth century, Karl Terzaghi and Ralph Peck, noted (1948, p. 3) that in “the field of structural engineering, an account of the failure of a beam would be of little value unless it contained, in addition to other essential data, a statement as to whether the beam was made of steel or cast iron. In all the older records of foundation experience, the
nature of the soils is indicated merely by such general terms as ‘fine sand’ or ‘soft clay.’ Yet, the differences between the mechanical properties of two fine sands from different localities can be greater and more significant than those between cast iron and steel.” In the 1800s, civil engineering had only reached a primitive level of development with regard to what we call geotechnical engineering today.

The Development of Geotechnical Engineering in the 1900s

*Erdbaumechanik* (1925) by Karl Terzaghi (1883-1963) can be cited as the classic book establishing the new discipline of geotechnical engineering. The book’s title, soil mechanics in English, clearly indicates that Terzaghi conceptualized soil as a collection of particles that structurally interacted, just as mechanics could be applied to the way the struts in a truss interacted with the neighboring struts that they touched. Terzhagi established the importance of considering not only the characteristics of the soil particles but also the spaces in between them, the voids or pores. Perhaps Terzhagi’s training as a structural engineer aided him in the structural way of looking at soil. In the last half of the twentieth century, other prominent engineers who made large contributions to geotechnical engineering, including Robert V. Whitman (Massachusetts Institute of Technology), Harry B. Seed (University of California at Berkeley), and Nathan M. Newmark (University of Illinois at Urbana-Champaign), were also trained as structural engineers and came to geotechnical engineering only later in their careers.

An analogy can be made between the development of chemistry and that of geotechnical engineering (Reitherman 2012, pp. 534-535). For centuries, common compounds and mixtures, such as water and our atmosphere, were treated as if they were elemental substances (derived from the “earth, air, fire, water” categorization of ancient Greeks) without realizing that there were things called elements, which in turn each had patterns of electrons, and that only by understanding the behavior of the electrons could chemical phenomena such as fire be understood. Although preceding the discovery of the electron, Antoine-Laurent de Lavoisier (1743-1794) not only named the elements hydrogen and oxygen, he found that you could make water out of them. Conversely, one could extract these two elements from water, quite a non-intuitive finding given that each of these two elements is so flammable. One can describe qualities of water in qualitative ways, (analogous to the way soils engineers generalized about a given locale’s sandy loam or silty clay), but until modern chemistry arrived, one could not explain water’s surface tension, why an ice cube floats, why water induces rust, or why it dissolves many substances. Similarly, until the micro-level of understanding of soil (i.e., soil mechanics) evolved, one could not predict how a soil would behave when its moisture content varied. Following soil mechanics came soil dynamics, which quantified such problems as what level of acceleration and duration of excitation of earthquake shaking would cause a slope to slide. One of the homework assignments the late Harry Seed used to assign his students was to include a drawing at actual scale of the cross-section of the homework problem’s soil sample. Geotechnical engineers today conceptualize soil at the level of the individual particles, which is the scale at which soil mechanics operates.

One of the first modern technological advances was the invention of the Standard Penetration Test (SPT), whose early years are summarized by Rogers (2006). The method was developed initially by Colonel Charles R. Gow at the turn of the nineteenth-twentieth centuries, later refined by Harry Mohr in the 1920s and 1930s. Karl Terzaghi and Arthur Casagrande, professors at Harvard University, collaborated with Mohr and moved the technique into the realm of a national standard in the late 1930s. The number of standard blows, or blow count, to pound the pipe-like sampler down a given distance became a common way to characterize soils instead of using qualitative adjectives such as soft or hard. The graph of standard penetrometer blow counts vis-à-vis depth often has an irregular, jagged appearance, as the sampler, which also collects a soil sample, is driven downward by a 140-pound weight falling 30 inches and encounters different soil properties. Without such detailed subsurface profiling of soil properties, one might mistakenly assume that what is near the surface is the same as deeper below, whereas there can be large variation. Or that the soil always gets firmer with depth, whereas a stratum some distance down may be less firm than what lies above it. Or that the strata have neat, planar divisions and are like horizontal slabs, whereas a stratum can tilt and vary in thickness from one location to another under the footprint of a building. In 1932, the Cone Penetrometer Test (CPT) was developed by P. Barentsen in the Netherlands, a method that also used a probe shoved
down into the soil, but with its tip’s strain being converted to the resistance it met. Sites that were previously treated as similar, such as being classified as soft alluvial soil, might appear quite different from one another once CPT and SPT data began to be collected. Not until much later were either of these techniques commonly applied to earthquake engineering. Also in the 1930s, Arthur Casagrande developed the triaxial shear test for laboratory evaluation of soil samples, another method that became standard (and which also was not applied to post-earthquake geotechnical investigations or geotechnical earthquake design work until much later). The problem of removing soil samples without disturbing them was a problem the field increasingly dealt with in the 1940s, as discussed by William Moore of Dames & Moore (Moore 1998, pp. 23-26).

In parallel with the development of the knowledge base and the technologies of field and laboratory investigations, the practice of geotechnical engineering developed at a relatively slow pace until after the middle of the twentieth century, especially as applied to seismic design. William Moore discusses in his oral history how hard it was to convince the engineering field to use consultants who were expert in the latest techniques. He describes a job he had for an agency designing a dam where soil data of various kinds was collected without a strategy of how it would be used. The design engineer in charge made no sense of all the soils tests and ended up taking a handbook off the shelf and saying they would use four tons per square foot. “That was the allowable bearing pressure, which came out of the handbook—none of the soil test data the soil lab had collected had one thing to do with the design of what was built. That really made an impression on me that I think has lasted all my life.” (Moore 1998, p. 12) Another geotechnical engineer (called then soil engineer), Leroy Crandall, whose Los Angeles consulting firm became a leader in the field, noted that it was difficult to start that practice: “I think most builders and design professionals thought we were like the guys with the water witching techniques. It was all mumbo-jumbo—who needed all that stuff? It was a question of convincing people that by taking samples and running tests and doing engineering analyses, you could develop good, useful information (Crandall 2008, p. 31).” Today, geotechnical engineering is recognized as an important aspect of the practice of civil engineering. Some states, such as California, restrict the use of the title “geotechnical engineer” to civil engineers who have gone on to fulfil additional examination and experience requirements.

Engineers had long been interested in classifying soils in terms of their allowable bearing values, but for seismic design purposes, the vibration properties needed to be considered, not just the static strength and deformation of the soil holding up the foundation. The first shake table in the United States, developed by Professor F. J. Rogers of Stanford University following the 1906 earthquake released by the San Andreas Fault, was devoted to testing cart-loads of soil that had varying amounts of moisture. The first edition of the Uniform Building Code (UBC) in 1927 defined soft soil for seismic design purposes as having an allowable bearing pressure of two tons per square foot (192 kPa) or less, and buildings on those soft soil sites were designed for one-third more equivalent static lateral force. Some subsequent editions of the UBC eliminated this soils factor, then it was included again in 1976, the same year that California was for the first time divided into more than one seismic zone. In Japan over the timespan from the 1923 Great Kanto Earthquake to the 1970s, there was more consistency in placing importance on a soils factor. The NEHRP Recommended Provisions for Seismic Regulations for New Buildings (Building Seismic Safety Council 1985), which drew on the Tentative Provisions for the Development of Seismic Regulations for Buildings (Applied Technology Council 1978), included the effect of a site’s soil on its ground motion, and it has been an important part of the NEHRP Provisions ever since. The NEHRP Provisions produced by the Building Seismic Safety Council are now implemented via ASCE 7, Minimum Design Loads for Buildings and Other Structures (ASCE 2010). Research by Roger Borcherdt on borehole and strong motion data resulted in his influential “Estimates of Site-Dependent Response Spectra for Design (Methodology and Justification)” (1994). Borcherdt presciently noted (p. 646) that the site classes he developed “provide a rigorous framework for estimates of site-dependent amplification that can be readily refined as new data and results are acquired regarding the in situ response of soil deposits.” ASCE 7-10 tabulates (Table 20.3-1) five site classes, very similarly to Borcherdt’s original scheme: A, hard rock; B, rock; C, very dense soil and soft rock; D, stiff soil; E, soft clay soil; and F, liquefiable soils, quick and highly sensitive clays, and
collapsible weakly cemented soils. Three kinds of data define each class: average shear wave velocity, average standard penetration resistance, and average undrained shear strength, all applying to the upper 100 feet (30 meters). Thus, the early twentieth century rather crude classification of soils into either a soft or hard category (or perhaps a third, rock), without precise and consistent criteria, was replaced by the late twentieth century with a more detailed categorization and, as importantly, one defined by standardized geotechnical data.

A big boost to the young soil engineering or geotechnical field came with research and consulting activity in the early years of the Cold War in the 1950s. Nuclear weapons were so powerful that a structure that was underground could still be significantly affected by blast waves. Vitelmo Bertero describes in his EERI oral history (Bertero 2009, pp. 24-25) how a number of researchers were at work on the problems of how blast waves could hit the earth and affect an underground structure via that dynamic soil loading. At MIT, those researchers included Bob Hansen, Myle Holley, Jr., and John Biggs, and Robert Whitman later did research in the same area. At the University of Illinois at Urbana-Champaign, Nathan Newmark and William Hall worked on military-related soil dynamics problems. The tremendous difference in the rate of loading made the nuclear blast-related work only marginally relevant to the earthquake problem, but what was significant was that some bright minds such as those mentioned above were being tooled up to later deal with seismic design soil dynamics issues. Whitman’s oral history (Whitman 2009, pp. 34-35) describes the interesting story of his contribution to the landslide-prediction method finalized by Newmark (1965) and which goes by the name Newmark sliding block analysis. It is a little-known story of how a research topic that originated in nuclear blast effects ended up a standard method in earthquake engineering.

It was 1953. Don Taylor was on a consulting project with Nathan Newmark, Arthur Casagrande, and likely some others, having to do with what would happen to the soils along the Panama Canal if it were subject to nuclear attack. Taylor asked me about it, and I responded with an analytical scheme to evaluate how far a rigid block of soil would slide down a slope if it were subjected to transient ground motions large enough to cause shear stresses that momentarily exceeded the strength of the soil. Employing numerical integration performed by hand calculations, I evaluated the net relative displacement resulting from six cycles of applied ground motion. I wrote Taylor a memo that he took to the meeting, which he later incorporated into a report, attributing the approach to me. Taylor came back to MIT and reported to me concerning the meeting. Newmark read my memo on the Panama Canal slope stability issue, in which I described this new sliding block analysis idea. Newmark said he was impressed and that if I did not pursue it, he would. I was busy with other things. Newmark did go ahead and develop that method and apply it to earthquake problems a decade later.

Geotechnical Engineering Studies of Earthquake-Caused Ground Failures

Along with earthquake-induced landslides, there are the other seismic hazards of liquefaction, surface fault rupture, and settlement. Geotechnical engineers as well as geologists deal with those hazards. While the occurrence of any of them in extreme form can be very destructive, the more widespread cause of earthquake damage is ground shaking.

Landslides such as occurred in the 1959 Hebgen Lake, 1970 Peru, or 1976 Tangshan Earthquakes can be huge and devastating. In a sense, earthquakes are nature’s way of pointing out which slopes are most landslide-prone. The sliding block method devised in the 1950s and 1960s is still in use today. Liquefaction was not to be well studied until after the 1964 Alaska and Niigata Earthquakes. Surface fault rupture had long been studied, but it was not until the 1970s that public policy was made to prevent construction across such zones. Settlement of foundations caused by seismic compaction of soil is perhaps the most widespread of the earthquake geologic hazards, though it is usually a property loss rather than safety issue.

Geologists and engineering geologists have expertise that overlaps with that of the geotechnical engineer with respect to ground failure hazards. Perhaps the simplest way to distinguish geotechnical engineers is that they are civil engineers who specialize in how the ground behaves, whereas the geologists are earth scientists who study the same topic. The effect of a ground failure on construction necessarily involves engineering, and thus those aspects become the province of the geotechnical engineer.

Geotechnical Engineering Studies of Ground Motion

Geotechnical engineers share with geologists and seismologists the job of estimating how the ground will shake in future earthquakes. The oversimplified way of differentiating geologists and seismologists is to say that
geologists study rocks and seismologists study waves. Geologists identify faults and their activity rates, especially focusing on those faults that have ruptured in the past 10,000 or 11,000 years (our current Holocene Epoch). Seismologists increasingly model seismic vibrations from the source, the rupturing surface of the fault, as those waves travel through often complex assemblages of different geologic materials and their morphologies. When the waves arrive at a site, they begin to depart the seismologist’s realm and enter the geotechnical engineer’s. Another over-simplification is that the geotechnical engineer’s sphere of influence extends through the upper 30 meters of the soil, and beyond that the seismologist is chiefly involved. Geotechnical engineers, being civil engineers, understand the needs of their civil engineering colleagues, the structural engineers, better than the earth scientists, and geotechnical engineers collaborate closely with the structural engineers on design projects, especially concerning foundations and retaining walls.

Due to the spread of seismic regulations adopted and enforced in local building codes, geotechnical earthquake engineering is a national endeavor in the United States, though in practice only the more highly seismic areas receive detailed geotechnical seismic consulting input, except for special facilities such as nuclear facilities, large dams, or hospitals. It might seem that engineering and construction projects throughout the United States should always use the most advanced geotechnical earthquake engineering techniques, but on the other hand, one might be thankful that they are as widely applied as is the case. Nine of Japan’s ten largest cities face a significant level of the seismic hazard of ground shaking, defined here as a level above the “low” level of GSHAP (Giardine et al. 1999). In the United States, only two cities are in that category. Around the world, much more territory has a low risk of strong shaking than the other way around. Today in the United States, ASCE 7 (American Society of Civil Engineers 2010) prescribes seismic requirements that apply in almost all areas of the country, though in approximately half the country, where the peak ground acceleration for a 2% chance of exceedence in 50 years is 10% g or less (U.S. Geological Survey 2014), and especially for low-occupancy structures, seismic requirements are very low or sometimes do not apply at all. Taking a peak ground acceleration of at least 40% g with that same probability as a measure of a high level of seismic shaking hazard, portions of only about 18 of the 50 states meet that threshold, covering only about 5% of the country. These approximate statistics are in contrast to the usual figure used by federal agencies to promote their earthquake programs, with the most recent statements being that 39 states are subject to significant earthquake risk. That statistic about 39 states approximately matches the 10% g (2% in 50 years) risk level, a level that is probably lower than most Americans would consider “significant” if they understood how low an intensity 10% g is, especially in comparison with other natural and manmade hazards. Terzaghi and Peck (1948, p. 529) opined that “for fairly strong earthquakes” the peak ground acceleration was 10% g, whereas over the following decades as strong motion records have been obtained, 10% g now seems a low level.

In whatever way one paints the picture of seismic risk of ground motion in the United States, in the past three decades building code seismic requirements that were formerly mostly confined to the Rocky Mountains and farther west have spread east all the way across the country. Thus, geotechnical earthquake engineering, which was highly developed with regard to ground motion studies during those decades, has been able to play an important role as this nationalizing of earthquake design requirements has been occurring. And because the seismic provisions of the building code are what primarily drive the market for earthquake engineering research and consulting, the market for geotechnical earthquake engineering know-how has become nationwide.
Early twentieth century earthquake engineers usually divided up soils into two very general classes -- soft and hard (or sometimes three classes, including rock). In 1958, C. Martin Duke of UCLA published *Bibliography of Effects of Soil Conditions on Earthquake Damage*, in which he annotated research and observations extending back to the 1800s. He found that most investigators concluded that soft soil increased response and damage. As more was learned, it became apparent a more detailed soil scale based on quantitative definitions was needed.

**Geotechnical Earthquake Engineering Site Classifications**

<table>
<thead>
<tr>
<th>Site Class</th>
<th>$\bar{v}_s$</th>
<th>$\bar{N}$ or $\bar{N}_{oh}$</th>
<th>$\bar{s}_u$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Hard rock</td>
<td>&gt;5,000 ft/s</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>B. Rock</td>
<td>2,500 to 5,000 ft/s</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>C. Very dense soil and soft rock</td>
<td>1,200 to 2,500 ft/s</td>
<td>&gt;50</td>
<td>&gt;2,000 psf</td>
</tr>
<tr>
<td>D. Stiff soil</td>
<td>600 to 1,200 ft/s</td>
<td>15 to 50</td>
<td>1,000 to 2,000 psf</td>
</tr>
<tr>
<td>E. Soft clay soil</td>
<td>&lt;600 ft/s</td>
<td>&lt;15</td>
<td>&lt;1,000 psf</td>
</tr>
<tr>
<td>F. Soils requiring site response analysis</td>
<td>See Section 20.3.1</td>
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</tbody>
</table>

Today, average shear wave velocity is a key determinant of site class in the ASCE 7-10 provisions (see Table 20.3-1 on right).
There were about 1,000 structurally similar reinforced concrete frame buildings seven to twelve stories tall in Caracas when the July 29, 1967 M 6.5 earthquake occurred. All four of the structural collapses, and most of the 237 significantly damaged buildings, were in the Los Palos Grandes district. Studies by geotechnical engineers such as Harry Seed, Robert Whitman, I.M. Idriss, and Ricardo Dobry, and structural engineer Karl Steinbrugge, identified the culprit as the local soil conditions in that area. The earthquake showed that a simple magnitude - distance attenuation relationship could not “see” the influence of varying subsurface conditions that were sometimes very significant. The 1985 Mexico City Earthquake was later to emphasize the same point. Not only the type of soil but its depth was important in modifying the incoming bedrock motions to tune into structures of a matching period of vibration.

The selected earthquakes highlighted here were historically important in advancing geotechnical earthquake engineering. In most cases, these earthquakes were not the first to teach the lessons, for earlier earthquakes often demonstrated the same principles. However, the engineering knowledge base had to be sufficiently developed as of the time of an earthquake for the lesson to be learned. For example, liquefaction, discussed later, was evidenced in many earthquakes prior to the 1964 Niigata and Alaska Earthquakes, but its causes were not understood.

Geotechnical Lessons Learned from Earthquakes

The 1940 El Centro, California earthquake produced a very useful accelerogram only eight years after accelerographs were first introduced. The lesson it provided, however, about the severity of ground motion, may have been somewhat deceptive, because its peak acceleration was one-third g, whereas later records, such as from the 1971 San Fernando Earthquake, would show that motions well over 1 g were possible.
Planners began to incorporate knowledge about earthquake hazards in the last three or four decades of the twentieth century. The development permit process in seismic regions now often includes regulations that either prohibit construction in some hazard-prone areas, limit the occupancy or structural type in those areas, or require special site-specific studies. Planners need to take a “wide-angle” rather than site-specific view of an area and consider how geotechnical and geological knowledge about earthquakes and other conditions can be feasibly implemented via regulations.

The town of Portola Valley in the San Francisco Bay Region was a leader in the 1960s in using geologic information to design development regulations (Mader et al. 1988). This table shows how increased risk was linked to increased development restrictions.

**CRITERIA FOR PERMISSIBLE LAND USE IN PORTOLA VALLEY**

<table>
<thead>
<tr>
<th>MOST STABLE</th>
<th>LAND STABILITY SYMBOLS</th>
<th>ROADS (permitted)</th>
<th>HOUSES (permitted)</th>
<th>UTILITIES</th>
<th>WATER TANKS</th>
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<tbody>
<tr>
<td>Sbr</td>
<td>Y</td>
<td>Y</td>
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<td>Y</td>
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<tr>
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<td>Y</td>
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<td>Sex</td>
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<tr>
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</tr>
</tbody>
</table>

**LEAST STABLE**

| PF | [Y] | [Y] (Covered by zoning ordinance) | [N] | [N] |

**LEGEND**

- Y Yes (construction permitted)
- [Y] Normally permitted, given favorable geologic data and/or engineering solutions
- N No (construction not permitted)
- [N] Normally not permitted, unless geologic data and/or engineering solutions favorable

**LAND STABILITY SYMBOLS**

- S Stable
- P Potential movement
- M Moving
- br bedrock within three feet of surface
- d deep landsliding
- ex expansive shale interbedded with sandstone
- f permanent ground displacement within 100 feet of active fault zone
- ls ancient landslide debris
- mw mass wasting on steep slopes, rockfalls and slumping
- s shallow landsliding or slumping
- sc movement along scars of bedrock landslides
- un unconsolidated material on gentle slope

Mader (2014). Reproduced by permission of the Earthquake Engineering Research Institute

An example of the detailed geologic mapping of the San Francisco Bay Region that provides relevant information for land use planning.
A classic photograph of Niigata, Japan, subjected to the June 16, 1964 earthquake, showing the effect of the loss of bearing capacity of the soil supporting the foundations of apartment buildings. Out of 310 reinforced concrete buildings surveyed, 110 suffered damage from settlement or dramatic tilting as shown here (International Institute of Seismology and Earthquake Engineering 1965, p. 44). Towhata (2008) explains that only a few decades prior to the earthquake, dune sand had been used in this area to fill in large portions of a bay and river. Today, it is known that uncompacted sandy soil in combination with a high water table is conducive to liquefaction.

Does liquefied soil actually behave like a liquid? The angle of repose of saturated granular soil (wet sand), without any earthquake shaking, is about 25 degrees, a 2 (horizontal) to 1 (vertical) ratio. In the February 9, 1971 San Fernando Earthquake, the San Fernando Juvenile Hall complex of buildings was severely damaged, with liquefaction a major cause, although the average slope was only 1.5%. (In 100 feet, the elevation change was only 1.5 feet (in 30 meters, about half a meter) -- or “level” for most purposes.)

This may seem surprising, but when soil liquefies, it actually turns to a liquid consistency, and it can flow as a liquid does. The soil can spread out (lateral spreading), pulling foundations and buildings apart in the process. In this case, the lateral spreading reached about five feet (1.5 meters) in extent. (Bennett 1989). The silty sands that liquefied were in alluvial channel deposits. The soils reports of the early 1960s for the construction of the facility did not investigate liquefaction potential, and shallow footings on two feet of compacted fill were used as would be typical for a firm ground site. Today’s geotechnical investigations would identify subsurface conditions that would require special design efforts, such as deep (pile) foundations or de-watering of the soil.

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Liquefaction

One of the more influential textbooks on earthquakes, Charles F. Richter’s *Elementary Seismology* (1958), provides a benchmark for documenting the state of knowledge about liquefaction as of then: the word “liquefaction” does not appear in it, and what a geotechnical engineer would recognize today as liquefaction in photos in the book is described as, in effect, the squeezing of aquifers by vibrating slab-like soil overburden layers resulting in water spurting to the surface through earthquake-caused cracks. The 1964 Niigata and Alaska Earthquakes changed that level of understanding.
This May 31, M 7.9 earthquake in Peru is an exception to the rule that earthquakes don’t kill people, buildings do. The earthquake-induced slide of snow, rock (some boulders the size of houses), mud, and soil 12,000 feet (3,700 meters) down the steep slope of Nevado Huascaran, traveling approximately 175 to 210 mph (280 to 335 kph), with a volume of approximately 65 to 130 million cubic yards (50 to 100 million cubic meters), killed 20,000 people in the towns of Yungay and Ranrahirca (Plafker et al. 1971). Above in the inset is the pre-earthquake view. An eyewitness account by a geophysicist of the Geophysics Institute of Peru, Mateo Casaverde, who happened to be there at the time told the horrific story. “He saw several adobe homes fall and the small bridge ahead of them collapse (from the shaking). Knowing of the imminent danger and of the past history of avalanches or debris flows in Ranrahirca in 1962 and in Huaraz in 1941 they ran for the cemetery hill about 150 to 200 yards away. At the time there was a strong blast of wind accompanied by a continuous deafening rumble. Upon arrival at the base of the cemetery hill, Mr. Casaverde turned to look back toward Mount Huascaran and saw a huge wave of debris above Yungay. He ran up to the third tier of the cemetery just as the mud flow reached this highest level. Two women about 12 feet behind him did not reach the safety of this level and were swept away to their death” (Stratta et al. 1970, pp. 50-51).

**Seismic Slope Stability**

Most landslides are not caused by earthquakes, but when a slope that is prone to slippage under gravity loading alone is also shaken, the probability of a landslide increases. The two geotechnical aspects of the problem are (1) the properties of the soil and its slope, and (2) the earthquake shaking. Both aspects became increasingly understood and studied by geotechnical engineers and geologists as subsurface investigation techniques improved and as a large number of earthquake ground motion records were obtained.
In Situ Site Characterization

Oceanographers can descend with scuba gear or in submarines to actually see the details of their “sites,” and meteorologists have obtained a significant amount of information by simply looking up through the transparent atmosphere to observe cloud formations. But geotechnical engineers deal with an opaque medium, and one that has great variability over small vertical and horizontal distances. Two of the most common techniques used by geotechnical engineers to “see” down into the site are the Standard Penetrometer Test (SPT) and the Cone Penetrometer Test (CPT).

The Standard Penetrometer Test (ASTM D1586-11) “hammers” a cylindrical pipe-shaped probe into the ground, measuring how many blows it takes for it to penetrate one foot. The cylindrical sampler can be split apart (right) to remove the soil sample that was collected at a particular depth.

The Cone Penetrometer Test (ASTM D3341) steadily “shoves” a probe into the ground, with the resistance of the soil to that penetration measured in terms of the strain experienced by the probe.

The hydraulic equipment mounted on the truck bed provides the power to push the probe into the ground. (University of Michigan)

A “collision” with a single rock can provide erroneous results as to the depth of bedrock, unless the testing is thorough. (Rogers 2006, p. 166)
Cyclic Simple Shear (CSS) Test
The CSS tests are used to simulate vertically propagating shear waves that can induce liquefaction. As in other geotechnical laboratory tests, the boundary conditions are a challenge to represent, in this case with constraint around the cylindrical soil sample (wires or stacked rings around the flexible membrane) but flexibly configured to allow shear deformation to occur.

Laboratory Testing of Soil Samples
The two basic components of a laboratory test of a soil sample are the apparatus and method used, on the one hand, and the soil sample, on the other. As Kramer (1996, p. 216) notes, “For the results of laboratory tests to reflect the actual behavior of the in situ soil as closely as possible, high-quality undisturbed samples must be obtained.” A sample of a cohesive, clay soil can be extracted from some depth with little disturbance (with little alteration of its properties, such as density). A cohesionless, sandy or gravelly soil, is much more difficult to collect without changing its properties.

Small Scale Models of Structures
The NSF-funded “Soil-Structure Interaction on the Scale of a City Block” (Jonathan Bray, U.C. Berkeley, Principal Investigator) used small scale models of structures in a soil test bed in the U.C. Davis centrifuge to test the effects of adjacency.

Resonant Column Test
Somewhat analogous to the way a structure can be vibrated at various frequencies to find the one (or ones, for high modes) at which it most vigorously responds, a sample of soil filling a cylindrical container can be vibrated through a spectrum of frequencies.
The Effects of a Site’s Soils on Ground Motions

After geologists study faults and identify their location, length, the level of activity in the past, and the amount of past displacements, seismologists enter the process and study the release of waves from the rupturing fault and the way the waves travel to various sites. Once the waves enter the earth near the site, “near” usually defined as the top 100 feet (30 meters) of earth, the geotechnical engineers take over and estimate important design factors such as frequency content of the motion, any near-fault pulse aspects, and ground displacement values to use for seismic isolation projects.

Shown above are the earthquake response spectra for the September 19, 1985 Mexico City Earthquake (Seed et al. 1988). The strong motion instrument at the SCT (Secretaria de Comunicaciones y Transportes) site recorded motions that had a spectral peak at about a period of two seconds. The site’s soil layers happened to respond quite vigorously to the earthquake shaking coming from the bedrock, as compared to nearby sites or to the UNAM bedrock site. “From an engineering point of view these sites (SCT, CAF, CAO) might be considered to be very similar with regard to the depths and stiffnesses of the underlying soils, but...the minor differences in soil conditions were apparently sufficient to cause significant differences in the response spectra of the ground surface motions (Seed et al 1988).”

Robert Reitherman
The first strong motion seismograph or accelerograph was introduced in 1932. Earthquakes that occurred even in California, New Zealand, or Japan were recorded by only a few instruments (and none were obtained for two of the largest earthquakes on record, 1960 Chile and 1964 Alaska earthquakes), but in the 1971 San Fernando Earthquake, 241 records were collected. There are approximately 25,000 accelerographs in the world today.
Fortunately, geologists and geotechnical engineers can usually geographically define the hazard of surface fault rupture with more precision than is the case with liquefaction or landslides caused by earthquakes. By the time of the 1891 Nobi Earthquake, when Professor Bunjiro Koto of the University of Tokyo studied the dramatic offset of the causative fault, the debate in the 1800s about whether the shaking caused the rupture or whether the rupture caused the shaking was decided in favor of the latter.
While the weight of the superstructure that is transferred to the foundation and then to the soil can be accurately calculated, the effect of earthquakes on the structure and on the soil is more uncertain. Soil properties change as the soil is shaken, especially if shaken to nonlinear levels. Simultaneously the response of the superstructure to the shaking can cause some foundation elements, such as those at the edges of shear walls, to alternatingly push down and pull up with large forces that add to or substract from the gravity loads.

Foundations

5,117 Oregon pine piles about 80 feet long, extending through the soft mud and alluvial soil at the edge of San Francisco Bay, were used to support the Ferry Building in San Francisco when it was built in 1898. The performance of the foundation in the 1906 earthquake was excellent, and because the timbers were sealed by a concrete cap at their top and mud farther down, they have been protected from fungal rot and teredos (marine boring animals), and they are still serviceable today. Piles now are usually made of reinforced or prestressed concrete. They are an important part of the geotechnical and structural engineering toolkit for dealing with earthquakes, either for their end bearing support in firmer strata, the friction developed along their surface areas, or both.

In the twentieth century, Félix Candela inverted his hyperbolic paraboloid “umbrella” roof structures to also form foundations. The thin concrete foundations worked the same way as the roofs, as shells. Garlock (2008)

Upside down? Yes, intentionally so. Masonry foundations of the inverted arch type were sometimes used in the 1800s to serve as grade beams connecting up footings, prior to the advent of reinforced concrete. If the reader flips the page upside down, the illustration at left looks like a perfectly normal masonry arch building, with weight on the arch carried in compression through the arch to the columns. The free body diagram is identical when the inverted arch is used, but the weight is delivered by the columns to the arches that span between them, with the soil pushing upward. The tie rod handles the lateral thrust of the arch action in either case.

Alan Kren, Rutherford & Chekene

Colliery Engineering Company (1899)
Earthfill Dams

Dams and the reservoirs they create are the largest constructions of humankind. All dams require careful geotechnical consideration of the foundation conditions, but in the case of an earthfill or rockfill dam, as compared to an arch, buttress, or gravity dam made of concrete, the dam itself is a geotechnical structure. The 1906 San Francisco Earthquake did not point out the earthquake vulnerability of earthfill dams, for all twenty of them in the San Francisco Bay Region performed safely (Seed et al. 1978), not because of earthquake engineering but because by chance the soil materials used were not susceptible to liquefaction.

Reservoir-triggered seismicity

At first thought, it seems like no human activity could affect the massive earth and its faults, but filling a valley with water means increasing the weight on the valley floor about 800 times. That has been enough in some cases to trigger or induce an earthquake (where a pre-existing fault was present.)

Near complete failure of the Lower San Fernando Dam, 1971 San Fernando Earthquake is pictured above. Had the reservoir been at capacity, 10 to 20 meters (30-60 feet) of water would have rushed over the crest of the dam, which slumped 30 feet (10 meters), eroded the dam, and caused a flash flood of the nearby residential area that had a population of 80,000. Liquefaction of the earthfill materials was identified as the culprit.

The largest such landslide/dam to date occurred on February 18, 1911 in Tajikistan on the Murghab River. The volume of rock and dirt totalled 1.7 cubic miles (7 cubic kilometers), or over twice that of the Montana earthquake slide pictured above.

More impressively, the Tajikistan earthquake-created dam was 1,800 ft tall (550 meters). The tallest manmade dam is the Jinping-I Dam in China, with a height of 1,001 feet (305 meters).

Earthquakes can not only damage dams -- they can create them. The August 17, 1959 Hebgen Lake earthquake in Montana triggered a landslide with a volume of 33 million cubic yards (43 million cubic meters), which created Quake Lake (below).

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American Society of Civil Engineers (2010). *Minimum design loads for buildings and other structures*, (ASCE 7-10), Reston, VA.


Duke, C. Martin (1958). *Bibliography of effects of soil conditions on earthquake damage*, Earthquake Engineering Research Institute, Oakland, CA.


