

# **S-3029: Understanding of the Theories and Practices of Earthquake-Resistant Design of Structures**

**An Online Continuing Education Course for Engineers**

**Course Number: S-3029**

**Credit: 3 Hours / 3 PDH / 3 CPD**

# Understanding of the Theories and Practices of Earthquake-Resistant Design of Structures

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## Introduction

In dealing with earthquakes, we must contend with appreciable probabilities that failure will occur in the near future. Otherwise, all the wealth of the world would prove insufficient to fill our needs: the most modest structures would be fortresses. We must also face uncertainty on a large scale, for it is our task to design engineering systems – about whose pertinent properties we know little – to resist future earthquakes and tidal waves – about whose characteristics we know even less. In a way, earthquake engineering is a cartoon; earthquake effects on structures systematically bring out the mistakes made in design and construction, even the minutest mistakes.

***Several points are essential to an understanding of the theories and practices of earthquake-resistant design bear restating:***

1. Ordinarily, a large earthquake produces the most severe loading that a building is expected to survive. The probability that *failure* will occur is very real and is greater than for other loading phenomena. Also, in the case of earthquakes, the definition of *failure* is altered to permit certain types of behavior and damage that are considered unacceptable in relation to the effects of other phenomena.
2. The levels of uncertainty are much greater than those encountered in the design of structures to resist other phenomena. This is in spite of the tremendous strides made since the Federal government began strongly supporting research in earthquake engineering and seismology following the 1964 Prince William Sound and 1971 San Fernando earthquakes. The high uncertainty applies both to the knowledge of the loading function and to the resistance properties of the materials, members, and systems.
3. The details of construction are very important because flaws of no apparent consequence often will cause systematic and unacceptable damage simply because the earthquake loading is so severe and an extended range of behavior is permitted.

The remainder of this course is devoted to a very abbreviated discussion of fundamentals that reflect the concepts on which earthquake-resistant design are based. When appropriate, important aspects of the *NEHRP Recommended Seismic Provisions for New Buildings and Other Structures* are mentioned and reference is made to particularly relevant portions of that document or the standards that are incorporated by reference. The *2020 Provisions* (FEMA, 2020a) is composed of three parts:

- 1) "Provisions," 2) "Commentary," and 3) "Resource Papers on Special Topics in Seismic Design." Part 1 states the intent and then cites ASCE/SEI 7-16 *Minimum Design Loads for Buildings and Other Structures*

(ASCE, 2017) as the primary reference. The remainder of Part 1 contains recommended changes to update ASCE/SEI 7-16; the recommended changes include commentary on each specific recommendation. All three parts are referred to herein as the *Provisions*, but where pertinent, the specific part is referenced, and ASCE/SEI 7-16 is referred to as the *Standard*. ASCE/SEI 7-16 itself refers to several other standards for the seismic design of structures composed of specific materials and those standards are essential elements to achieve the intent of the *Provisions*.

## 1. Earthquake Phenomena

According to the most widely held scientific belief, most earthquakes occur when two segments of the earth's crust suddenly move in relation to one another. The surface along which movement occurs is known as a fault. The sudden movement releases strain energy and causes seismic waves to propagate through the crust surrounding the fault. These waves cause the surface of the ground to shake violently, and it is this ground shaking that is the principal concern of structural engineering to resist earthquakes.

Earthquakes have many effects, in addition to ground shaking. For various reasons, many of the other effects generally are not major considerations in the design of buildings and similar structures. For example, seismic sea waves or tsunamis can cause very forceful flood waves in coastal regions, and seiches (long-period sloshing) in lakes and inland seas can have similar effects along shorelines. These are outside the scope of the *Provisions*. The devastating tsunamis accompanying the 2004 Sumatra-Andaman and the 2010 Tohoku Earthquakes stimulated the development of methods to design structures to resist such hydrodynamic forces. ASCE/SEI 7-16 includes a chapter devoted to that effect. The *Provisions* address Long-period sloshing of the liquid contents of tanks.

Abrupt ground displacements occur where a fault intersects the ground surface. (This commonly occurs in California earthquakes but did not occur in the historic Charleston, South Carolina earthquake or the very large New Madrid, Missouri, earthquakes of the nineteenth century.) Mass soil failures such as landslides, liquefaction, and gross settlement result from ground shaking on susceptible soil formations. Once again, design for such events is specialized, and it is common to locate structures so that mass soil failures and fault rupture are of no major consequence to their performance. Modifying soil properties to protect against liquefaction is one important exception; large portions of a few metropolitan areas with the potential for significant ground shaking are susceptible to liquefaction. Lifelines that cross faults require special design beyond the scope of the *Provisions*. The structural loads specified in the *Provisions* are based solely on ground shaking; they do not provide for ground failure. Resource Paper 12 ("Evaluation of Geologic Hazards and Determination of Seismic Lateral Earth Pressures") in Part 3 of the 2009 *Provisions* (FEMA, 2009) includes a description of current procedures for predicting seismic-induced slope instability, liquefaction, and surface fault rupture. Selected portions of that work are now included in the *Provisions*.

Nearly all large earthquakes are *tectonic* in origin. They are associated with movements of and strains in large segments of the earth's crust, called *plates*, and virtually all such earthquakes occur at or near the boundaries of these plates. This is the case with earthquakes in the far western portion of the United

States, where two very large plates, the North American continent and the Pacific basin, come together. In the central and eastern United States, however, earthquakes are not associated with such a plate boundary, and their causes are not as completely understood. This factor, combined with the smaller amount of data about central and eastern earthquakes (because of their infrequency), means that the uncertainty associated with earthquake loadings is higher in the central and eastern portions of the nation than in the West. Even in the West, the uncertainty (when considered as a fraction of the predicted level) about the hazard level is probably greater in areas where the mapped hazard is low than in areas where the mapped hazard is high.

Two basic data sources are used in establishing the likelihood of earthquake ground shaking, or seismicity, at a given location. The first is the historical record of earthquake effects, and the second is the geological record of earthquake effects. Given the infrequency of major earthquakes, there is no place in the United States where the historical record is long enough to be used as a reliable basis for earthquake prediction – certainly not as reliable as with other phenomena such as wind and snow. Even on the eastern seaboard, the historical record is too short to justify sole reliance on the historical record. Thus, the geological record is essential. Such data requires very careful interpretation, but they are used widely to improve knowledge of seismicity. Geological data have been developed for many locations as part of the nuclear power plant design process. Overall, there is more geological data available for the far western United States than for other regions of the country. Both sets of data have been taken into account in the *Provision* seismic ground shaking maps. In recent years, data from earthquakes associated with pumping fluid into deep wells have also been considered in understanding the geologic procedures.

The amplitude of earthquake ground shaking diminishes with distance from the source, and the rate of attenuation is less for lower frequencies of motion than for higher frequencies. This effect is captured by the fact that the *Provisions* specify response acceleration parameters at 22 frequencies of vibration to define the hazard of seismic ground shaking for structures. They are based on a statistical analysis of the database of seismological information. The *Provisions* provide one additional parameter for the definition of response to ground shaking, *TL*. It defines an important transition point for long period (low frequency) behavior; it is not based upon as robust of an analysis as the other parameters.

The *Commentary* provides a more thorough discussion of the development of the maps, their probabilistic basis, the necessarily crude lumping of parameters, and other related issues. Prior to its 1997 edition, the basis of the *Provisions* was to “minimize the hazard to life...” at the design earthquake motion, which was defined as having a 10 percent probability of being exceeded in a 50-year reference period (FEMA, 1995). As of the 1997 edition (FEMA, 1997), the basis became to avoid *structural collapse* at the maximum considered earthquake (MCE) ground motion, which is defined as having a 2 percent probability of being exceeded in a 50-year reference period. In the 2009 edition of the *Provisions*, the design basis was refined to target a 1% probability of structural collapse for ordinary buildings in 50 years. The MCE ground motion has been adjusted to deliver this level of risk combined with a 10% probability of collapse should the MCE ground motion occur. This new approach incorporates a fuller consideration of the nature of the seismic hazard at a location than was possible with the earlier

definitions of ground shaking hazard, which were tied to a single level of probability of ground shaking occurrence.

The nature of the uncertainty in earthquake occurrence and in-ground shaking amplitude combine to predict very high ground motions near faults that produce large earthquakes relatively frequently. Empirical evidence of building performance in past earthquakes indicates that design for such extreme motions is not necessary. Consequently, when the MCE concept was introduced, the *Provisions* included a semi-deterministic upper bound on the accelerations produced by the purely probabilistic method. The concept used was to combine the occurrence of a reasonable upper-bound earthquake at the known fault location with a somewhat conservative estimate (mean plus one standard deviation) of the ground shaking at a site. The details of this method have evolved in subsequent editions of the *Provisions*, but the philosophical basis remains the same.

## 2. Structural Response to Ground Shaking

The first important difference between structural response to an earthquake and response to most other loadings is that the earthquake response is *dynamic*, not *static*. For most structures, even the response to wind is essentially static. Forces within the structure are due almost entirely to the pressure loading rather than the acceleration of the mass of the structure. But with earthquake ground shaking, the above ground portion of a structure is not subjected to any applied force. The stresses and strains within the superstructure are created entirely by its dynamic response to the movement of its base, the ground. Even though the most used design procedure resorts to the use of a concept called the equivalent static force for actual calculations, some knowledge of the theory of vibrations of structures is essential.

### 2.1 Response Spectra

Figure 1 shows accelerograms, records of the acceleration at one point along one axis, for several representative earthquakes. Note the erratic nature of the ground shaking and the different characteristics of the different accelerograms. Precise analysis of the elastic response of an ideal structure to such a pattern of ground motion is possible; however, it is not commonly done for ordinary structures. The increasing power and declining cost of computational aids are making such analyses more common. However, at this time, only a small minority of structures designed across the country are analyzed for specific responses to a specific ground motion.

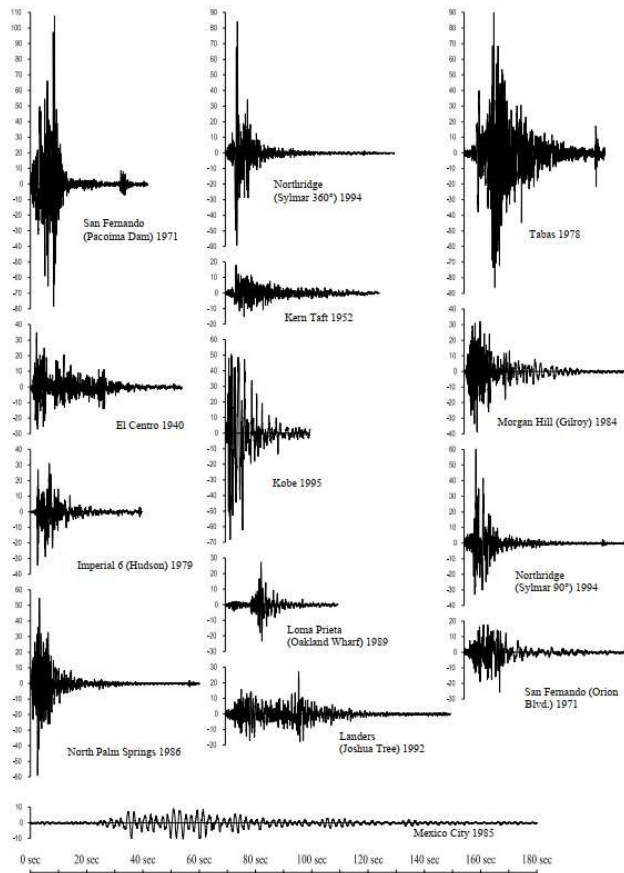
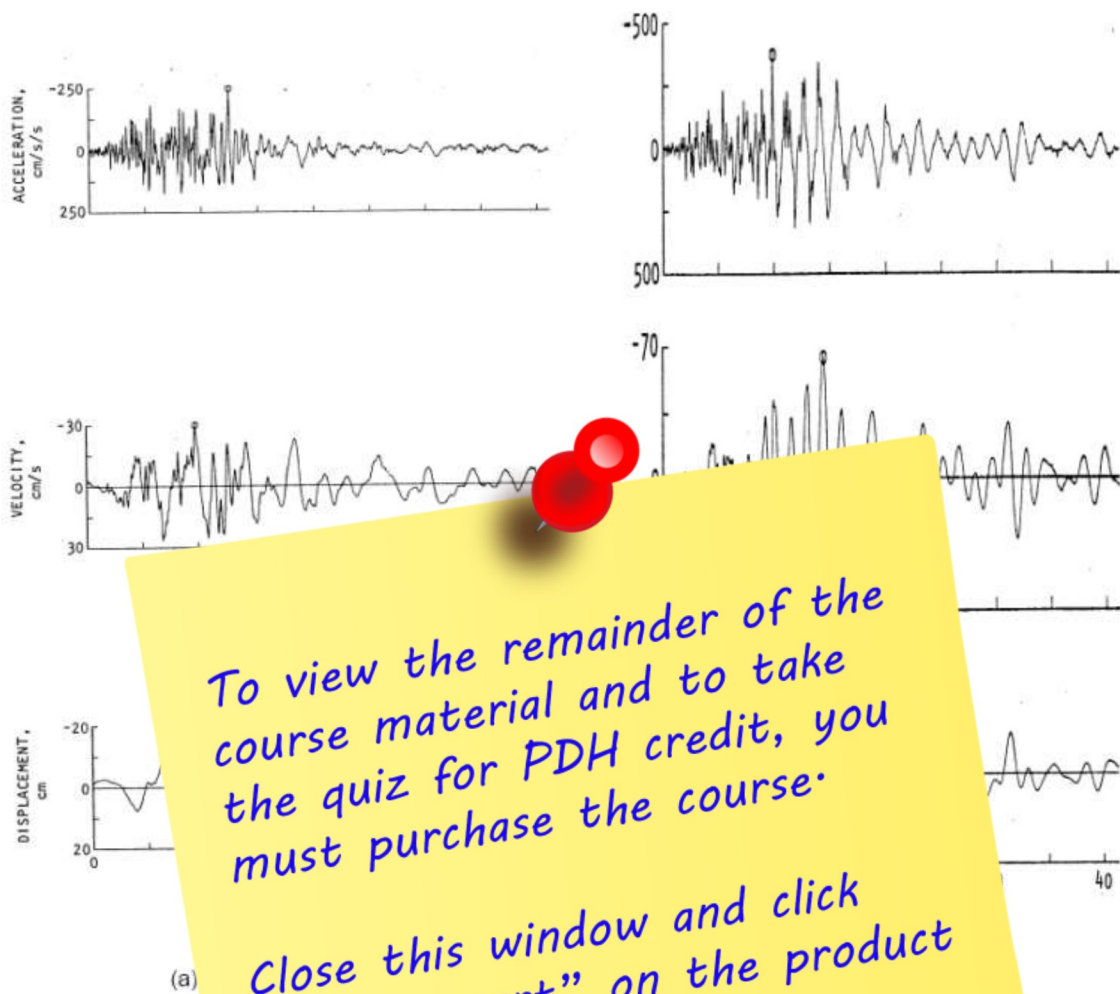


Figure 1. Earthquake Ground Acceleration in Epicentral Regions. ( Note: All accelerograms are plotted to the same scale for time and acceleration – the vertical axis is % gravity. Great earthquakes extend for much longer periods.)

Figure 2 shows further detail developed from an accelerogram. Part (a) shows the ground acceleration along with the ground velocity and ground displacement derived from it. Part (b) shows the acceleration, velocity, and displacement for the same event at the roof of the building located where the ground motion was recorded. Note that the peak values are larger in the diagrams of Figure 2(b) (the vertical scales are essentially the same). This increase in response to the structure at the roof level over the motion of the ground itself is known as dynamic amplification. It depends very much on the vibrational characteristics of the structure and the characteristic frequencies of the ground shaking at the site.



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Figure 2. Holiday Inn Ground Motion Record (a) North-South Ground Acceleration (cm/s/s) (b) North-South Ground Velocity (cm/s) (c) North-South Ground Displacement (cm) (Holiday Inn Ground Motion Record) (a) North-South Ground Acceleration (cm/s/s) (b) North-South Ground Velocity (cm/s) (c) North-South Ground Displacement (cm) (Holiday Inn Ground Motion Record)

In design, the response of a specific structure to an earthquake is ordinarily estimated from a design response spectrum such as what is specified in the *Provisions*. The first step in creating a design response spectrum is to determine the maximum response of a given structure to a specific ground motion (see the maximum response points denoted by the circles in Figure 2b). The underlying theory is based entirely on the response of a single-degree-of-freedom oscillator, such as a simple one-story frame with the mass concentrated at the roof. The vibrational characteristics of such a simple oscillator may be reduced to two: the natural period<sup>1</sup> and the amount of damping. By recalculating the record of response versus time to a specific ground motion for a wide range of natural periods and each of a set of