Earthquake Effects on Buildings

An Online Continuing Education Course for Engineers

Course Number: BD-2031

Credit: 2 Hours / 2 PDH / 2 CPD

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INTRODUCTION

This course explains how various aspects of earthquake ground motion affect structures and how certain building attributes modify the ways in which the building responds to the ground motion. The interaction of these characteristics determines the overall seismic performance of the building: whether it is undamaged; suffers minor damage; becomes unusable for days, weeks, or months; or collapses with great loss of life.

Explanations of some characteristics of ground motion are followed by descriptions of several material, structural, and building attributes that, by interacting with ground motion, determine the building's seismic performance-the extent and nature of its damage.

INERTIAL FORCES AND ACCELERATION

The seismic body and surface waves create inertial forces within the building. Inertial forces are created within an object when an outside force tries to make it move if it is at rest or changes its rate or direction of motion if it is moving. Inertial force takes us back to high school physics and to Newton's Second Law of Motion, for when a building shakes it is subject to inertial forces and must obey this law just as if it were a plane, a ship, or an athlete. Newton's Second Law of Motion states that an inertial force, F, equals mass, M, multiplied by the acceleration, A. (Figure 1)

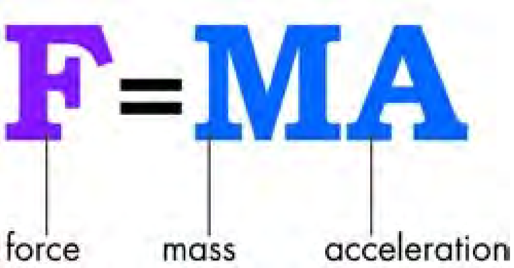

Figure 1: Newton's Second Law of Motion

Mass can be assumed as equivalent (at ground level) to the weight of the building, and so this part of the law explains why light buildings, such as wood frame houses, tend to perform better in earthquakes than large heavy ones the forces on the building are less.

The acceleration, or the rate of change of the velocity of the waves setting the building in motion, determines the percentage of the building mass or weight that must be dealt with as a horizontal force.

Acceleration is measured in terms of the acceleration due to gravity or g (Figure 2). One g is the rate of change of velocity of a free-falling body in space. This is an additive velocity of 32 feet per second per second. Thus, at the end of the first second, the velocity is 32 feet per second; a second later it is 64 feet per second, and so on. When parachutists or bungee jumpers are in free fall, they are experiencing an acceleration of 1g. A building in an earthquake experiences a fraction of a second of g forces in one direction before they abruptly change direction.

Figure 2: Some typical accelerations.

The parachutists are experiencing 1g, while the roller-coaster riders reach as much as 4g. The aerobatic pilots are undergoing about 9g. The human body is very sensitive and can feel accelerations as small as 0.001g.

Engineering creations (planes, ships, cars, etc.) that are designed for a dynamic or moving environment can accommodate very large accelerations. Military jet planes, for example, are designed for accelerations of up to 9g. At this acceleration, the pilot experiences 9 times the body weight pressing down on the organs and blacks out.

A commercial airliner in severe turbulence may experience about 20 percent g (or 0.2g), although unbuckled passengers and attendants have been known to hit the ceiling because of an acceleration "drop" of over Ig. A fast-moving train on a rough track may also experience up to about 0.2g.

Poorly constructed buildings begin to suffer damage at about 10 percent g (or 0.1g). In a moderate earthquake, the waves of vibration may last for a few seconds, and accelerations may be approximately 0.2g. For people on the ground or at the bottom of a building, the sensations will be very similar to those of the occupants of the plane in turbulence or passengers standing in the fast-moving train: they feel unsteady and may need to grab onto something to help them remain standing. Earthquakes cause additional alarm because when the shaking starts, those experiencing it do not know whether it will quickly end or is the beginning of a damaging and dangerous quake. Short accelerations may, for a fraction of a second, exceed 1.0g. In the Northridge earthquake in 1994, a recording station in Tarzana, five miles (8 km) from the epicenter, recorded 1.92g.

DURATION, VELOCITY, AND DISPLACEMENT

Because of the inertial force formula, acceleration is a key factor in determining the forces on a building, but a more significant measure is that of acceleration combined with duration, which considers the impact of earthquake forces over time. In general, a number of cycles of moderate acceleration, sustained over time, can be much more difficult for a building to withstand than a single much larger peak. Continued shaking weakens a building structure and reduces its resistance to earthquake damage.

A useful measure of strong-motion duration is termed the bracketed duration. This is the shaking duration above a certain threshold acceleration value, commonly taken as 0.05g, and is defined as the time between the first and last peaks of motion that exceeds this threshold value. In the San Fernando earthquake of 1971, the bracketed duration was only about 6 seconds. In both the Loma Prieta and the Northridge earthquakes, the strong motion lasted a little over ten seconds, yet caused much destruction. In the 1906 San Francisco earthquake, the severe shaking lasted 45 seconds, while in Alaska, in 1964, the severe motion lasted for over three minutes.

Two other measures of wave motion are directly related to acceleration and can be mathematically derived from it. Velocity, which is measured in inches or centimeters per second, refers to the rate of motion of the seismic waves as they travel through the earth. This is very fast. Typically, the P wave travels at between 3 km/sec and 8 km/sec or 7,000 to 18,000 mph. The S wave is slower, traveling at between 2 km/sec and 5 km/sec, or 4,500 mph to 11,000 mph.

Displacement refers to the distance that points on the ground are moved from their initial locations by the seismic waves. These distances, except immediately adjacent to or over the fault rupture, are quite small and are measured in inches or centimeters. For example, in the Northridge earthquake, a parking structure at Burbank, about 18 miles (29 km) from the epicenter recorded displacements at the roof of 1.6 inches (4.0 cm) at an acceleration of 0.47g. In the same earthquake, the Olive View hospital in Sylmar, about 7.5 miles (12 km) from the epicenter, recorded a roof displacement of 13.5 inches (34 cm) at an acceleration of 1.50g.

The velocity of motion on the ground caused by seismic waves is quite slow-huge quantities of earth and rock are being moved. The velocity varies from about 2 cm/sec in a small earthquake to about 60 cm/sec in a major shake. Thus, typical building motion is slow, and the distances are small, but thousands of tons of steel and concrete are wrenched in all directions several times a second.

In earthquakes, the values of ground acceleration, velocity, and displacement vary a great deal in relation to the frequency of the wave motion. High-frequency waves (higher than 10 hertz) tend to have high amplitudes of acceleration but small amplitudes of displacement, compared to low-frequency waves, which have small accelerations and relatively large velocities and displacements.

GROUND AMPLIFICATION

Earthquake shaking is initiated by a fault slippage in the underlying rock. As the shaking propagates to the surface, it may be amplified, depending on the intensity of shaking, the nature of the rock and, above all, the surface soil type and depth.

A layer of soft soil, measuring from a few feet to a hundred feet or so, may result in an amplification factor of from 1.5 to 6 over the rock shaking. This amplification is most pronounced at longer periods and may not be so significant at short periods. The amplification also tends to decrease as the level of shaking increases.

As a result, earthquake damage tends to be more severe in areas of soft ground. This characteristic became very clear when the 1906 San Francisco earthquake was studied, and maps were drawn that showed building damage in relation to the ground conditions. Inspection of records from soft clay sites during the 1989 Loma Prieta earthquake indicated a maximum amplification of long-period shaking of three to six times. Extensive damage was caused to buildings in San Francisco's Marina district, which was largely built on filled ground, some of it rubble deposited after the 1906 earthquake.

Because of the possibility of considerable shaking amplification related to the nature of the ground, seismic codes have some very specific requirements that relate to the characteristics of the site. These require the structure to be designed for higher force levels if it is located on poor soil. Specially designed foundations may also be necessary.

PERIOD AND RESONANCE

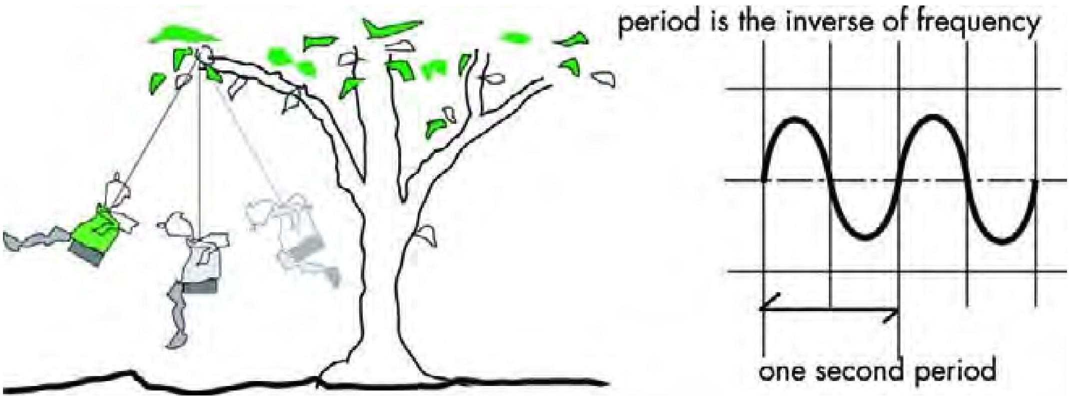

Figure 3: The Fundamental Period

Natural Periods

Another very important characteristic of earthquake waves is their period or frequency; that is, whether the waves are quick and abrupt or slow and rolling. This phenomenon is particularly important for determining building seismic forces.

All objects have a natural or fundamental period; this is the rate at which they will move back and forth if they are given a horizontal push (Figure 3). In fact, without pulling and pushing it back and forth, it is not possible to make an object vibrate at anything other than its natural period.

When a child in a swing is started with a push, to be effective this shove must be as close as possible to the natural period of the swing. If correctly gauged, a very small push will set the swing going nicely. Similarly, when earthquake motion starts a building vibrating, it will tend to sway back and forth at its natural period.

Period is the time in seconds (or fractions of a second) that is needed to complete one cycle of a seismic wave. Frequency is the inverse of this-the number of cycles that will occur in a second-and is measured in "Hertz". One Hertz is one cycle per second.

Natural periods vary from about 0.05 seconds for a piece of equipment, such as a filing cabinet, to about 0.1 seconds for a one-story building. Period is the inverse of frequency, so the cabinet will vibrate at 1 divided by 0.05 = 20 cycles a second or 20 Hertz.

A four-story building will sway at about a 0.5 second period, and taller buildings between about 10 and 20 stories will swing at periods of about 1 to 2 seconds. A large suspension bridge may have a period of around 6 seconds. A rule of thumb is that the building period equals the number of stories divided by 10; therefore, period is primarily a function of building height. The 60-story Citicorp office building in New York has a measured period of 7 seconds; give it a push, and it will sway slowly back and forth completing a cycle every 7 seconds. Other factors, such as the building's structural system, its construction materials, its contents, and its geometric proportions, also affect the period, but height is the most important consideration (Figure 4).

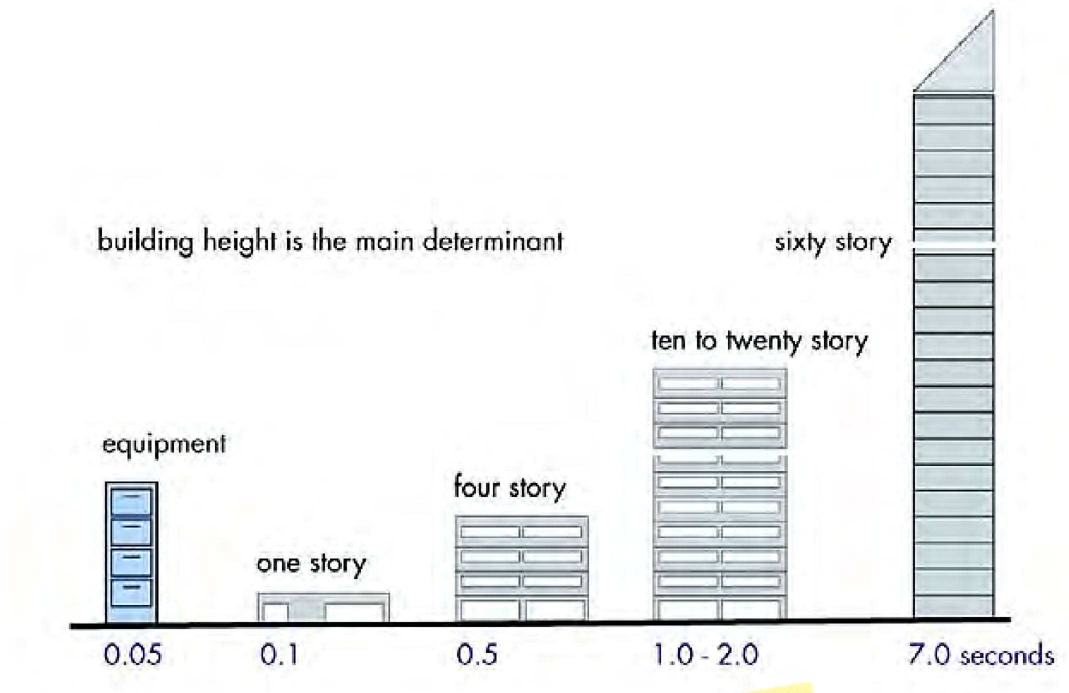

Figure 4: Comparative building perio... ...ues are approximations: the structural ... affect the period.

The building's peric... ...hen a reinforced concrete structure e... ...ack: this has the effect of increasing the str... ...ning." This may result in the structure's pe... ...cing resonance, which may prove fatal to ar... ...may also occur: a steel structure may s... ...steel yields and deforms.

Ground Motion, Build...

When a vibrating or sw... ...at its natural period, its vibrations in... ...ll pushes and, in fact, its accelerations m... ...phenomenon is called resonance.

The ground obeys the same physical law and vibrates at its natural period, if set in motion by an earthquake. The natural period of ground varies from about 0.4 seconds to 2 seconds, depending on the nature of the ground. Hard ground or rock will experience short period vibration. Very soft ground may have a period of up to 2 seconds but, unlike a structure, it cannot sustain longer period motions except under certain unusual conditions. Since this range is well within the range of common building periods, it is quite possible that the pushes that earthquake ground motion imparts to the building will be at the natural period