Seismic Considerations for Road Tunnels

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CHAPTER 13
SEISMIC CONSIDERATIONS

13.1 INTRODUCTION

Tunnels, in general, have performed better during earthquakes than have above ground structures such as bridges and buildings. Tunnel structures are constrained by the surrounding ground and, in general, cannot be excited independent of the ground or be subject to strong vibratory amplification, such as the inertial response of a bridge structure during earthquakes. Another factor contributing to the reduced tunnel damage is that the amplitude of seismic ground motion tends to reduce with depth below the ground surface. Adequate design and construction of seismic resistant tunnel structures, however, should never be overlooked, as moderate to major damage has been experienced by many tunnels during earthquakes, as summarized by Dowding and Rozen (1978), Owen and Scholl (1981), Sharma and Judd (1991), and Power et al. (1998), among others. The greatest incidence of severe damage has been associated with large ground displacements due to ground failure, i.e., fault rupture through a tunnel, landsliding (especially at tunnel portals), and soil liquefaction. Ground shaking in the absence of ground failure has produced a lower incidence and degree of damage in general, but has resulted in moderate to major damage to some tunnels in recent earthquakes. The most recent reminder of seismic risk to underground structures under the ground shaking effect is the damage and near collapse at the Daikai and Nagata subway stations (Kobe Rapid Transit Railway) during the 1995 Kobe Earthquake in Japan. Near-surface rectangular cut-and-cover tunnels and immersed tube tunnels in soil have also been vulnerable to transient seismic lateral ground displacements, which tend to cause racking of a tunnel over its height and increased lateral pressures on the tunnel walls. Their seismic performance could be vital, particularly when they comprise important components of a critical transportation system (e.g., a transit system) to which little redundancy exists.

The general procedure for seismic design and analysis of tunnel structures should be based primarily on the ground deformation approach (as opposed to the inertial force approach); i.e., the structures should be designed to accommodate the deformations imposed by the ground. The analysis of the structure response can be conducted first by ignoring the stiffness of the structure, leading to a conservative estimate of the ground deformations. This simplified procedure is generally applicable for structures embedded in rock or very stiff/dense soil. In cases where the structure is stiff relative to the surrounding soil, the effect of soil-structure interaction must be taken into consideration. Other critical conditions that warrant special seismic considerations include cases where a tunnel intersects or meets another tunnel (e.g., tunnel junction or tunnel/cross-passage interface) or a different structure (such as a ventilation building). Under these special conditions, the tunnel structure may be restrained from moving at the junction point due to the stiffness of the adjoining structure, thereby inducing stress concentrations at the critical section. Complex numerical methods are generally required for cases such as these where the complex nature of the seismic soil-structure interaction system exists.

13.2 DETERMINATION OF SEISMIC ENVIRONMENT

13.2.1 Earthquake Fundamental

General: Earthquakes are produced by abrupt relative movements on fractures or fracture zones in the earth's crust. These fractures or fracture zones are termed *earthquake faults*. The mechanism of fault movement is elastic rebound from the sudden release of built-up strain energy in the crust. The built-up strain energy accumulates in the earth's crust through the relative movement of large, essentially intact

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pieces of the earth's crust called *tectonic plates*. This relief of strain energy, commonly called *fault rupture*, takes place along the *rupture zone*. When fault rupture occurs, the strained rock rebounds elastically. This rebound produces vibrations that pass through the earth crust and along the earth's surface, generating the ground motions that are the source of most damage attributable to earthquakes. If the fault along which the rupture occurs propagates upward to the ground surface and the surface is uncovered by sediments, the relative movement may manifest itself as *surface rupture*. Surface ruptures are also a source of earthquake damage to constructed facilities including tunnels.

The major tectonic plates of the earth's crust are shown in Figure 13-1 (modified from Park, 1983). There are also numerous smaller, minor plates not shown on this figure. Earthquakes also occur in the interior of the plates, although with a much lower frequency than at plate boundaries.

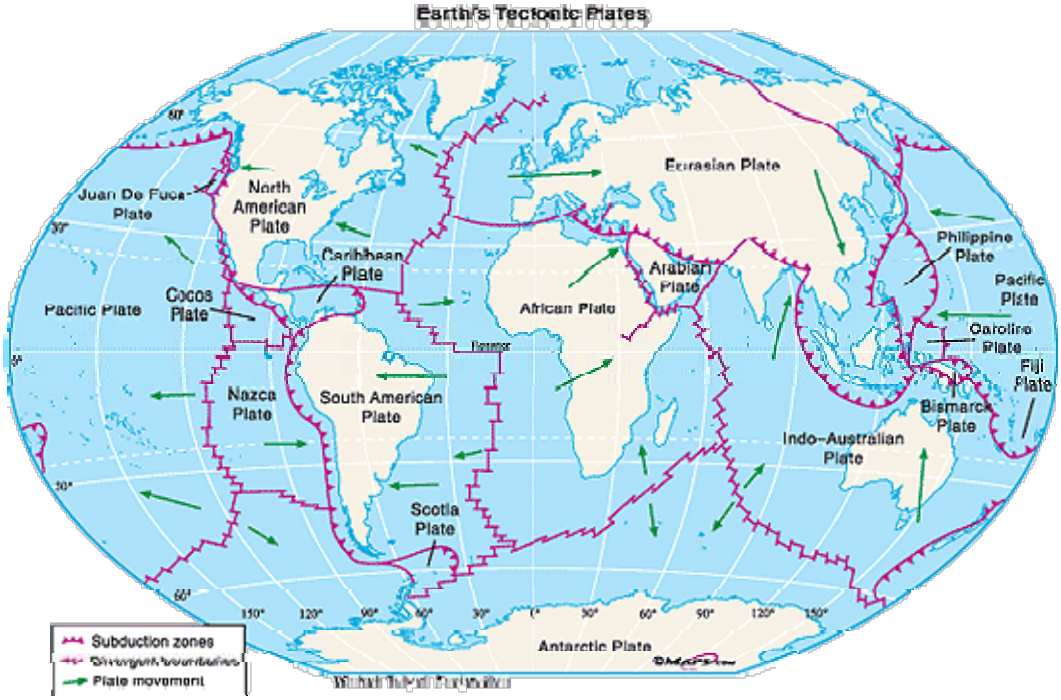

Figure 13-1 Major Tectonic Plates and Their Approximate Direction of Movement. (Source: www.maps.com)

For the continental United States, the principal tectonic plate boundary is along the western coast of the continent, where the North American Plate and the Pacific Plate are in contact. In California, the boundary between these plates is a transform fault wherein the relative movement is generally one of lateral slippage of one plate past the other. Elsewhere along the west coast (e.g., off the coast of Oregon, Washington, and Alaska), the plate boundary is a *subduction zone* wherein one plate dives (subducts) beneath the other plate. In the western interior of the United States, adjacent to the western edge of the American Plate, there may be subplates that have formed as a result of subcrustal flow. Earthquake sources in Utah and Montana may be attributable to such subplate sources. Earthquake source areas in the central and eastern United States and along the Saint Lawrence Valley are within the American Plate and are considered to be intraplate source zones. The mechanisms generating earthquakes in these intraplate zones are poorly understood, but may be related to relief of locked-in stresses from ancient tectonic movements, crustal rebound from the ice ages, re-adjustment of stress in the interior of the plate due to boundary loads, sediment load such as the Mississippi River basin, or other unrecognized

mechanisms. Earthquakes in Hawaii are believed to be associated with an isolated plume of molten rock from the mantle referred to as a hot spot.

The intensity and impact of earthquakes may be as great or greater in the plate interiors as they are at the active plate boundaries. The differences between plate boundary and intraplate earthquakes are in their geographic spread and the frequency of occurrence. Earthquake activity is much greater along the plate boundaries than in the plate interior. However, ground motions from intraplate earthquakes tend to attenuate, or dissipate, much more slowly than those from plate boundary events. Plate boundary faults are relatively longer than those in the plate interior and tend to be associated with a smaller *stress drop* (the stress drop is the sudden reduction of stress across the fault plane during rupture), longer duration of shaking, and a more frequent rate of earthquake occurrence.

Fault Movements: Faults are created when the stresses within geologic materials exceed the ability of those materials to withstand the stresses. Most faults that exist today are the result of tectonic activity that occurred in earlier geological times. These faults are usually non-seismogenic (i.e., incapable of generating earthquakes, or inactive). However, faults related to past tectonism may be reactivated by present-day tectonism in seismically active areas and can also be activated by anthropogenic (man-made) activities such as impoundment of a reservoir by a dam or injection of fluids (e.g., waste liquids) deep into the subsurface. The maximum size of an earthquake on an anthropogenically reactivated fault is a subject of some controversy, but earthquakes as large as moment magnitude 6.5 have been attributed to reservoir impoundment.

Not all faults along which relative movement is occurring are a source of earthquakes. Some faults may be surfaces along which relative movement is occurring at a slow, relatively continuous rate, with an insufficient stress drop to cause an earthquake. Such movement is called *fault creep*. Fault creep may occur along a shallow fault, where the low overburden stress on the fault results in a relatively low threshold stress for initiating displacement along the fault. Alternatively, a creeping fault may be at depth in soft and/or ductile materials that deform plastically. Also, there may be a lack of frictional resistance or asperities (non-uniformities) along the fault plane, allowing steady creep and the associated release of the strain energy along the fault. Fault creep may also prevail where phenomena such as magma intrusion or growing salt domes activate small shallow faults in soft sediments. Faults generated by extraction of fluids (e.g., oil or water in southern California), which causes ground settlement and thus activates faults near the surface may also result in fault creep. Faults activated by other non-tectonic mechanisms, e.g., faults generated by gravity slides that take place in thick, unconsolidated sediments, could also produce fault creep.

Active faults that extend into crystalline bedrock are generally capable of building up the strain energy needed to produce, upon rupture, earthquakes strong enough to affect transportation facilities. Fault ruptures may propagate from the crystalline bedrock to the ground surface and produce ground rupture. Fault ruptures which propagate to the surface in a relatively narrow zone of deformation that can be traced back to the causative fault in crystalline rock are sometimes referred to as primary fault ruptures. Fault ruptures may also propagate to the surface in diffuse, distributed zones of deformation which cannot be traced directly back to the basement rock. In this case, the surface deformation may be referred to as secondary fault rupture.

Whether or not a fault has the potential to produce earthquakes is usually judged by the recency of previous fault movements. If a fault has propagated to the ground surface, evidence of faulting is usually found in geomorphic features associated with fault rupture (e.g., relative displacement of geologically young sediments). For faults that do not propagate to the ground surface, geomorphic evidence of previous earthquakes may be more subdued and more difficult to evaluate (e.g., near surface folding in sediments or evidence of liquefaction or slumping generated by the earthquakes). If a fault has undergone

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relative displacement in relatively recent geologic time (within the time frame of the current tectonic setting), it is reasonable to assume that this fault has the potential to move again. If the fault moved in the distant geologic past, during the time of a different tectonic stress regime, and if the fault has not moved in recent (Holocene) time (generally the past 11,000 years), it may be considered inactive. For some very important and critical facilities, such as those whose design is governed by the US Nuclear Regulatory Commission (NRC), a timeframe much longer than the 11,000-yr criterion has been used. In accordance with the US NRC regulations a fault is defined as “capable” (as opposed to “active”) if it has shown activity within the past 35,000 years or longer.

Geomorphic evidence of fault movement cannot always be dated. In practice, if a fault displaces the base of unconsolidated alluvium, glacial deposits, or surficial soils, then the fault is likely to be active. Also, if there is micro-seismic activity associated with the fault, the fault may be judged as active and capable of generating earthquakes. Microearthquakes occurring within basement rocks at depths of 7 to 20 km may be indicative of the potential for large earthquakes. Microearthquakes occurring at depths of 1 to 3 km are not necessarily indicative of the potential for large, damaging earthquake events. In the absence of geomorphic, tectonic, or historical evidence of large damaging earthquakes, shallow microtremors may simply indicate a potential for small or moderate seismic events. Shallow microearthquakes of magnitude 3 or less may also sometimes be associated with mining or other non-seismogenic mechanisms. If there is no geomorphic evidence of recent seismic activity and there is no microseismic activity in the area, then the fault may be inactive and not capable of generating earthquakes.

In some instances, fault rupture may be confined to the subsurface with no relative displacement at the ground surface due to the fault movement. Subsurface faulting without primary fault rupture at the ground surface is characteristic of almost all but the largest magnitude earthquakes in the central and eastern United States. Due to the rarity of large magnitude intraplate events, geological processes may erase surface manifestations of major earthquakes in these areas. Therefore, intraplate seismic source zones often must be evaluated using instrumental seismicity and paleoseismicity studies. This is particularly true if the intraplate sources are covered by a thick mantle of sediments, as in the New Madrid, Tennessee, and Charleston, South Carolina, intraplate seismic zones. Instrumental recording of small magnitude events can be particularly effective in defining seismic source zones.

Essentially all of the active faults with surface fault traces in the United States are shallow crustal faults west of the Rocky Mountains. However, not all shallow crustal faults west of the Rocky Mountains have surface fault traces. Several recent significant earthquakes along the Pacific Coast plate boundary (e.g., the 1987 Whittier Narrows earthquake and the 1994 Northridge earthquake) were due to rupture of thrust (compressional) faults that did not break the ground surface, termed *blind thrust* faults.

A long fault, like the San Andreas Fault in California or the Wasatch Fault in Utah, typically will not move along its entire length at any one time. Such faults typically move in portions, one segment at a time. An immobile (or "locked") segment, a segment which has remained stationary while the adjacent segments of the fault have moved, is a strong candidate for the next episode of movement.

Type of Faults: Faults may be broadly classified according to their mode, or style of relative movement. The principal modes of relative displacement are illustrated in Figure 13-2 and are described subsequently.

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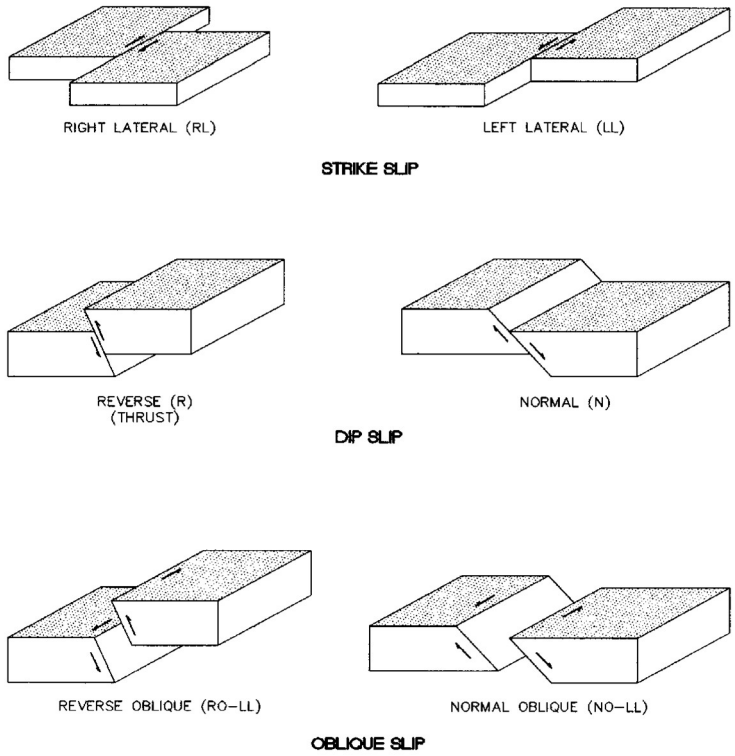

Figure 13-2 Types of Fault Movement

Strike Slip Faults: Faults along which relative movement is essentially horizontal (i.e., the opposite sides of the fault slide past each other laterally), are called strike slip faults. Strike slip faults are often essentially linear (or planar) features. Strike slip faults that are not fairly linear may produce complex surface features. The San Andreas fault is a strike slip fault that is essentially a north-south linear feature over most of its length. Strike slip faults may sometimes be aligned in en-echelon fashion wherein individual sub-parallel segments are aligned along a linear trend. En-echelon strike slip faulting is sometimes accompanied by step over zones where fault displacement is transferred from adjacent strike slip faults. Ground rupture patterns within these zones may be particularly complex.

Dip Slip Faults: Faults in which the deformation is perpendicular to the fault plane may occur due to either *normal* (extensional) or *reverse* (compressional) motion. These faults are referred to as *dip slip* faults. Reverse faults are also referred to as *thrust faults*. Dip slip faults may produce multiple fractures within rather wide and irregular fault zones.

Other Special Cases: Faults that show both strike slip and dip slip displacement may be referred to as *oblique slip faults*.

Earthquake Magnitude: *Earthquake magnitude*, M, is a measure of the energy released by an earthquake. A variety of different earthquake magnitude scales exist. The differences among these scales is attributable to the earthquake characteristic used to quantify the energy content. Characteristics used to quantify earthquake energy content include the local intensity of ground motions, the body waves generated by the earthquake, and the surface waves generated by the earthquake. In the eastern United States, earthquake magnitude is commonly measured as a (short period) *body wave magnitude*, m_b. However, the (long period) body wave magnitude, m_B, scale is also sometimes used in the central and

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