Earthquake Engineering for Dams and Reservoirs

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Earthquake Engineering for Dams and Reservoirs

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Abbreviations

AAR	alkali-aggregate reaction
ACED	asphalt core embankment dam
ACRD	asphalt core rockfill dam
AEP	annual exceedance probability
AFED	asphalt faced embankment dam
AFRD	asphalt faced rockfill dam
ASCE	American Society of Civil Engineers
asl	above sea level
ASTM	American Society for Testing and Materials
atm	atmosphere, standard (unit of pressure)
CE	construction earthquake
CFRD	concrete faced rockfill dam
CID	cumulative inelastic duration
cm	centimetre
CPT	cone penetration test
CRR	cyclic resistance ratio
CSG	cemented sand and gravel dam (in Japan)
CSGR	cemented sand, gravel and rock dam (in China)
CSR	cyclic stress ratio
D_r	relative density
DBE	design basis earthquake (often taken as 475-year return period for appurtenant structures)
DCR	demand–capacity ratio
DIN	Deutsche Industrie Norm (German industrial standard)
E	Young’s modulus
ECRD	earth core rockfill dam
EPC	engineer, procure, construct (contract type)
FSHD	faced symmetrical hardfill dam
FST	full scale trial
$\boldsymbol{g}$	acceleration due to gravity (9.81 m/s^2)
GBR	geotechnical baseline report
GEM	Global Earthquake Model
GEVR	grout enriched vibrated RCC
GPa	gigapascal
GR	Gutenberg–Richter (law)
HFTD	hybrid frequency-time domain
HPP	hydropower plant
HPU	hydraulic power unit
Hz	hertz
ICOLD	International Commission on Large Dams
IGA	Integrated Geohazard Assessment
kg	kilogramme
km	kilometre
LDOF	landslide dam outburst flood
M_L	local magnitude
M_m	moment magnitude
M_s	surface wave magnitude

MCE	maximum credible earthquake (usually deterministically defined)
MDE	maximum design earthquake (usually 10 000-year return period)
mm	millimetre
MPa	megapascal
MRSF	massive rock slope failure
MSF	magnitude scaling factor
Mt	million tonnes
MW	megawatt
NDA	non-linear dynamic analysis
OBE	operating basis earthquake (often taken as event with 145-year return period)
PGA	peak ground acceleration
PGD	peak ground displacement
PGV	peak ground velocity
PHGA	peak horizontal ground acceleration
PVGA	peak verticall ground acceleration
PI	plasticity index
PSHA	probabilistic seismic hazard assessment
PVC	polyvinyl chloride
RCC	roller-compacted concrete
RCD	roller-compacted dam (in Japan)
RSA	response spectrum analysis
RTS	reservoir-triggered seismicity
SA	spectral acceleration
SCM	supplementary cementitious material
SEE	safety evaluation earthquake (usually the MCE or event with return period of about 10 000 years)
SPT	standard penetration test
TSF	tailings storage facility
USBR	US Bureau of Reclamation (now called simply ‘Reclamation’)
USSD	United States Society on Dams
VE	value engineering
W_c	water content

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Chapter 1
Introduction

Jonathan Hinks

Earthquakes are extremely dangerous natural phenomena. They are responsible for many deaths and much damage around the world each year. For example, in the aftermath of the magnitude 7.9 Wenchuan earthquake of 12 May 2008 in China, some 86 419 people were reported killed or missing and 374 176 injured. Millions were said to have been made homeless. The cost of relief and reconstruction was estimated at £100 billion. A feature of the event was the destruction of the road network by rockfalls and landslides. Many road bridges were also destroyed. During a visit to the area a year after the earthquake, the author was taken to see a primary school. There were hardly any children in the playground (Figure 1.1) as most of their fellow pupils had been killed by falling buildings.

This book is a sister volume to *Earthquake Design Practice for Buildings* by Edmund Booth (2014). That volume has been very helpful for the present work, for which the various chapters have been written or reviewed by experts in the relevant fields.

The approach in this book is somewhat different from that of Edmund Booth's, with its aim being to address all of the subjects likely to be of interest to dam professionals, fellow engineers and students, with the objective of achieving wide coverage of the issues relating to the seismic design of dams and reservoirs. As well as the coverage of dams themselves, it includes discussion of earthquake-triggered

Figure 1.1 The few remaining pupils at a primary school destroyed in the Wenchuan earthquake on 12 May 2008

landslides, safety-critical spillways and intake towers, and tailings dams. Some of the subjects covered, such as seismic seiches, have not always received the attention that they deserve.

The failure of the 63 m-high Barahona tailings dam in Chile in 1928, after an earthquake of magnitude 8.0, caused the deaths of 54 people. This was followed in 1965 by the collapse of two tailings dams at the El Cobre copper mine, also in Chile, when 350–400 people were killed. Since then, many dams, mainly small homogeneous embankment dams in China, India and Japan, have failed in earthquakes, although the International Commission on Large Dams (ICOLD) (2019) and Foster *et al.* (2000) say that overall only about 2.2% of dam failures worldwide are due to seismic activity.

The development of seismic design for dams has been greatly influenced by various key events, such as the cracking of the Koyna gravity dam in India in 1967 and the near collapse of the Lower San Fernando embankment dam in California in 1971, when the crest settled by 8.5 m. Hsingfengkiang buttress dam in China suffered cracking during a magnitude 6.1 earthquake in 1962, as did the Sefid Rud buttress dam in Iran in an earthquake of about magnitude 7.7 in 1990.

It is worth noting that many early embankment dams were designed without allowance for seismic forces, and that when aseismic designs were adopted, the pseudo-static method was used. Over recent years, it has become apparent that many of the collapsed dams should not have failed if the pseudo-static method was valid. In particular, the liquefaction failure of the Lower San Fernando dam in 1971 highlighted the need for more sophisticated methods of analysis.

Similarly, the near failure of the Koyna dam in India in 1967 showed the need for better methods of analysis for concrete dams.

In the following chapters, comments are offered on the vulnerability of various types of dams not only to earthquakes, but also to other events, such as landslides, which may be extremely serious, whether triggered by earthquakes or by other causes.

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Chapter 2

Earthquakes – an overview

Brian Baptie and Jonathan Hinks

2.1. Introduction

Earthquakes are among the deadliest of natural hazards. Globally, there are around 100 earthquakes each year of a size that could cause serious damage, and millions of people around the world (e.g. central and south-east Asia, South and Central America) are exposed to high levels of earthquake hazard. Earthquakes strike without warning, and when they occur in areas of high population density the results can be catastrophic, with terrible loss of human lives and huge economic cost. This problem has been exacerbated by rapid population growth and a prevalence of vulnerable structures in many regions as a result of limited planning, lack of earthquake-resistant design and poor building quality.

Although earthquakes can occur almost anywhere, they are most frequent, and most severe, near the world's tectonic plate boundaries. This is particularly the case around the rim of the Pacific Ocean, along the Sunda arc, in the Himalayas, through Iran and Turkey and in south-east Europe.

Loss of life caused by earthquake damage to dams for the storage of water has generally been slight, although tailings dams, for the storage of mining waste, have a poor record (see Chapter 14).

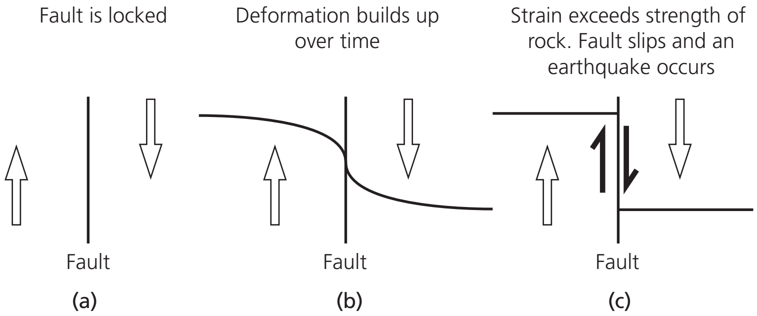
This chapter discusses the tectonic and other mechanisms that lead to earthquakes, with examples drawn from several fault systems.

2.2. What is an earthquake?

Earthquakes are the result of sudden movement along faults within the earth's crust that cause the release of stored-up elastic strain energy in the form of seismic waves that propagate through the earth and cause the ground surface to shake. The ground shaking causes damage to surface structures because inertial forces cause the centre of gravity of buildings to move relative to their base or foundation. Such movement on faults is generally a response to long-term deformation and build-up of stress.

Following the great San Francisco earthquake in 1906, Harry Fielding Reid put forward his elastic rebound theory, in which he suggested that the earthquake was the result of the sudden release of previously stored elastic strain energy through the sudden movement on the fault (Reid, 1910). Reid proposed that distant forces acting in opposite directions result in the accumulation of strain energy along the fault over hundreds of years (Figure 2.1). For long periods of time the fault remains locked in place, but eventually the accumulated strain overcomes the friction between the rocks on either side of the fault and an earthquake occurs, as in 1906. During an earthquake, the rocks snap back into their original undeformed state, releasing the accumulated strain. The strain energy that has accumulated gradually over many years is released in just a few seconds. Reid's theory is largely supported by precise global positioning system measurements, although it fails to answer questions such as how the Young's modulus and shear modulus of the rock vary with depth.

Figure 2.1 Elastic rebound theory. As the rocks on either side of the fault are subjected to force, they accumulate energy and slowly deform until their internal strength is exceeded. At that time, a sudden movement occurs along the fault, releasing the accumulated energy, and the rocks snap back to their original undeformed state



The size of any earthquake depends on both the area of the fault that ruptures and the average amount of slip or displacement on the rupture plane. Larger rupture areas and larger displacements lead to larger earthquakes. The largest earthquakes occur on ruptures that are many hundreds of kilometres long, with areas of several thousand square kilometres, and that have displacements of many metres. Seismic moment is a measure of the size of an earthquake based on the area of fault rupture, the average amount of slip, and the force required to overcome the friction sticking together the rocks that were offset by faulting. The latter is known as the modulus of rigidity of the faulted rock, which typically has values of 32 GPa in the earth's crust and 75 GPa in the mantle.

2.3. Earthquake faulting

Faults form in undamaged rock when the yield stress of a material is exceeded, causing the material to fail locally. However, where there are pre-existing planes of weakness, as is commonly the case in the earth's crust, there is little or no cohesion and failure depends on the relationship between the shear stress acting along the fault, the normal stress acting perpendicular to the fault and the coefficient of static friction on the fault plane (Figure 2.2). When the shear stress exceeds the product of the normal stress and the static friction that resists motion, the rocks on either side of the fault slip or slide past each other. In the upper 10–20 km of the earth's crust, typically only brittle failure, friction, reactivation and the influence of fluid pressure in the pores of the material are considered.

During an earthquake, the rock on one side of the fault suddenly slips with respect to that on the other. The fault surface can be horizontal or vertical or at any angle in between. Faults are classified using the angle of the fault with respect to the horizontal (known as the dip), the azimuth of the fault on the surface (the strike) and the direction of slip along the fault (Figure 2.3). Faults which move horizontally are known as strike-slip faults and are classified as either right-lateral or left-lateral, depending on the direction of motion. Faults that move along the vertical direction of the dip plane are dip-slip faults. These are described as either normal or reverse (thrust), depending on their motion. Normal faulting occurs when the block above the fault slides down relative to the block below the fault. Reverse faulting occurs when the lower fault block slides down relative to the upper block. Faults which show both dip-slip and strike-slip motion are known as oblique-slip faults.

Anderson (1905) explained the three basic types of faulting in terms of the orientation of the stress tensor relative to the earth's surface. The theory is based on three assumptions: (a) rocks can be considered

Figure 2.2 Shearing of a jointed block. A block is subjected to a normal force, F_n, and a shear force, F_s, with fluid inside the joint at pressure P. Slip along the joint is triggered when the shear stress, T, is equal to the frictional strength $\mu_s(\sigma_n - P_f)$, where μ_s is the coefficient of static friction on the fault plane, σ_n is the normal stress acting perpendicular to the fault, and P_f is the pore pressure on the fault, which acts against the normal stress

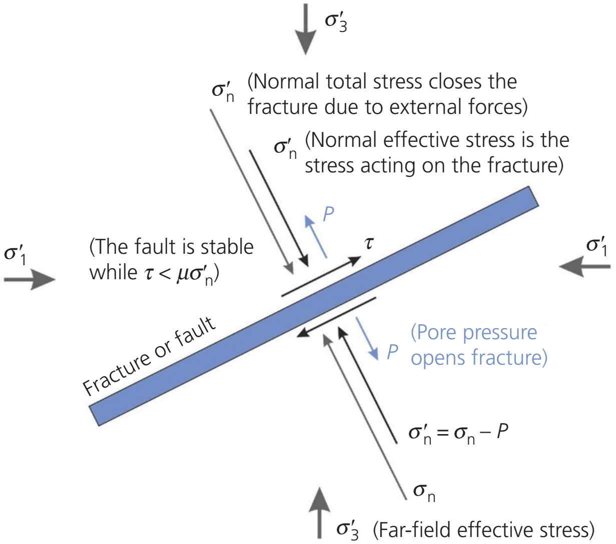


Figure 2.3 Schematic diagrams showing four different types of faulting: (a) strike-slip fault, (b) reverse fault, (c) normal fault, (d) oblique-slip fault

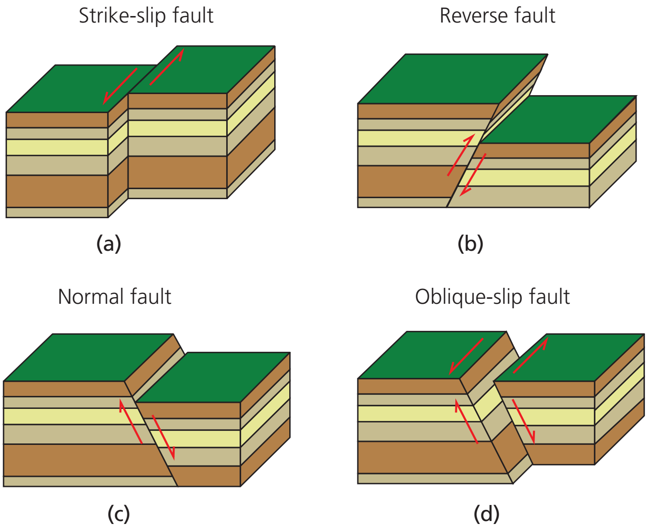
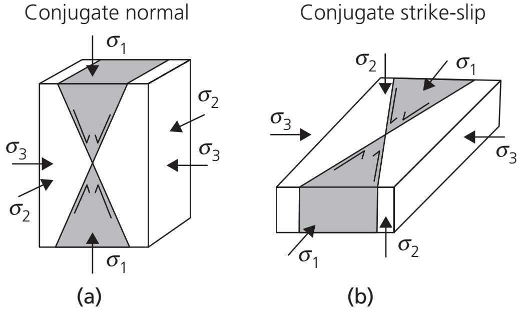


Figure 2.4 Anderson type faulting in (a) extensional and (b) strike-slip regimes: σ_1, σ_2 and σ_3 are the maximum, intermediate and minimum compressive stresses



isotropic; (b) rocks fail along shear planes when the state of stress satisfies a Coulomb failure criterion; and (c) the earth's free surface requires that one of the principal stress directions is vertical and the other two are horizontal. In extensional regimes, the maximum compressive stress, σ_1, is vertical, leading to normal faults with high dip angles (around 60°). In compressional regimes, the minimum compressive stress, σ_3, is vertical and low-angle thrust faults develop (around 30°). In strike-slip settings, the intermediate compressive stress, σ_2, is vertical, leading to sub-vertical strike-slip faults. This leads to conjugate pairs of possible fault planes in which the σ_1 direction bisects the angle between the two fault planes (Figure 2.4).

However, there are two main limitations to Anderson's theory. First, the assumption of isotropy means that failure occurs on optimally oriented conjugate fault planes only, which is not consistent with the fact that slip usually occurs on pre-existing faults. Second, slip only occurs along the fault plane strike or dip direction, which does not account for oblique slip. Wallace (1951) and Bott (1959) proposed models of frictional slip on pre-existing planes of weakness that overcame the isotropy assumption. These models also provided an explanation for oblique slips that do not require a rotation of the stress axes.

Earthquakes are often considered as single point forces. Realistically, it takes a finite time for a particle on the fault to move from its start position to its end positions. This is known as the rise time. For large earthquakes, the local duration of slip or rise time, τ_r, is generally expected to be much less than the total duration of rupture, τ_d, the time it takes for the fault rupture to grow to its final size. In addition, the apparent rupture duration will depend on the orientation of the fault relative to an observer and the direction and velocity of the rupture. However, during a very large earthquake it can take more than a minute for the rupture to grow to the final size. While some authors suggest that it may be possible to make deterministic prediction about the final size of an earthquake from how it starts, other authors suggest that small and large earthquakes start identically.

2.4. Measuring earthquakes

The size of an earthquake is usually described by earthquake magnitude, which is a measure of the amount of energy released. This is a property of the earthquake and does not vary according to the position of the observer. The strength of shaking caused during an earthquake varies from place to place, but it is usually greatest close to the earthquake's epicentre and decreases with distance. A variety of parameters are used to measure strength of shaking, including peak ground acceleration and earthquake intensity.

Several different magnitude scales have been developed. They are generally based on the amplitude of different parts of the observed record of ground motion, often in a particular frequency range and with specific corrections for distance. The first magnitude scale was developed by Richter (1935) using observations of earthquakes in southern California, USA, and, although strictly the scale is only applicable there, has been used all around the world. It is commonly referred to as local magnitude, M_L. However, the most standard and reliable measure of earthquake size is moment magnitude, M_w, which is related to the logarithm (to the base 10) of the seismic moment. The latter is related to both the area of the rupture and the displacement on the rupture and can be calculated from the amplitude spectra of seismic waves measured by seismometers.

For small earthquakes, magnitude scales linearly with the logarithm of rupture area (Aki, 1972), and rupture displacement or slip scales linearly with rupture length. This linearity is interpreted to be due to constant average stress drop (Chinnery, 1969); that is, for simple rupture geometries (e.g. circular faults), the difference between the stress across a fault before and after an earthquake is independent of earthquake size and is consistent with theoretical moment and stress drops (Brune, 1970). The rupture displacement in an earthquake is typically about 1/20 000 of the rupture length. For example, a 1 km-long rupture from a magnitude 4.0 event has a displacement of about 50 mm.

The potential for damage from ground shaking depends on the nature and intensity of the shaking, which in turn depends on the amount of seismic energy released by the earthquake, the distance from the earthquake source to a given structure and the nature of the ground on which the structure stands. Ground shaking can be quantified using several different parameters. The simplest of these is the maximum absolute value of the ground acceleration, referred to as peak ground acceleration (PGA). Peak ground velocity (PGV) is also used in many engineering applications. PGV is a better indicator of the damage potential of the motion than PGA because it is more closely related to the energy in the motion. Earthquake intensity scales are also widely used to describe possible impacts on different building types. For dam projects, peak horizontal ground acceleration (PHGA) and peak vertical ground acceleration (PVGA) are commonly used.

2.5. Where do earthquakes occur?

A map of earthquake occurrence over the past 100 years or so shows that most earthquakes occur in a series of relatively narrow and well-defined bands or belts. Some of these belts lie at the edges of continents, such as the west of North and South America, Asia and southern Europe. Others lie in the oceans, in narrow bands along mid-ocean ridges. There are also more diffuse zones of earthquake activity in central Asia, as well as a small number of earthquakes in continental interiors, such as in North America and Australia. This pattern of distribution of earthquakes is directly linked to the theory of large-scale tectonic processes called plate tectonics.

Plate tectonics is based on the concept that the relatively strong outer shell of the earth, called the lithosphere, is divided into rigid plates or slabs which are continually in motion. These plates are around 100 km thick and consist of the crust and the uppermost mantle of the earth, although they are thinner in oceanic regions and thicker in continental ones. These plates sit on top of a weaker asthenosphere (Figure 2.5), where the high pressures and temperatures mean that the viscosity is low enough to allow viscous flow over geological timescales. Heat from the decay of radioactive elements results in convection in the asthenosphere which drives the motion of the lithospheric plates.

Earthquake activity is greatest at the boundaries between the earth's tectonic plates, where the differential movements of plates result in repeated accumulation and release of strain, in keeping with Reid's elastic rebound theory (Figure 2.6). These include the margins of the Pacific and the collision zones between both India and Eurasia, and Africa and Eurasia. As the plates move, friction causes their edges to become stuck

Figure 2.5 Lithospheric plates sit on top of a convecting asthenosphere

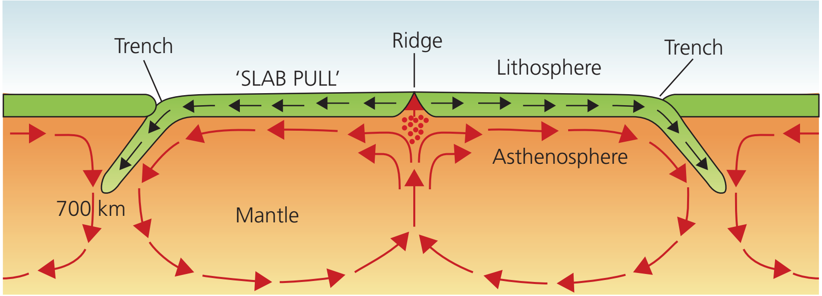
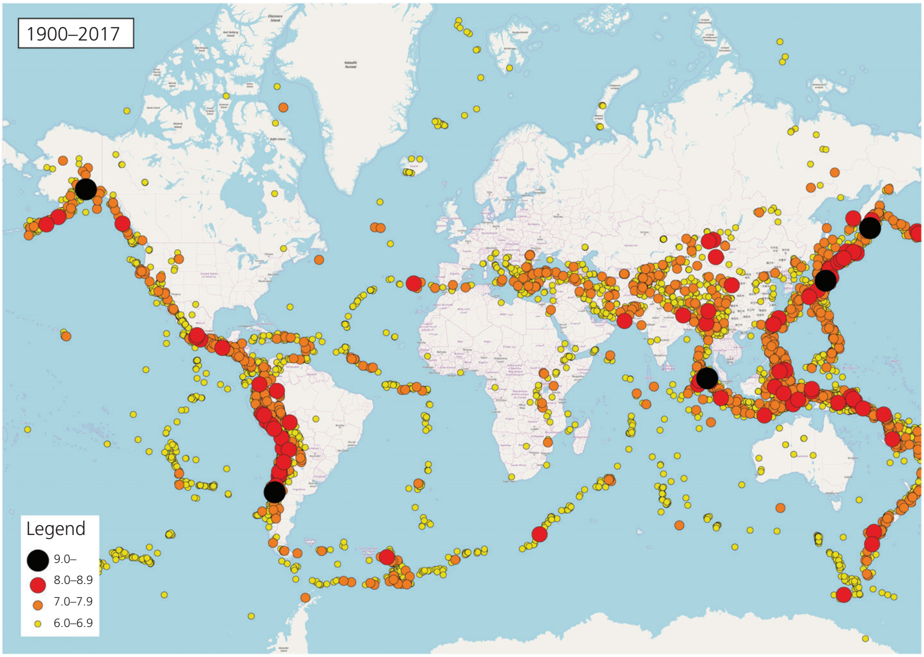


Figure 2.6 Locations of earthquakes of magnitude 6.0 or above between 1900 and 2017



together and so strain builds up along the plate boundaries. Eventually, the strain overcomes the friction on either side of the boundary and the plates suddenly move, releasing the built-up energy as an earthquake.

The history of plate tectonics dates back to the early twentieth century, when in 1915 Wegener put forward the idea that the continents had once formed a single initial landmass, which has split and drifted apart over millions of years. This idea was controversial at the time and was not validated until the mid-1960s, when widespread geophysical evidence became available. This evidence included apparent changes in the relative position of the magnetic north pole through time (Runcorn, 1959), patterns of magnetic anomalies in the oceanic crust (Vine and Matthews, 1963), and mapping of earthquake locations in Wadati–Benioff zones in the ocean trenches bounding many continental margins.