Technical Note 03 – Earthquake Behaviour

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1 Why do Earthquakes Occur?

An earthquake involves the shaking of the ground as a result of a build-up of strain energy along tectonic plate boundaries as they move against each other. As the plates slide past each other, the stored energy builds up in the same way as energy builds up in a spring when it is wound. When the stress finally exceeds the rock's strength, the rock fractures along a fault, often along a zone of existing weakness within the rock. The stored energy is suddenly released, and leads to an earthquake (www.bgs.ac.uk, n.d.). Large earthquakes are always followed by a sequence of aftershocks.

An earthquake's location is described in two ways:

- Hypocenter – the location below the earth's surface where the earthquake starts
- Epicenter – the location on the surface of the earth directly above the hypocentre

New Zealand sits on the Pacific "Ring of Fire" on the boundary between the Pacific and Indo-Australian plates where earthquakes are frequent. The country is unique in that, due to its location, the subduction zones physically change between the North and South Islands. The Pacific plate is descending under the North Island on the east coast and the Australian plate is moving under the South Island on the west coast. The central section lies on a transform fault boundary.

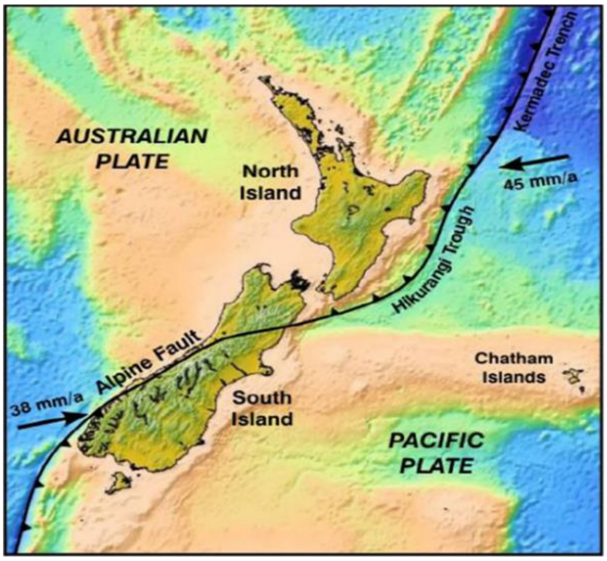

Figure 1-1 The position of New Zealand in relation to tectonic plates

2 Describing Earthquakes

An earthquake's size is based on the amount of energy released. This is generally quoted in terms of the Richter scale.

The Modified Mercalli Intensity scale (MMI) is based on a qualitative assessment of an earthquake's size. This scale is often correlated with ground shaking expressed as strong motion parameters, Peak Ground Acceleration (PGA) and Peak Ground Velocity (PGV), see Section 4.

Most Magnitude scales are based on measured signals of ground motion characteristics from seismograms. The Richter scale, which is the most famous, is a logarithmic scale. This means, for example, the amplitude of a magnitude 6 earthquake is 30 times greater than a magnitude 5 earthquake.

3 Seismic Waves

Seismic waves generated by an earthquake spread out from the initial rupture point, like ripples on a pond. These waves are what makes the ground shake; they can travel large distances in all directions. There are two main types of waves: body waves and surface waves. http://www.geo.mtu.edu/UPSeis/waves.html provides links to animations showing how the different waves travel.

3.1 Body Waves

The fastest body waves are Primary waves (P-waves). They carry energy through the Earth as longitudinal waves by moving particles in the same line as the direction of the wave. They can travel through all layers of the Earth and are often referred to as compressional or longitudinal waves (National Information Centre of Earthquake Engineering, 2007).

Shear waves (S-waves) are the body waves that cause material particles to oscillate at right angles to the direction of energy transmission. S-waves cannot travel through fluids, such as air, water or molten rock (National Information Centre of Earthquake Engineering, 2007).

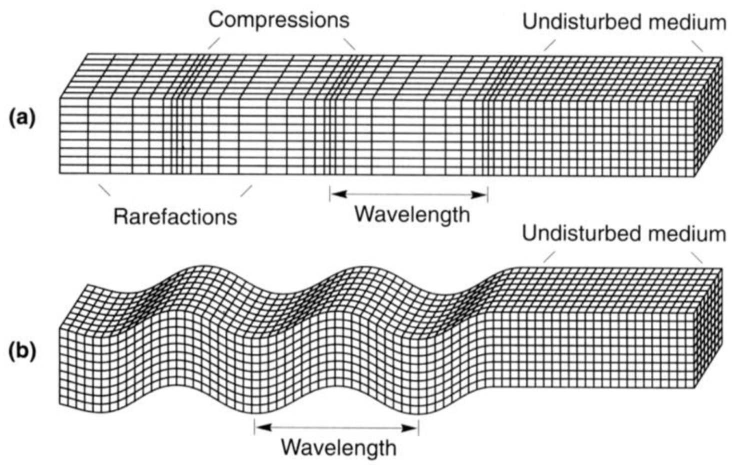

Figure 3-1: Deformations produced by body waves: a) P-wave; b) S-wave ((Bolt, B. A., 1993) and (Tromans, I., 2004))

When considering the effective propagation velocity for body waves, the S-waves are the most critical. S-waves carry more energy and tend to generate larger ground motions than P-waves. For the S-wave, the horizontal propagation velocity, (the propagation velocity with respect to the ground surface) is the key parameter (O'Rourke, M.J. and Liu, X., 1999).

3.2 Surface Waves

Surface waves are waves of energy resulting from body waves interacting with the earth's surface.

Rayleigh waves (R-waves) are surface waves that cause ground particles to oscillate in an elliptical path in the vertical plane along the direction of the traveling wave.

Love waves (L-waves) are surface seismic waves that cause horizontal ground movement from side to side in a horizontal plane but at right angles to the direction of propagation.

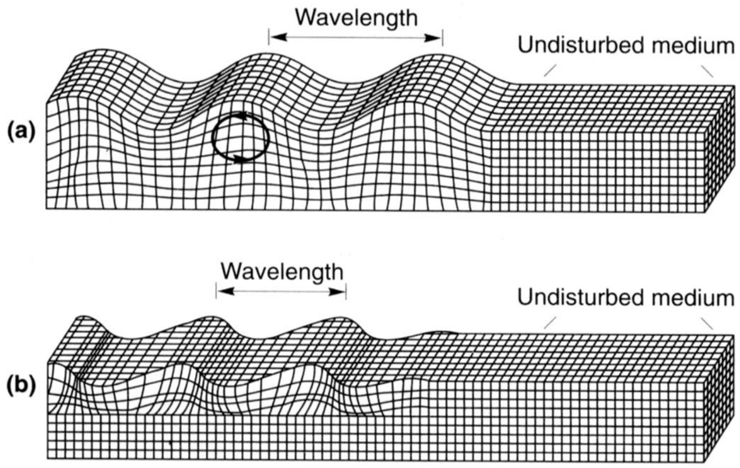

Figure 3-2 : Deformations produced by surface waves: a) R-wave; b) L-wave ((Bolt, B. A., 1993) and (Tromans, I., 2004))

For Surface waves, the Rayleigh waves are the most important for calculating the effective propagation velocity. The Love waves generate bending strains in buried pipelines but are usually a lot less than the axial strain induced by the Rayleigh waves (O'Rourke, M.J. and Liu, X., 1999).

4 Ground Motion Parameters

There are three main characteristics of earthquake ground motions (ground motion parameters) which describe the seismic waves. These are amplitude, frequency and duration; they are usually graphed as a time history obtained from the seismograph.

Seismic hazard analyses and the development of design ground motions rely heavily on the characterization of strong ground motion by ground motion parameters. Characteristion by a single parameter is only rarely appropriate; the use of several parameters is usually required to describe adequately the important characteristics of a particular ground motion. Since different engineering problems are influenced by different ground motion characteristics, the significance of different parameters depends on the types of problems for which they are used, (Kramer, S. L., 1996).

Figure 4-1 shows an example of a seismic trace from an earthquake. Due to the distance between the earthquake and the seismometer, the difference in time (and therefore speed) at which the various waves reach the seismograph can be seen. The P-wave travels fastest, arriving first, then the S-wave and then the Surface waves.

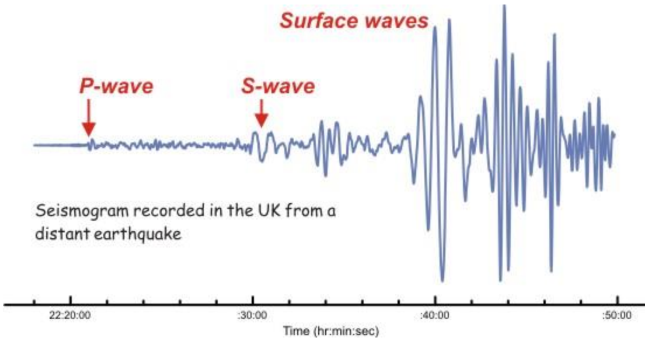

Figure 4-1: Seismogram recorded from an earthquake some distance from the seismometer. http://www.bgs.ac.uk/discoveringGeology/hazards/earthquakes/howWeMeasureThem.html

4.1 Amplitude

The amplitude parameter can be expressed as Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV) or Peak Ground Displacement.

A study (Technical Note on Fragility Functions) comparing the break rates of utilities using the different PGA, PGV and MMI based estimate methods, found that, for each methodology, the outputs gave similar result but it was stated that the PGA is easier to use.

The most commonly used measure of amplitude for a particular ground motion is PGA.

4.1.1 Peak Ground Acceleration

PGA is the maximum expected seismic wave acceleration at the ground surface as a result of a seismic event. It usually refers to horizontal motion (National Information Centre of Earthquake Engineering, 2007) however in areas where the expected seismic wave is close to the earthquake epicentre the vertical motion should also be assessed, see section 5.1.1.

4.1.2 Peak Ground Velocity

PGV is the maximum expected seismic wave velocity at the ground surface as a result of a seismic event. It refers to the horizontal motion unless specified otherwise (National Information Centre of Earthquake Engineering, 2007).

In an assessment of a likely typical earthquake event or an analysis of an actual event, it is common to only have one parameter, ie either PGA or PGV. If the original trace is not available and PGA or PGV cannot be determined directly, then the relationship detailed in American Lifelines Alliance (American Lifelines Alliance, 2005) guideline gives an estimation of the conversion between PGA and PGV.

(Tromans, I., 2004) noted that PGV estimations are particularly useful for predicting earthquake-induced pipeline damage rates.

4.1.3 Peak Ground Displacement

The peak ground displacement is the maximum displacement of the ground surface due to the seismic wave action. Kramer (1996) states that this parameter is less commonly used because of difficulties in processing the data at the lower end of the frequency components of earthquake motion.

Note: Peak ground displacement should not be confused with in the acronym (PGD) Permanent Ground Deformation.

4.2 Frequency

Earthquakes produce complicated loading with motion components that span a broad range of frequencies. The frequency content describes how the amplitude of a ground motion is distributed among different frequencies. Since the frequency content of an earthquake motion will strongly influence the effects of that motion, characterizing it cannot be complete without considering its frequency content (Kramer, S. L., 1996).

The frequency content of a strong ground motion is generally described through the use of different types of spectra. For more information on how to calculate the different spectra (Kramer, S. L., 1996).

For designing structures at or under ground level (ie pipelines) the period, T, of the site spectra should be taken as zero (NZS 1170.5:2004).

4.3 Duration

The duration of a strong ground motion is related to the time required for accumulated strain energy to be released by rupturing along the fault. Therefore, strong motion duration increases with increasing earthquake magnitude.

The accelerogram trace generally contains all accelerations from the time an earthquake begins until the motion has returned to the level of background noise. For engineering purposes, only the strong-motion portion of the accelerogram is of interest. There are a number of studies which estimate the position of the strong-motion portion of the accelerogram (Kramer, S. L., 1996).

The duration of strong ground motion can have a major influence on earthquake damage. Many physical processes, such as the degradation of stiffness and strength of certain types of structures and the build-up of pore water pressures in loose, saturated sands, are sensitive to the number of load or stress reversals that occur during an earthquake (Kramer, S. L., 1996).

5 Earthquake Induced Ground Damage

Buried pipelines can be damaged by either transient (ground shaking) seismic wave propagation or by permanent movement of the ground (O'Rourke, M.J. and Liu, X., 1999). In general, damage from wave propagation tends to be lower, but spread over the whole of the system, whereas secondary effects such as permanent ground movement/displacement tends to be localised with high damage rates (Tromans, I., 2004).

5.1 Earthquake Ground Shaking (Transient Ground Movement)

The effects of ground shaking on underground utilities can be described as the Wave Propagation Hazard, which is also sometimes known as the Transient Ground Movement during an earthquake.

When a seismic wave travels along the ground surface, any two points located along the propagation path will undergo out-of-phase motions. Those motions induce both axial and bending strains in buried pipelines because of interaction at the pipe-soil interface. The critical strain in the pipeline is usually the axial strain, as the bending strain is small relative to the axial strain. Although seismic wave propagation damage to continuous pipelines is less common, the observed failure mechanism is typically local buckling (O'Rourke, M.J. and Liu, X., 1999).

The following sections discuss the main features influencing the Wave Propagation Hazard.

5.1.1 Distance and Attenuation

Body waves attenuate as they move away from the epicentre more rapidly than Surface waves. At a distance (discussed below) from the epicentre the Surface waves produce the largest amplitude when compared to those of the Body waves. However, near the focus or epicentre, both Body and Surface waves can be large (Kramer, S. L., 1996).

The ratio between Peak Vertical Acceleration (PVA) and Peak Horizontal Acceleration (PHA) is generally greater than two-thirds near the epicentre of a moderate to large earthquake and less than two-thirds at large distances away from the epicentre ((Campbell, K.W., 1985) (Abrahamson, N.A. and Lithehiser, J.J., 1989) (Kramer, S. L., 1996)).

To evaluate the axial strain in utility pipes, as a general rule, the S-wave velocity is used for the sites within the distance of five times the focal depth. On the other hand, the R-wave velocity is considered for the sites having distance more than five times focal depth (National Information Centre of Earthquake Engineering, 2007).

The apparent wave propagation velocity of both Body and Surface waves is of interest, since the pipelines are typically buried at shallow depth (1 – 3 m) below ground surface.

5.1.2 Variable Subsurface Conditions

Local site conditions can profoundly influence the nature of shaking at the ground surface and therefore all of the important strong ground motion characteristics: amplitude, frequency content, and duration. Since soil conditions often vary dramatically over short distances, ground shaking levels can vary significantly within a small area. The extent of their influence depends on the geometry and material properties of the subsurface materials, site topography and the input motion characteristic.

Soil deposits tend to act as "filters" to seismic waves by attenuating motion at certain frequencies and amplifying it at others (Kramer, S. L., 1996). In general, the amplification is greater in softer soils (with lower shear wave velocities) than stiffer soils (with higher shear wave velocities). However, an increase in ground shaking intensity also increases the non-linearity of soil stress-strain and increases soil damping, which reduces amplification (National Information Centre of Earthquake Engineering, 2007).

Calculating the effects of specific variable subsurface conditions should be undertaken by a geotechnical engineer experienced in seismic analysis.

5.1.3 Depth

The seismic wave effect usually reduces with depth; above ground structures are more susceptible to the seismic wave hazards than underground structures. For underground utilities, shallow burial can increase the likelihood of damage by falling masonry and collapsing buildings and can influence the form of failure in pipes exposed to compressive loads. The burial depth is therefore an important design parameters for buried pipelines. Placing the pipeline at greater depth can reduce the design levels of ground shaking.

In general, the top 30m of soil is assessed for calculating the soil strength design parameters for earthquake loading. Most utilities are installed within the top 2m, with very few installed deeper than 5m. For practical purposes, it's reasonable to assume that all buried assets are within this 30 m zone so that the soil strength design parameters do not vary with depth.

For installations deeper than 5m, or for sites with specific geotechnical considerations, the site should be assessed by a Geotechnical engineer experienced in this area.

5.2 Permanent Ground Damage

The secondary effect of ground shaking is permanent ground damage. In general, damage from transient ground movement tends to be less frequent than that from permanent ground movements, but spread over the whole of the underground system. Whereas damage from permanent ground movement tends to be localised but with high damage rates (Tromans, I., 2004)

Earthquake induced permanent ground damage can have a significant effect on underground utilities' performance. The following should be considered:

- Surface fault rupture
- Slope failures or landslides
- Liquefaction and associated ground damage (settlement and lateral spread)

5.2.1 Surface Fault Rupture

A study of the fault surface traces of known active faults should be identified from geological, regional hazard maps and/or from site specific studies.

(NZS 1170.5, 2004) Figure 3.5 shows the major faults in New Zealand. The New Zealand Active Fault Database gives further details of known active faults throughout NZ .

If fault rupture is expected, an estimate of the fault rupture zone and the extent of movement expected can be calculated. This is estimated from existing published paleo-seismic studies of the fault. Where this information does not exist, site specific studies may be commissioned.

The hazards maps can also be used for planning new utility networks to ensure potential damage is minimised.

5.2.2 Slope Failure or Landslides

Earthquakes can cause slope failures or landslides on moderate to steep slopes. However landslides have also been recorded on relatively minor slopes, depending on the underlying geology.

Earthquake induced slope failure hazard studies have been carried out and published for some regions of New Zealand (e.g. Wellington). The studies provide general guidance on the distribution of slope failure hazards in the area, at a regional or district level. At a localised level, slope hazards may also exist.

Often utilities follow road corridors or alignments that have been modified by construction. This can lead to localized earthquake induced slope failure hazards. For example, sidling cut and fills are often formed to construct roads, and sidling fill is often placed in a loose state or supported by retaining walls, which may be vulnerable to movement or failure in an earthquake. Pipelines located downslope of potential landsides are also more vulnerable to damage from ground movement.

Where slope failure hazard studies do not exist and utilities are located on moderate to steep ground, a geotechnical engineer should be engaged to assess the earthquake induced slope failure hazards. This will involve a review of the geology and ground conditions, review of aerial photography and site reconnaissance along the pipeline corridors (Brabhaharan, 2010).

5.2.3 Liquefaction and Associated Ground Damage

Loose to moderately dense, saturated cohesionless sands, silts and sandy gravels can liquefy during strong earthquake shaking, and lose much of their strength and stiffness Figure 5-1.

Liquefaction can cause:

- Loss of strength and stiffness and support to buried utilities
- Ground subsidence (vertical deformation)
- Differential settlement (due to variable soils strengths over the pipe network)
- Sand boils
- Intrusion into pipelines through joints, defects and damage.
- Buoyancy and uplift of buried utilities
- Foundation failure of associated structures founded on liquefiable ground
- Lateral spreading of the ground, particularly towards free surfaces such as water courses.

Figure 5-1: Liquefaction – lack of ground support

Areas prone to liquefaction can be identified using the guidance provided by the New Zealand Geotechnical Society (2010). Utilise liquefaction hazard maps that have been developed and published for some regions or districts of New Zealand where these are available. Alternatively, engage a geotechnical engineer with experience in liquefaction hazard mapping to assess the liquefaction hazards for an underground utility network. Brabhaharan (2010).provides guidance on liquefaction hazard mapping for utility facility assessment.

The assessment should not only consider the potential for liquefaction in selected earthquake events, but also the potential for ground damage such as subsidence and lateral spreading Brabhaharan (2000).

Also, historic watercourses/channels that have been cut off and reclaimed have the potential to liquefy but may not be necessarily obvious on the surface. These areas can be found using historical accounts and regional maps.

It was found after the Canterbury earthquake sequence that significant liquefaction damage occurred at historic watercourses/channels that had been cut off since the 1850s and old land reclamation areas (Wotherspoon, Pender, & Orense, 2010)

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