2 General Characteristics of Seismic Response of Deep Alluvial Soils

Deep alluvial soils influence the performance of land, infrastructure, and buildings during strong earthquakes in two profound ways. As seismic waves propagate through the alluvial soils, from the base rock towards the ground surface, the alluvial soils significantly modify the characteristics of ground shaking. They amplify the shaking and seismic forces for some structures, while for others they reduce or de-amplify the shaking. The composition of alluvial soils, their stratification, thickness and stiffness (resistance to deformation) define the particular features of the modification of the ground motion. In addition, as seismic waves pass through the soils, they deform the soils producing both transient deformations (temporary displacements) and permanent movements and deformations (residual horizontal and vertical displacements, ground distortion, undulation of ground surface, ground cracks and fissures). In cases when the ground deformation is excessive and seriously affecting the performance of land or structures, the soils are considered to have ‘failed’. Thus, soil failure does not necessarily imply a catastrophic collapse, but rather implies excessive deformations that are not tolerable for structures. Soil liquefaction is one form of such failure since it usually results in excessive ground deformation and displacement that severely affects the built environment.

2.1 Soil Liquefaction and Lateral Spreading

Soil liquefaction is a process in which over a very short period of time (several seconds or tens of seconds) during strong ground shaking, the soil transforms from its normal solid state into a heavy liquid mass. As a consequence of liquefaction, the soil essentially loses its strength and bearing capacity (i.e. the capacity to support gravity loads of heavy structures), thus causing sinking of heavy structures into the ground. Conversely, light and buoyant structures (that have smaller mass density than the liquefied soil mass) will be uplifted and float above the surface. Ground deformation associated with liquefaction takes various forms and is often excessive, non-uniform and involves large permanent vertical displacements (settlement) and lateral deformations commonly resulting in large cracks and fissures in the ground, substantial ground distortion and sand/silt/water ejecta covering the ground surface. The large pressures created in the groundwater during liquefaction are in excess of the equilibrium pressures, thus triggering flow of water towards the ground surface. Since these water pressures are very high, the water will carry a significant amount of soil on its way towards the ground surface and eject this on the ground surface. This process inevitably leads to loosening of some parts of the foundation soils and often results in creation of local ‘collapse zones’, sinkholes and ‘vents’ for pore pressure dissipation and flow of pore water.

Lateral spreading is a particular form of land movement associated with liquefaction that produces very large lateral ground displacements from tens of centimetres to several metres, and hence, is very damaging for buildings and infrastructure. Lateral spreading typically occurs in sloping ground or level ground close to water ways (e.g. river banks, streams, in the backfills behind quay walls). Even a very gentle slope in the ground (of several degrees) will create a bias in the cyclic loads acting on the soil mass during earthquakes which will drive the soil to move in the down-slope direction. If the underlying soils liquefy then the liquefied soil mass (‘heavy liquid’) will naturally move down-slope and will continue this movement until equilibrium is re-established (or resisting forces reach the level of driving forces). In areas of Christchurch and Kaiapoi affected by lateral spreading in the 2010 and 2011 earthquakes, the residual slope of the
land affected by spreading was often very small (only 2-3 degrees) indicating very low residual strength of the liquefied soils. The process of spreading in backfills behind retaining walls is similar, with large ground shaking first displacing the retaining structure outwards (e.g. towards a waterway), which is then followed by lateral spreading in the backfills.

Liquefaction induces very large strains (i.e. the decrease in the thickness of a soil layer divided by its original thickness, which defines the relative deformation within the soil), typically on the order of several percent. Hence, if for example a 10 m thick layer liquefies, the horizontal displacement of the top of the layer (e.g. at the ground surface) relative to its base (10 m depth) could be in the order of 50-60 cm of cyclic (i.e. back-and-forth) movement during the shaking. A buried structure, including piled foundations through the liquefied layer will be subjected to very large and non-uniform lateral loads from these ground movements and oscillation of the building. There are two particular locations where damage to piles in liquefied soils typically occurs: near the pile top and at the interface between the liquefied soil and underlying unliquefied soil. In some cases, this interface is at large depth, and hence, it imposes serious constraints in firstly identifying if there has been damage caused by the earthquake, and then in repairing or strengthening of the piles, if required. The large ground distortion and highly non-uniform displacements caused by liquefaction often result in stretching of the ground beneath the footprint of the building imposing large loads and damage to shallow foundations if they are not strong enough to resist such forces. Substantial total settlements, differential settlements and tilt of buildings are common consequences of soil liquefaction.

All of the above features and modes of ground deformation are present and very pronounced in the case of lateral spreading. As the ground spreads laterally in one direction, it loads the foundation permanently in this direction in addition to the cyclic transient loadings. Thus, there is a biased push of the foundation in the direction of the spread in addition to the cyclic ground movements. The biased loads associated with spreading are particularly dangerous because they ‘test’ the ductility of structures and their capacity to sustain large deformation without failure or collapse.

The significant softening of the soils due to liquefaction causes filtering out (removal) of the high frequencies of the ground motion, but also amplification of the long-period components of the shaking, resulting in elongated oscillation cycles at liquefied sites. Finally, one should recognize that soil liquefaction is just one form of geotechnical earthquake hazard, in addition to the other more prevalent earthquake hazard, i.e., the ground shaking itself.

2.2 Mechanism Causing Liquefaction

Soil liquefaction occurs in granular soils such as sands, gravels, non-plastic silts and their mixtures. These soils derive their stiffness and strength through grain-to-grain contact stresses. Shallow soils have small grain-to-grain contact stresses, so they are relatively soft and weak. Soils at great depth have large grain-to-grain contact stresses so they are relatively stiff and strong.

When subjected to shaking (straining), granular soils tend to densify or reduce the size of the voids within their granular structure. However, if the soils are fully saturated, i.e. the voids are completely filled with water, then this tendency for densification cannot materialize over a very short period of time (several seconds or tens of seconds of
strong shaking) since the water and solid particles are practically incompressible. Instead, this tendency for densification will result in an increase in the pressure in the groundwater (pore water pressure). Liquefaction occurs when the increase in the pore water pressure will reach a level which will effectively cancel out the gravity forces and will essentially separate the particles from each other. The loss of contact between the particles effectively turns the soil into a heavy liquid state, and soil liquefaction results in nearly complete loss of stiffness and strength of soils.

The additional pressures generated in the groundwater (termed excess pore water pressures), increase with depth, and are in excess of the equilibrium pressures under gravity loads. Hence, redistribution of pressures and flow of groundwater is triggered immediately at the onset of liquefaction, resulting in upward flow of water from the high excess pressures at larger depths towards the zero pore pressures at the ground surface. This is why soon after the triggering of liquefaction, water and soil mixture start spurting and littering the ground surface.

Loose soils have more voids in their inherent structure (since they were not well compacted when deposited). Hence, when shaken, they show large tendency for densification (contraction) which in turn leads to rapid pore water pressure build-up and eventual liquefaction in only few cycles of strong shaking. Since these soils are loosely packed and are highly deformable (compressible), liquefaction will be severely manifested and will result in very large ground movements and nearly complete loss of load carrying capacity. This is why loose soils are particularly prone to liquefaction and show very severe consequences of liquefaction. Conversely, very dense soils show very limited tendency for densification and hence produce low excess pore water pressures, and therefore they have much higher liquefaction resistance.

Clays, clayey soils and plastic soils in general, derive stiffness and strength from an additional mechanism (cohesion) and hence are considered non-liquefiable. Softening of these soils and large deformation especially of soft clays and peat can produce severe ground deformation and impacts on buildings and infrastructure, but their response mechanism is different from the soil liquefaction outlined above.

2.3 **Liquefaction Assessment**

The conventional method (state-of-the-practice) for liquefaction assessment involves the following evaluation steps.

1. **Liquefaction susceptibility**: In this step, based on the grain-size composition and plasticity of soils, it is determined whether the soils at the site in questions are liquefiable or not. If the soils are deemed non-liquefiable, then further liquefaction evaluation is not required (Bray and Sancio, 2006; Idriss and Boulanger, 2008; NZGS, 2010).

2. **Liquefaction triggering**: If the soils (or some of the layers) are liquefiable, then a triggering analysis is conducted to determine whether (and which) soil layers are going to liquefy when shaken by a particular ground motion (the design earthquake) specified in terms of peak ground acceleration (PGA) and earthquake magnitude ($M_w$). In this analysis step, a factor of safety against triggering of liquefaction is calculated as a ratio of the liquefaction resistance (cyclic strength of the soil, or resistance capacity) and cyclic stresses in the soil induced by the design earthquake (seismic load/demand) (Youd et al., 2001; Seed and Idriss, 1982; Idriss and Boulanger, 2008). In the simplified procedure, the peak ground acceleration (PGA) is used as a measure for the amplitude of
ground shaking while the earthquake (moment) magnitude ($M_w$) is used as a proxy for the duration of shaking (i.e. number of significant stress cycles).

(3) Liquefaction-induced ground deformation: In this step, consequences of liquefaction in terms of ground displacements/deformation are estimated for a free field (land not affected by structures or built environment) level ground or sloping ground conditions. Using the computed factor of safety and estimated thickness of the liquefied soils in the triggering analysis, liquefaction-induced settlements and lateral ground displacements are calculated using empirical methods (e.g. Ishihara and Yoshimine, 1992; Tokimatsu and Seed, 1987; Tokimatsu and Asaka, 1998). Similar approaches are used for estimating lateral ground displacements due to spreading (e.g., Youd et al., 2002).

(4) Impacts of liquefaction on building foundations: Using the ground displacements and loads estimated in the previous step, the impacts of liquefaction on building foundations are then analyzed. This includes calculation of loads acting on the foundations, displacement and deformation of the foundations, as well as estimating the resulting damage to the foundation.

(5) Countermeasures against liquefaction: In the final step of the assessment, countermeasures against liquefaction are considered either to prevent the occurrence of liquefaction or to reduce its impacts on ground deformation and foundations, and bring their seismic performance within tolerable limits. Ground improvement and foundation strengthening are the two principal mechanisms used as countermeasures against liquefaction.

More details of the liquefaction evaluation procedure and further references are given in NZGS (2010).