Excess Pore Pressures Around Underground Structures Following Earthquake Induced Liquefaction

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ABSTRACT

Underground structures located in liquefiable soil deposits are susceptible to flotation following an earthquake event due to their lower unit weight relative to the surrounding saturated soil. This inherent buoyancy may cause lightweight structures to float when the soil liquefies. Centrifuge tests have been carried out to study the excess pore pressure generation and dissipation in liquefiable soils. In these tests, near full liquefaction conditions were attained within a few cycles of the earthquake loading. In the case of high hydraulic conductivity sands, significant dissipation could take place even during the earthquake loading which inhibits full liquefaction from occurring. In the case of excess pore pressure generation and dissipation around a floating structure, the cyclic response of the structure may lead to the reduction in excess pore pressure near the face of the structure as compared to the far field. This reduction in excess pore pressure is due to shear-induced dilation and suction pressures arising from tensile stresses at the soil-structure interface. Given the lower excess pore pressure around the structure; the soil around the structure retains a portion of this shear strength which in turn can discourage significant uplift of the underground structure.

Keywords: Centrifuge Modelling, Floatation, Liquefaction, Pore Pressures, Soil-Structure Interaction, Underground Structures

INTRODUCTION

Vital lifelines such as transportation highways and railways, water, electricity and telecommunication networks are commonly buried in soil to avoid conflict of activities above the ground. These underground structures can be susceptible to damage as evident in past earthquake events such as the 1993 Kushiro-Oki earthquake (Koseki et al., 1997), 1995 Kobe earthquake (Towhata, 2008), 2004 and 2007 Chuetsu earthquakes (Tobita et al., 2009; Ghayamghamian et al., 2007), 2010 Chile earthquake (GEER, 2010) and the recent 2011 Tohoku earthquake (Chian et al., 2012), where manholes, pipelines and tanks have floated significantly. The floatation of underground
structures in liquefiable soils can pose serious implications to the integrity and operation of these structures after a major earthquake. In centrifuge tests at the University of Cambridge, similar failure to underground structures was replicated. It was found that the uplift response of an underground structure in liquefiable soil is highly influenced by the loss of shear strength of the soil caused by liquefaction. The loss of shear strength can lead to the decrease in the resisting forces from the overlying soil. In addition, liquefaction leads to an increase in the fluidity of the liquefied soil which allows the buoyant structure to displace through the soil easily. The study of the development and dissipation of excess pore pressure generated by the earthquake is therefore essential in determining the susceptibility of underground structure to floatation. However, the excess pore pressure around the structure may not reflect the same as in the far-field. Past research has indicated the possibility of a reduction in excess pore pressure in the soil near the interface of buried pipes during an earthquake. This paper presents the cyclic movement of rigid underground structures induced by earthquakes and their effect on the reduction in excess pore pressure around structures.

REDUCTION IN EXCESS PORE PRESSURE DUE TO SOIL-STRUCTURE INTERACTION

In the analysis of pipelines and tunnels buried in liquefiable soil deposits, reduction of excess pore pressure around the structure was observed by Ling et al. (2003), Stringer and Madabhushi (2007), Chian and Madabhushi (2011), and Chou et al. (2011) in centrifuge and 1-g shaking table tests. The reduction in pore pressure as compared to the far-field was observed to be most significant at the invert and crown of the pipe. Ling et al. (2003) suggested that the reduction in pore pressure around the structure was due to implied flow along the vicinity of the pipe. Stringer and Madabhushi (2007) postulated that suction beneath the pipe exist and causes the soil under the pipe to retain its full shear strength, thereby inhibiting the pipe from floatation. Chou et al. (2011) indicated that the hydraulic gradient at the middle of the base of the structure draws water and soil at the invert of the structure to fill the space vacated by the uplifting structure. This can be inferred by the soil displacement vectors pointing towards the pipe invert in Figure 1.

Due to the limited literature describing the cause of excess pore pressure reduction around buried structures, a more comprehensive description can be adapted from soil-structure interactions of footings and piles in liquefiable soil. In the case of the footing of a tower structure, Madabhushi (1991) observed that the response of excess pore pressure under the footing is the consequence of the rocking action of the footing pounding onto and lifting off the underlying soil. This is substantiated with a 180° out of phase relationship between the pore pressure readings on opposite sides of the footing of a tower structure in centrifuge tests. Similar comments were made by Mitrani (2006) and Coelho (2007) on frame structures and shallow foundations of small-span bridges respectively. The lower excess pore pressure beneath the footings as compared to far-field measurements imply that the region of the soil immediately under the footings is not subjected to full liquefaction during the earthquake. A nearly undrained process of soil dilation induced by an increase in the static shear stress from the surcharge of the footing prevents the complete loss of effective stress under the footing (Coelho, 2007). Once the earthquake shaking ceases, the excess pore pressure begins to rise again. This is because at the end of the earthquake the pore pressure in the zone below the footing is lower than the far-field, which sets up a hydraulic gradient, allowing the flow of pore water which causes excess pore pressure under the structure to build up again even though the earthquake has ceased (Mitrani & Madabhushi, 2010). This interpretation is similar to Chou et al.’s (2011) comments with underground tunnels.
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