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# Static liquefaction of very loose sand–slag–bentonite mixtures

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**Abstract**

Static liquefaction is a highly destructive mechanism in the failure of soil deposits caused by a sudden loss of effective stress accompanied by vast deformations and a rapid build-up of pore water pressure that can cause soils to behave like liquids. This study examined liquefaction phenomena in saturated clean Perth sand, sand containing 3% bentonite, sand containing slag (2%, 4%, and 6%), and sand containing both 3% bentonite and slag (2%, 4%, and 6%). Undrained static triaxial compression tests were implemented on very loose mixtures at three initial confining pressures (100, 150, and 200 kPa). Static liquefaction (zero deviatoric stress and zero effective confining pressure) was observed at the lowest relative density and the lowest confining pressure. The liquefaction potential of the clean sand and the sand mixtures decreased with increases in confining pressure and relative density. The slag reduced the liquefaction susceptibility by reducing the inter-particle voids and producing a stable fabric. The optimum slag content was found to be 4%. Mixing clean sand with 3% bentonite produced a vulnerable fabric which exhibited high compressibility and a high level of excess pore water pressure. All sand–slag–bentonite mixtures showed non-flow behaviour and low excess pore water pressure. The mixture of sand with 4% slag and 3% bentonite exhibited the highest effective stress and the lowest excess pore pressure. It was revealed that the normalisation between the maximum and the minimum deviatoric stresses, namely, the brittleness index, can be used to quantify the liquefaction potential of clean sand and sand-slag-bentonite mixtures.
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*Keywords:* Clean sand; Slag; Bentonite; Static liquefaction; Limited liquefaction; Non-flow behaviour; Brittleness index

## 1. Introduction

Liquefaction is one of the most complicated and debated topics in geotechnical engineering because it is used to define various contrasting, but related, phenomena (Kramer, 1996). Liquefaction has been widely studied, and researchers have devised a common definition for it. Liquefaction is a phenomenon involving a significant reduction in effective stress; it is accompanied by excessive strain and a build-up of pore water pressure when saturated soils are subjected to undrained static or cyclic loading (Castro, 1969; El Mohtar et al., 2013; Hird and Hassona, 1990; Jafarian et al., 2013; Kramer, 1996; NRC, 1985; Vaid and Sivathayalan, 2000; Verdugo and Ishihara, 1996; Yamamuro and Lade, 1997). The criteria for liquefaction failure can be divided into two main groups depending on the type of loading: flow liquefaction and cyclic mobility (Kramer, 1996; NRC, 1985). Flow liquefaction may occur when the static shear stresses applied to a soil are greater than the shear strength of the soil in its liquefied state (Kramer, 1996; NRC, 1985). Cyclic mobility may occur during cyclic loading; however, it is not considered here. Flow liquefaction produces the most devastating effects of all liquefaction types, and massive instabilities are termed ‘flow failures’ (Kramer, 1996; NRC, 1985). The flow failure mechanism requires a triggering method to initiate the liquefaction and undrained strain-softening (Sadrekarimi, 2014). Liquefaction flow failures have been

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investigated extensively by many researchers, and various analysis methods, procedures, and terminologies have been proposed (Kramer, 1996). Based on the results of previous studies, the response of cohesionless soils with different densities under monotonic undrained loading can be classified into three different types: liquefaction, limited liquefaction, and non-flow behaviour. Liquefaction is characterised by a rapid reduction in deviator stress that occurs after the peak point in the stress-strain curve and continues until reaching the criteria ($\bar{\sigma_3} = 0$ or $\sigma_1 – \sigma_3 = 0$). In non-flow behaviour, the sand exhibits an increase in effective stress and a decrease in excess pore water pressure during shearing until the critical state. A limited flow response occurs in medium to loose sands when the strength of the sand decreases after the peak value in the stress-strain curve and is followed by increases in strength and decreases in pore water pressure at approximately large strains. Fig. 1 (a) and (b) shows the stress paths and stress-strain relationships, respectively, for the three types of behaviour under monotonic loading. The behaviour of liquefaction and limited liquefaction under static loading indicates a strain-softening type of undrained response (Vaid and Sivathayalan, 2000).

Different frameworks have been used to explain the behaviour of sandy soil under undrained static loading. Alarcon-Guzman et al. (1988) explained that the strain-softening of sandy soil depends on the concept of "structural collapse". According to this concept, cohesionless materials have unstable fabric in a loose state, and the contacts between the sand particles can be lost during undrained loading due to abrupt particle rearrangements. Eventually, the water undertakes the loads from the sand particles because of its relative incompressibility and inability to escape due to the speed of the phenomenon. The generation of excess pore water pressure depends on the changes in potential volume and the tendency to collapse. On the other hand, Been and Jefferies (2004) argued that the hypothesis for structural collapse is unable to explain the static liquefaction of sandy soil, as the flow failure response could be related to changes in the plastic strain rates rather than to sudden particle rearrangements. Andrade (2009) also observed that liquefaction phenomena are a function of the state of the sand rather than of the characteristics of the sand. Another framework connects the instability and the liquefaction of loose cohesionless soils under undrained static loading. Lade (1992) argued that instability is essential for liquefaction; however, they are not the same thing, even though both cause disastrous events. Fig. 1(a) shows the difference between a failure line and an instability line. Furthermore, Lade (1992) argued that the instability line indicates the beginning of the unstable states of stress. Instability can be demonstrated in the stress path $\bar{p}–q$ curve. When there is a peak in deviatoric stress followed by a sudden decrease in effective stress, accompanied by the rapid build-up of pore water pressure, this instability produces large permanent deformations in soils which then flow towards failure (Andrade, 2009). Lade and Pradel (1990) and Pradel and Lade (1990) demonstrated that the unstable behaviour of granular materials is associated with their degree of saturation and with a switch from a drained to an undrained condition.

The relationship between the susceptibility of sandy soil to liquefy under undrained static loading and relative density and confining pressure has been investigated using different testing techniques, as summarized by Ibsen (1998), Kramer and Seed (1988) and Yamamuro and Lade (1997). The test results have shown that the susceptibility of sandy soil to undergo static liquefaction decreases with increases in relative density and confining pressure. Yamamuro and Lade (1997) showed that very loose sand samples exhibit anomalous behaviour under undrained static loading. This anomalous behaviour is characterised by increases in the shear strength of samples with an increasing confining pressure. However, the normal response should be that the strength of the samples decreases with an increasing confining pressure. Yamamuro and Lade (1997) explained that this unusual behaviour is due to the ability of the samples to compress, which leads to increases in relative density and, consequently, to the shear strength of the samples. Another relationship between the sample

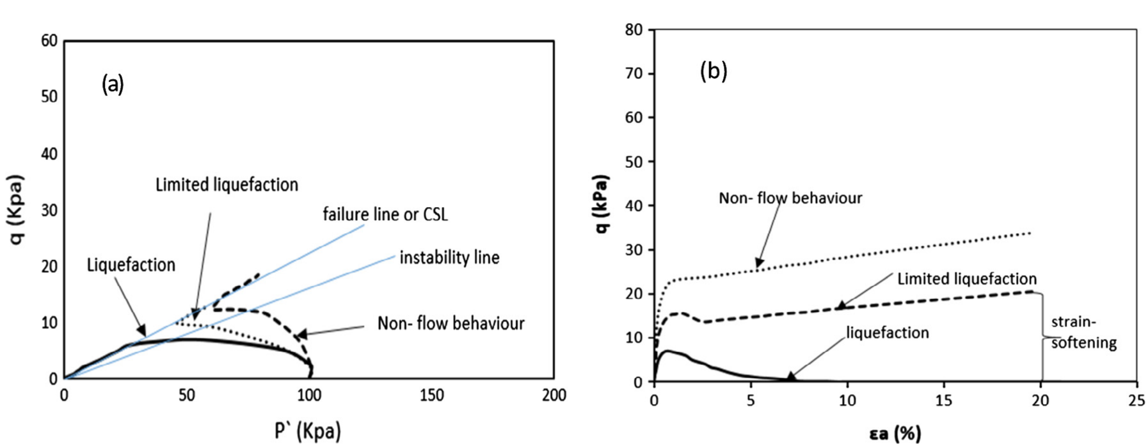


Fig. 1. Typical behaviour of sandy soil under undrained static loading.

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