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Effect of Fines on Liquefaction Susceptibility of Sandy Soil

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***Abstract*—**Investigation of liquefaction susceptibility of materials that have been used in embankments, slopes, dams, and foundations is very essential. Many catastrophic geo-hazards such as flow slides, declination of foundations, and damage to earth structure are associated with static liquefaction that may occur during abrupt shearing of these materials. Many artificial backfill materials are mixtures of sand with fines and other composition. In order to provide some clarifications and evaluations on the role of fines in static liquefaction behaviour of sand sandy soils, the effect of fines on the liquefaction susceptibility of sand was experimentally examined in the present work over a range of fines content, relative density, and initial confining pressure. The results of an experimental study on various sand-fines mixtures are presented. Undrained static triaxial compression tests were conducted on saturated Perth sand containing 5% bentonite at three different relative densities (10, 50, and 90%), and saturated Perth sand containing both 5% bentonite and slag (2%, 4%, and 6%) at single relative density 10%. Undrained static triaxial tests were performed at three different initial confining pressures (100, 150, and 200 kPa). The brittleness index was used to quantify the liquefaction potential of sand-bentonite-slag mixtures. The results demonstrated that the liquefaction susceptibility of sand-5% bentonite mixture was more than liquefaction susceptibility of clean sandy soil. However, liquefaction potential decreased when both of two fines (bentonite and slag) were used. Liquefaction susceptibility of all mixtures decreased with increasing relative density and initial confining pressure.

***Keywords*—**Bentonite, brittleness index, liquefaction, slag.

I. Introduction

TERM liquefaction includes all situations involving sudden losses in soil strength; it is accompanied by rapid development in pore water pressure and large deformation when saturated soil are subjected to undrained monotonic or cyclic loadings [1]-[7]. The sudden increment of pore water pressure is related to loss the contact between soil particles during shearing. The sand-water mixture behaves as a viscous liquid under loading, which able to rise through soil mass [1]. Depending on loading type the failure criteria for liquefaction can be divided into two types: flow failure and cyclic mobility [5], [6]. Under static loading, the failure criterion is known as flow liquefaction. However, it is recognised as cyclic mobility under cyclic loading. Cyclic mobility is out of the scope of the present study. There are many catastrophic geo-hazards associated with static liquefaction such as flow slides, declination of foundations, damage to earth structure, and disruption of services [8]. These hazards make the investigation of liquefaction susceptibility of embankments, slopes, dams, and foundations materials very essential. There are many examples of flow slides triggered by static liquefaction such as failures of slopes at Sau Mau Ping in Hong Kong on August 25, 1976, and Shenzhen in China on September 18, 2002. A significant amount of literature has been published on liquefaction behaviour of sandy soils. These studies reported that flow liquefaction of clean sandy soils is profoundly affected by many factors such as initial state (i.e., relative density and initial confining pressure), stress mode, sample preparation method, the degree of saturation, compositional characteristics, and fines content [4], [7], [9]-[15]. However, several experimental investigations have reported that the impact of fines on static liquefaction behaviour of sandy soils is located in the area of considerable controversy and uncertainty. The complexity of this matter is related to the nature of sand and fines, both of them are granular materials, and they individually interact with each other during loading. Some studies have found that the presences of fines reduced the liquefaction susceptibility of sandy soils [16], [17]. In contrast, [18]-[20] stated that the presence of fines increased the compressibility of sand-fine mixtures by reducing the contact between sand particles. Consequently, the liquefaction susceptibility was increased. Other studies proposed a threshold around which is the percentage of fines content has positive or negative impacts [21]-[23]. Liquefaction susceptibility of granular materials has been extensively investigated by experimental, theoretical, and empirical methods, few geological studies and field observations have been reported in the literature [4], [7], [11], [14]. Many parameters have been proposed in previous studies to evaluate the liquefaction susceptibility of soil such as state parameter, relative contractiveness and stress ratio (minimum deviator stress to initial peak deviator stress). Sadrekarimi [14] used the brittleness index, I_B which proposed by Bishop [24] to characterize the amount of reduction in undrained shear strength during liquefaction. The undrained brittleness index, I_B, can be expressed by:

$$I_B = \frac{q_{peak} - q_{min}}{q_{peak}} \tag{1}$$

where q_{peak} = peak deviator stress and q_{min} = minimum deviator stress.

The values of I_B are in the range 0-1, and non-flow or non-brittle behaviour (where a non-strength decline occurs during undrained static shear) is observed when I_B = 0. However,

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brittle soil behaviour or complete static liquefaction is associated with $I_B = 1$. Using waste materials in various engineering applications may positively impact on the environment by decreasing greenhouse gas emissions and problems related to disposal. Rising amount of waste materials has encouraged researchers to find alternative ways to use them in different applications. Slag is one of waste materials widely used in civil engineering projects. It can be defined as the side product of iron or steel making industry. There are many types of slag such as granulated blast furnace slag (GBFS) and air-cooled blast furnace slag. Slag has been widely used in structural engineering and for stabilising fine soils. However, research on the impact of slag on cohesionless soils is still limited. Budihardjo et al. [25] and Sabbar et al. [26] stated that the internal friction angles of sandy soil increased with increasing slag content. It is apparent from the literature that systematic studies on the effect of fines on liquefaction behaviour of sandy soils are still needed for a better understanding of the influence of other fines types such as waste materials. Therefore, this paper attempts to provide a more detailed investigation regarding the effects of two different types of fines on liquefaction susceptibility of sandy soil. Also, the present study aimed to explore the response of sand mixed with 5% of bentonite and various percentages of slag (2%, 4%, and 6%, by weight), using isotropically consolidated undrained static triaxial tests. Additionally, this work is a part of ongoing research at Curtin University [26]-[28].

II. Materials

Undrained static triaxial tests were conducted on soil specimens prepared by mixing Perth sand with 5% bentonite and 2%, 4% and 6% slag by dry weight of sand. Sand used in the present work was collected from Baldivis area, about 50 km south of Perth, Western Australia. This sand was a clean (i.e. 99.8% sand and 0.2% silt) and poorly graded (SP). The grain size distribution curves for the sand and sand-fines mixtures are demonstrated in Fig. 1. The slag utilised in this study was GBFS, manufactured by BGC Cement in Western Australia. The physical and chemical characterisations of slag are tabulated in Tables I and II, respectively. Bentonite used in present work was a powdered sodium-based bentonite, manufactured from Unimin Australia Limited, Queensland with at least 78% passing a 75-micron sieve, bulk density, loose 1.0 (t/m^3), and specific gravity 3.3. The chemical compositions of bentonite are presented in Table III. Table IV describes the properties of mixtures. Scanning electron microscope (SEM) images of materials are shown in Fig. 2. Bentonite and slag were added to the specimen by dry mixing of them with oven dried sand. Tests were conducted on cylindrical specimen 50 mm in diameter and 100 mm in height, prepared by moist tamping techniques. Back pressure saturation procedure described in Head [29] was adopted in the present study, and the sample is considered fully saturated when the value of $B \geq 0.95$. All tests were performed under strain-controlled conditions at 1 mm/min strain rate.

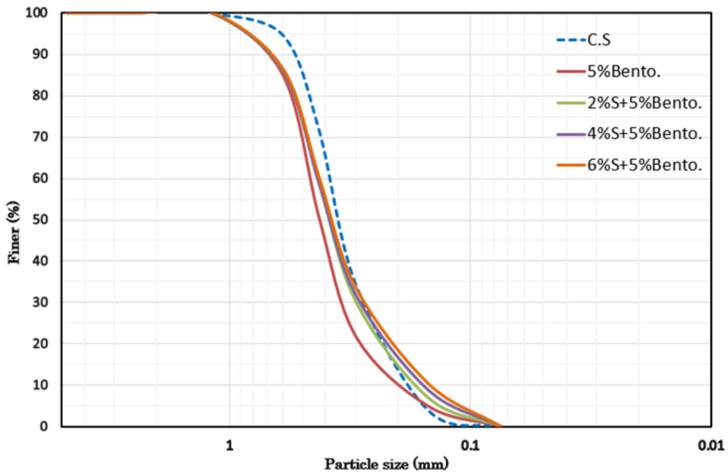


Fig. 1 Particle size distribution for the soil mixtures used in this study

TABLE I
PHYSICAL PROPORTIONS OF GBFS

Coloured	Relative density	Surface area
Off-white	2.85-2.95	400-600 m^2/kg

TABLE II
CHEMICAL ELEMENT PROPORTIONS OF GBFS, MEAN PERCENT BY WEIGHT

Elements	(Al_2O_3)	(CaO)	Silica, amorphous	Sulphur
(%)	5-15	30-50	35-40	<5

TABLE III
CHEMICAL ELEMENT PROPORTIONS OF BENTONITE, MEAN PERCENT BY WEIGHT

Element	(%)
Silicon dioxide (SiO_2)	63.6
Aluminium oxide (Al_2O_3)	14.6
Titanium dioxide (TiO_2)	0.4
Iron oxide (Fe_2O_3)	2.8
Calcium oxide (CaO)	0.3
Sodium oxide (Na_2O)	1.3
Magnesium oxide (MgO)	2
Potassium oxide (K_2O)	0.5
Loss on ignition	14.5

TABLE IV
PROPERTIES OF MIXTURES USED IN THIS STUDY

Materials	C_u	D_{50}	G_s	ρd_{max}	ρd_{min}	e_o
clean sand	2.235	0.35	2.580	1.670	1.560	0.643
Sand+5% Bentonite	2.30	0.41	2.670	1.770	1.590	0.657
5%Bentoinite+2%Slag	2.44	0.39	2.673	1.833	1.605	0.644
5%Bentoinite+4%Slag	2.47	0.37	2.675	1.840	1.616	0.634
5%Bentoinite+6%Slag	2.56	0.38	2.679	1.870	1.626	0.625

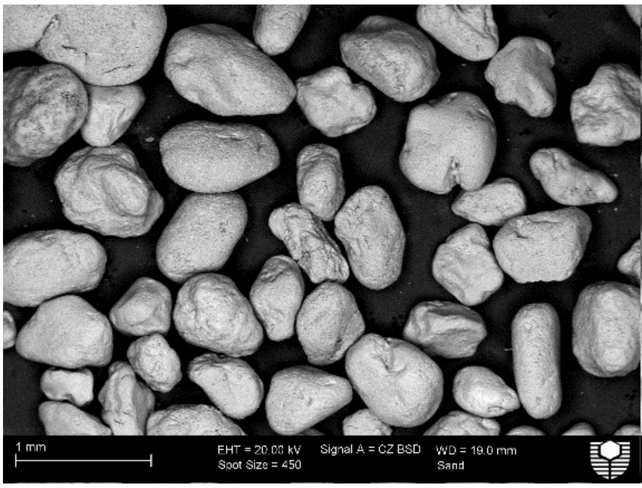
C_u= coefficient of uniformity, G_s= specific gravity; ρd_{max}= maximum dry density; ρd_{min}= minimum dry density; e_o= initial void ratio.

III. TESTING PROGRAM

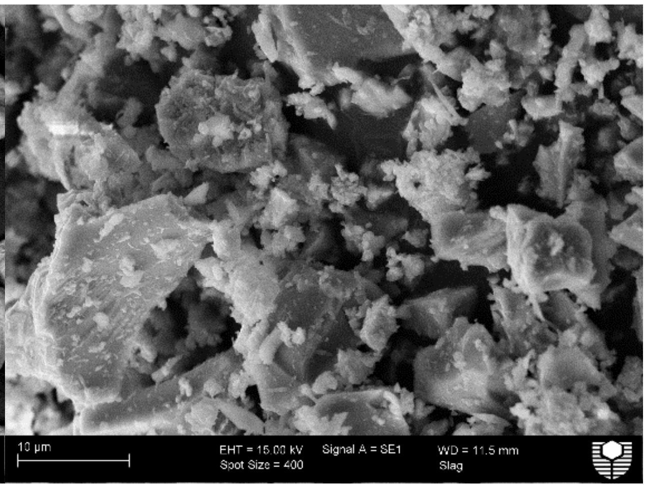
A total of 13 undrained static triaxial tests were performed on isotropically consolidated saturated loose to dense samples under three different confining pressures (100, 150 and 200 kPa). Testing program included five types of specimens produced by dry-mixing clean sand with 5% bentonite and three percentages of slag. The sample types are summarised in Table V.

TABLE V
SUMMARY OF SAMPLE TYPES

Materials	Symbol
Clean Sand	C.S
Sand + 5% Bentonite	5%Bento.
Sand + 5% Bentonite + 2% Slag	2%S+5%Bento.
Sand + 5% Bentonite + 4% Slag	4%S+5%Bento.
Sand + 5% Bentonite + 6% Slag	6%S+5%Bento.



(a)



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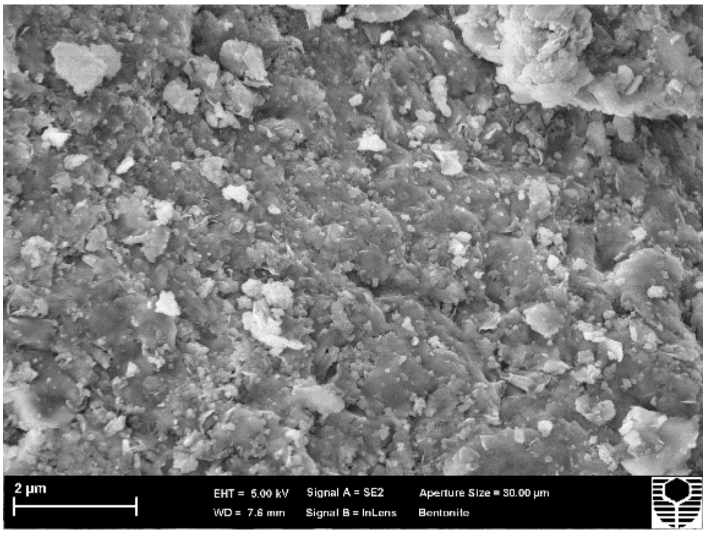
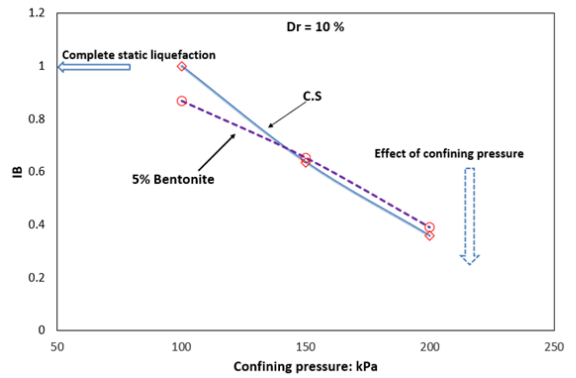


(c)

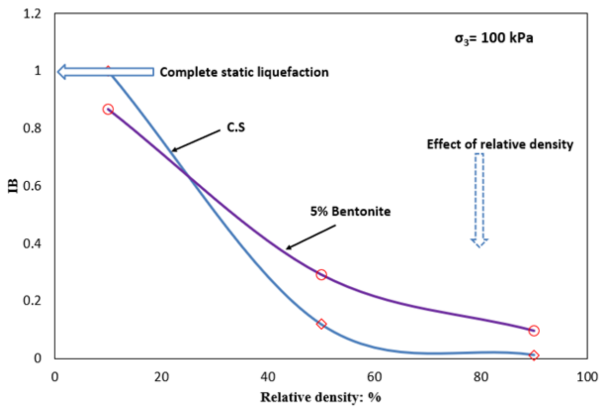
Fig. 2 SEM images of test materials: (a) clean sand; (b) GBFS Slag; (c) bentonite

IV. RESULTS AND DISCUSSION

A series of undrained static compression triaxial tests were conducted on saturated isotropically consolidated sand-bentonite and sand-bentonite-slag mixtures to investigate the effect of bentonite and combination of bentonite and slag on liquefaction susceptibility of sandy soil. Figs. 3 (a)-(c) show the effect of adding 5% of bentonite on liquefaction behaviour of sandy soil. As can be seen, the complete static liquefaction with I_B value 1 existed in lowest relative density and lowest confining pressure. Liquefaction susceptibility for mixtures decreased with increasing relative density and confining pressure.



(a)



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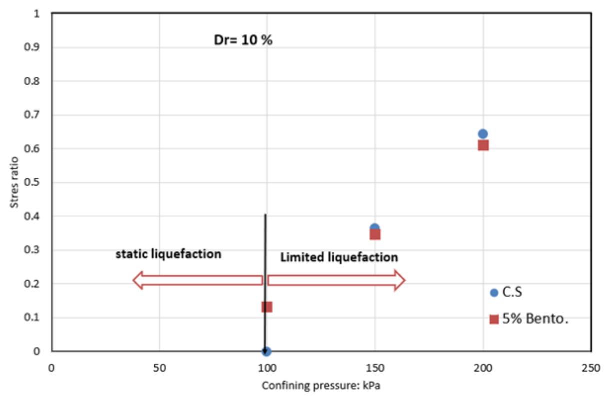
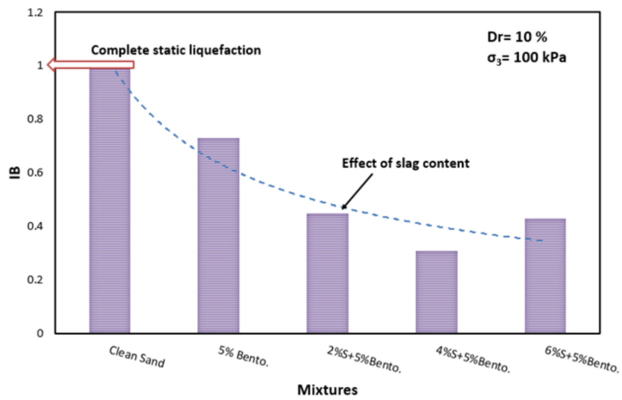


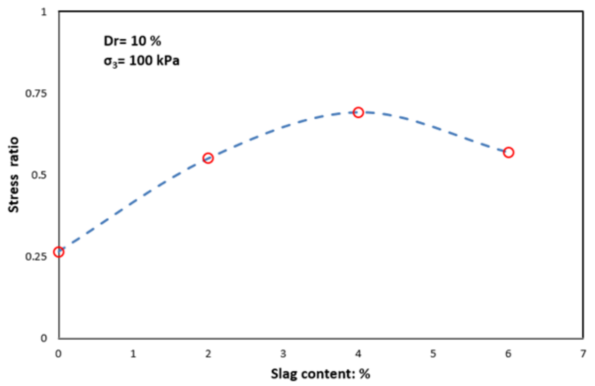
(c)

Fig. 3 Effect of bentonite on liquefaction behaviour of sandy soil: (a) brittleness index vs confining pressure ; (b) brittleness index vs relative density; (c) stress ratio vs confining pressure

Figs. 3 (a) and (b) demonstrate that liquefaction susceptibility of sandy soil increased when sand mixed with 5% bentonite. The value of I_B increased from 0.35 for loose clean sand at 200 kPa to 0.39 when mixed with 5% bentonite and tested at same confining pressure. Fig. 3 (b) illustrates that the I_B values decreased with increasing relative density for both materials. However sand-bentonite mixtures showed I_B values greater than clean sand at confining pressures 150 and 200 kPa. Fig. 3 (c) shows the relationship between stress ratio q_{min}/q_{peak} and confining pressure. Stress ratio q_{min}/q_{peak} is defined as the ratio between minimum deviator stress to peak deviator stress and it can be used to evaluate liquefaction susceptibility of soil. Complete static liquefaction is associated with q_{min}/q_{peak} ratio zero value. Non-flow behaviour is associated with q_{min}/q_{peak} ratio value of 1. As seen from Fig. 3 (c), the q_{min}/q_{peak} ratio of sand samples decreased when sand mixed with 5% bentonite and the confining pressure 100 kPa represent the boundary between the liquefaction and limited liquefaction behaviour. The negative impact of 5% bentonite on liquefaction susceptibility of sandy soils could be related to the role of bentonite that may significantly contribute to the reduced stability of sand fabric. Bentonite particles may occupy voids between sand grains, and as a result of its swelling ability, the contact between sand grains reduced which leads to increase the compressibility of samples. Research findings by [30]-[32] also point out that the sand-bentonite mixtures showed high liquefaction susceptibility when bentonite content less than 10%. The effect of slag content on liquefaction behaviour of sand-bentonite mixtures is shown in Figs. 4 (a)-(d). Figs. 4 (a) and (b) demonstrate that the brittleness index I_B decreased, and q_{min}/q_{peak} ratio increased with increasing slag content up to 4%. Fig. 4 (c) shows the relationship between excess pore water pressure ratio R_u and axial strain for all mixtures tested at relative density 10% and confining pressure 100 kPa.



(a)



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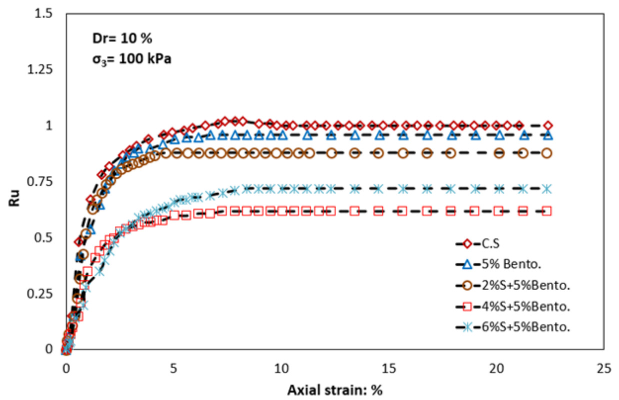
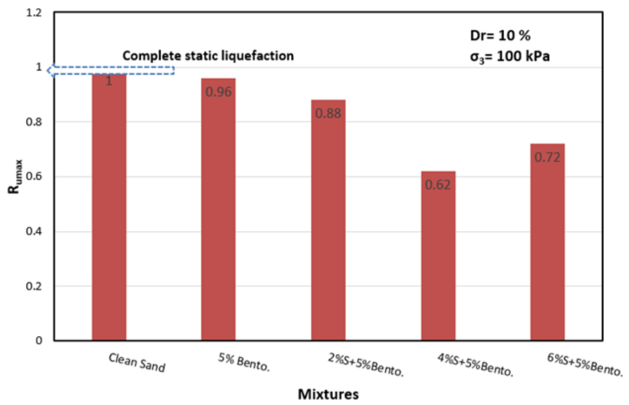


(c)



(d)

Fig. 4 Effect of slag on liquefaction behaviour of sand-5% bentonite mixtures: (a) brittleness index of mixtures ; (b) stress ratio vs slag content; (c) Excess pore water pressure ratio vs axial strain; (d) maximum excess pore water pressure ratio of mixtures

R_u can be defined as the ratio of excess pore water pressure to initial confining pressure. Positive values of R_u are associated with flow behaviour. However, negative values are associated with non-flow behaviour. As seen from Fig. 4 (c), all mixtures showed positive R_u values and it decreased with increasing slag content up to 4%. Fig. 4 (d) also indicates that the mixture of 4% slag showed the minimum value of maximum pore water pressure ratio R_{umax}. In summary, the slag content that has a slight effect on liquefaction susceptibility of sand-bentonite mixtures could be related to the behaviour of mixtures that are dominated by bentonite content.

VII. Summary and Conclusion

The present study was aimed to investigate the effect of adding bentonite and slag on the liquefaction susceptibility of sandy soil. A series of undrained static triaxial compression tests were performed under different test conditions. The results of this investigation show that all samples of sand-bentonite and sand-bentonite-slag showed flow behaviour with positive excess pore water pressure. It was also shown that the liquefaction susceptibility of clean sandy soil was increased when mixed with 5% bentonite. The brittleness index increased and stress ratio decreased when sand mixed with 5% bentonite. Adding bentonite to sand soil produced unstable fabric because bentonite reduced the contact between sand grains. The slag content had a slight effect on the liquefaction susceptibility of sand-bentonite mixtures because the behaviour of samples was dominated by bentonite effect. The brittleness index of clean sand and sand-fines mixtures reduced with increasing initial confining pressure and initial relative density. For a better understanding of the effect of fines on liquefaction behaviour of sandy soil, future studies on manipulating of bentonite and slag contents warrant further investigations.

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