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Liquefaction characteristics of coarse silt-graded A50 silica flour

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ABSTRACT

Centrifuge modelling is used for testing physical scale models under increased gravitational acceleration, in order to match model stresses to a model prototype. In geotechnical centrifuge testing, the model is usually prepared by the same soil as the prototype. However, the latter cannot always be supported in cases where particle size play a role. Thus, the used soil must be scaled down but, at the same time, behave as the prototype soil during shaking. This paper shows that silt – graded materials can be liquefiable and hence usable as a model material for liquefaction centrifuge testing. The soil chosen for further investigation was coarse silt A50 Silica. Since many case studies support that silts could be liquefiable, the sample was examined in the lab to determine its main mechanical and geotechnical properties. Liquid limit value was found within a range that could show preliminary signs of soil liquefiability. Moreover, cycling simple shear tests were performed which clearly showed a contractive behaviour of the coarse silt during shearing. Finally, the fine material was tested in the geotechnical centrifuge of Dundee University. Pore pressure rise was observed, in addition to soil densification which confirms that the coarse silt is a liquefiable soil and thus suitable for modelling coarser prototypes.

Keywords: silt, liquefaction, scaling laws, centrifuge modelling

SCALING ISSUES IN CENTRIFUGE MODELLING

Centrifuge modelling is an advanced physical modelling technique for testing small scale geotechnical engineering models in the enhanced gravity field of a centrifuge. The main principle of centrifuge testing is the equivalence between the used small scale models and the full-scale prototype via well - established scaling laws. More particular, the model dimensions are scaled down to 1/N, where N is the scaling factor. As a result, self-weight stresses on the model are N times smaller than on the prototype. In order to retain the stresses in full size levels, the centrifuge increases the strength of the gravity field N times (Ng). The outcome of modelling is the stress and soil behaviour similarity between the model and the field structure (Schofield, 1980). Fig. 1 represents schematically the basic principle of centrifuge testing.

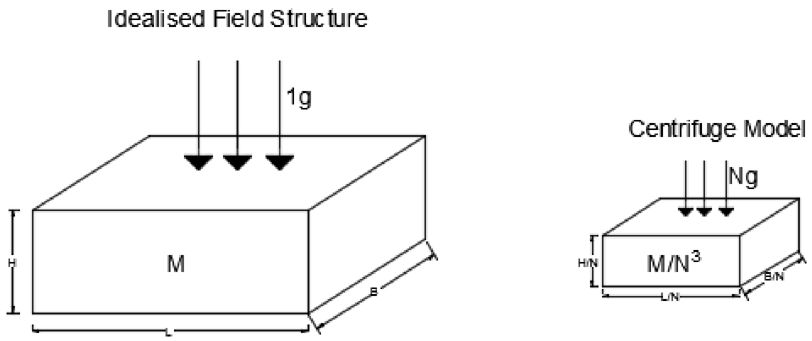

Figure 1. Basic principle of centrifuge modelling

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Earthquake centrifuge modelling has been developed as well, in order to understand the response of soil and infrastructure during extreme phenomena, such as large shaking and liquefaction. Conventional centrifuge testing procedure is to use identical soil in model and prototype. This involves treating the soil as a column with macroscopic mechanical properties and no particle size effects. However, in some cases, such as centrifuge testing of stone columns as a countermeasure against liquefaction, the stone columns should be modelled by using reduced scale particles, because prototype aggregate is too large in diameter for the model columns. For consistency then, the surrounding soil must be scaled by the same rule. Moreover, the fine material should be capable of liquefaction, as it represents a liquefiable soil. Particle scaling has an added benefit in that, water may be used as pore fluid rather than high - viscosity alternatives that are conventionally used in liquefaction modelling to correctly model seepage timescales (e.g. Stewart et al., 1998). The proposed model is a coarse silt liquefiable layer with sand in the model stone columns and water as the pore fluid. This paper presents a study of the suitability of this silt soil for representing liquefiable soil in centrifuge tests, based on assessment of physical properties, cyclic element behaviour and performance on the geotechnical centrifuge.

DESCRIPTION OF THE PROPOSED A50 SILICA SILT

Preliminary Choice Criteria of Coarse Silt-Graded A50 Silica Flour

A length scale factor of 40 was selected as most appropriate for stone column modelling, necessitating a test acceleration level of 40g. As a result, the chosen silty material was coarse silt A50 silica, which is equivalent to 1/40th scale coarse sand in terms of particle size.

In addition to the particle size correlation between the field and the model material, another reason for choosing A50 silica in this preliminary stage was the existence of recordings which claim that silty soils could be liquefiable. According to geological reference and case studies silt is a material that can liquefy (Carr et al., 2004). For instance, liquefaction potential investigation of a site in Québec, Canada, characterized mostly by clayey and silty deposits, showed that silts were susceptible to strength loss and capable of pore pressure increase (Sartain et al., 2014). Furthermore, a series of Standard Penetration Tests (SPT) (ASTM D1586-84) which were performed in sand layers mixed with large percentages of silt deposits near the city of Buffalo, New York, showed a moderate liquefaction probability (Budhu, 1989). Thus, a sample of the coarse silt A50 silica was investigated extensively in the lab to determine the mechanical and geotechnical properties and estimate its liquefiability under cycling loading.

Soil Properties of A50 Silica

Particle Size Distribution Curve

First of all, the A50 silica particle size distribution curve was determined, via a laser diffraction technique, by using the Malvern Mastersizer 2000 Particle Size Analyser (Fig. 2). As a result, the median grain size D_{50} was measured in order to confirm that is equivalent to 1/40th scale coarse sand. D_{50} was 33.81 μm, representing 1.35 mm at 1/40th scale, within the required coarse sand range (BSI, 2014). There is more to particles than just size, however. Fig. 3a shows the silt grains zoomed in 3000 times, captured by the scanning electron microscope in Dundee University. This shows that the particles are rather more angular than a typical coarse sand (Fig. 3b) and contain significant characteristics of a platy nature. These factors may affect the mechanical behaviour, necessitating further testing to confirm the soil suitability for the purpose.

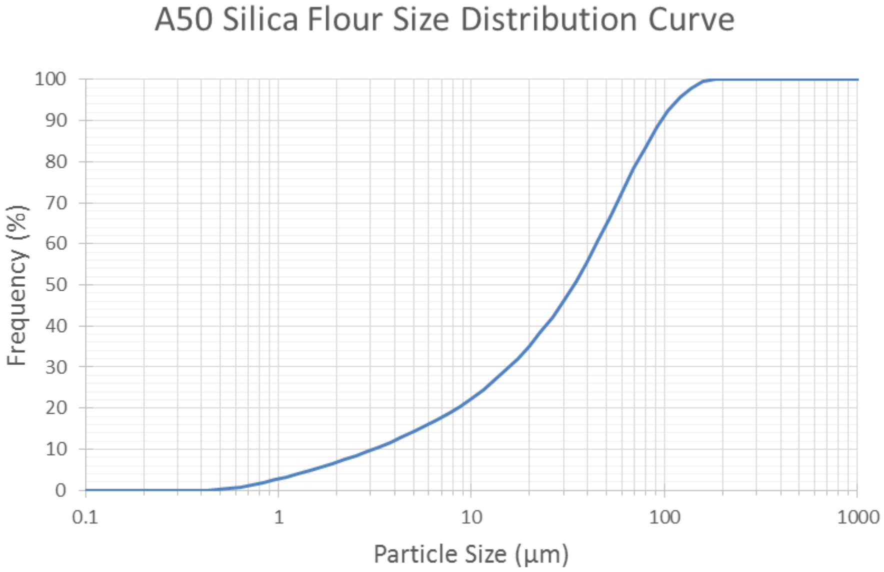

Figure 2. Particle size distribution curve of A50 silica flour

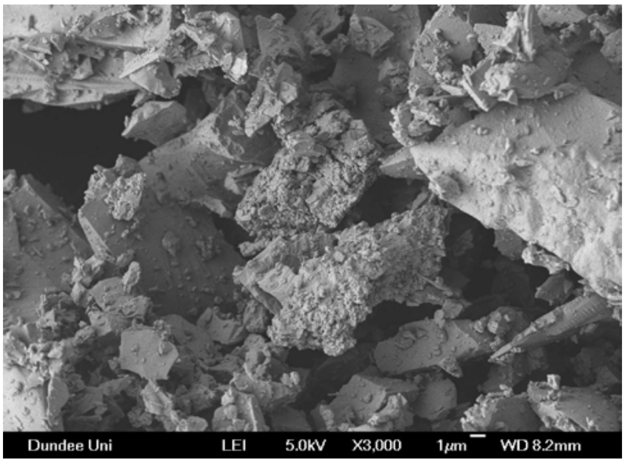

Figure 3a. Particle grains of A50 silica flour

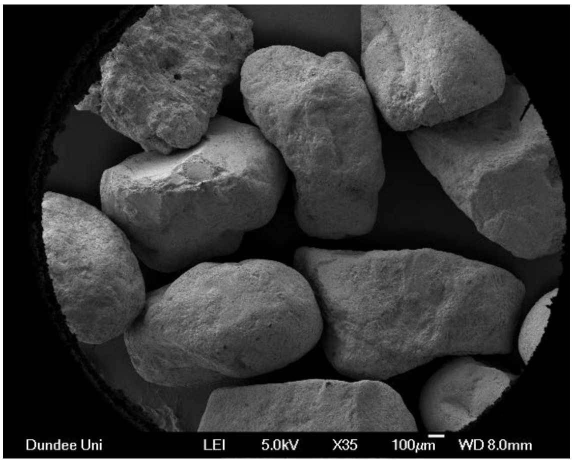

Figure 3b. Particle grains of coarse sand

Determination of Maximum and Minimum Void Ratios e_{max} and e_{min}

The maximum and minimum void ratios e_{max} and e_{min} of the silty material were determined, according to BS 1377 - 4:1990. The minimum void ratio, which corresponds to the maximum soil dry density was calculated via the Standard Compaction Method, where a soil sample is compacted with standard input energy in a specific mould. The outcome is the maximum dry density and the optimum water content, which is the water content where maximum dry density occurs. For the maximum void ratio, BS 1377 - 4:1990 propose the free fall of the soil specimen into a glass measuring cylinder. The method is stated to be applicable only to sands containing up to about 10 % of fine material. However, since A50 silica is a coarse silt, the closest to sand fine material, and since there is no alternative way to calculate e_{max} for a fine soil, the method was applied in this case anyway. The parameter e_{max} was found 1.385 and e_{min} was 0.612. Both values were anticipated for a uniform silt, so it could be concluded that e_{max} determination method gave satisfactory results for a coarse silt material.

Liquid Limit LL Test Determination

In addition, the liquid limit of the soil was determined, via the fall cone test (BS 17892-2:2014). At this point, it should be noted that the liquid limit value and the clay content of a silty soil are two key soil parameters that could give a preliminary sign of liquefiability (Andrews et al., 2000). More particular, if liquid limit for silt samples is lower than 32 and the clay content is less than 10%, the soil could be susceptible to liquefaction (table 1). The liquid limit parameter for A50 silica was found 24.60, which, in combination with the small clay content (much less than 10%), shows a liquefaction potential. Thus, since the described criterion was met for A50 silica, further soil characterization was made, as well as a series of shear tests under cycling loading.

Table 1. Liquefaction susceptibility criterion of silty soils (Andrews et al., 2000)

	Liquid Limit < 32	**Liquid Limit ≥ 32**
*Clay Content < 10% **	Susceptible	Further Studies Required
*Clay Content ≥ 10% **	Further Studies Required	Not Susceptible

*clay content defined as grains finer than 2.0 μm

Friction and Peak Friction Angle φ Test Determination

The soil sample was tested in a typical shear box equipment, in order to calculate the drained strength parameters. A sample of A50 silica was prepared in loose to medium state, with an initial relative density of 40% and an initial void ratio of 1.08. The dimensions of the sample were 60x60 mm and the initial height was 25 mm. During shearing, the sample showed a contractive behaviour, which is the required driving force for liquefiability of the soil (Fig. 4a). Against expectations, in high stress levels the compaction effect and the volume change were reduced. Interestingly, the conventional shear box size was unable to apply sufficient displacement to achieve a critical state. As a result, only peak friction angle could be determined. Fig. 4b shows the shear stresses that were observed for different values of normal stress. The peak shear strengths measured in the shear box test are shown in Fig. 5. The peak friction angle was found 28.0° for low normal stress levels and 32.0° for high normal stress levels. A plausible explanation for the difference in soil behaviour at low and high stresses could be the cementation of the tested sample when compressed. Thus, the fine angular grains of the silt are squeezed together, so both the peak friction angle and the material cohesion are increased at the same time. This is in line with the high stress level tests, where cementation provokes the reduction of sample volume change, and especially in the highest normal stress case, where axial displacement is practically negligible. After test, the soil specimen was a thick, solid sample, justifying the large increase of the cohesion parameter. It should be noted that the range of effective stresses in proposed centrifuge models is 0 - 81 kPa and should therefore be unaffected by any apparent cementation under higher stresses. The A50 silica soil properties are summarized in table 2.

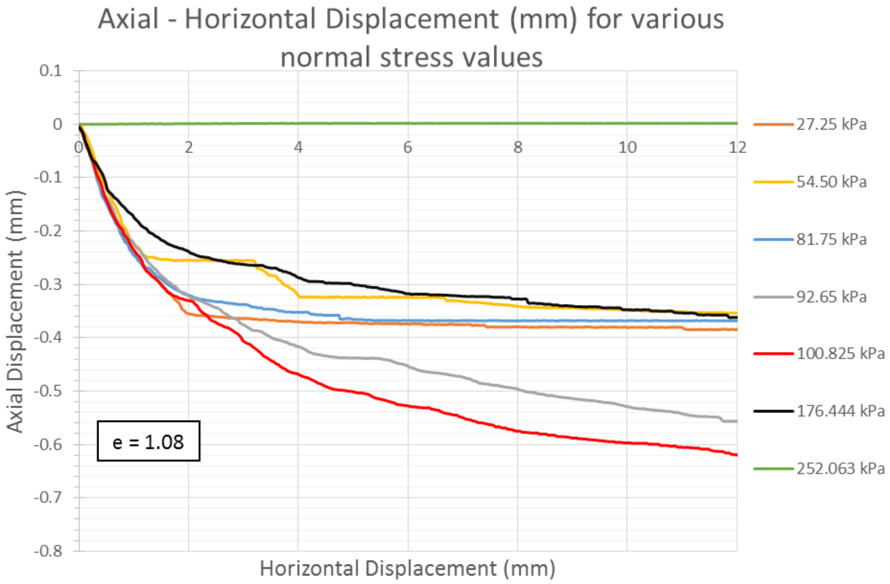

Figure 4a. Vertical displacement (contraction negative) of A50 silica for various normal stresses

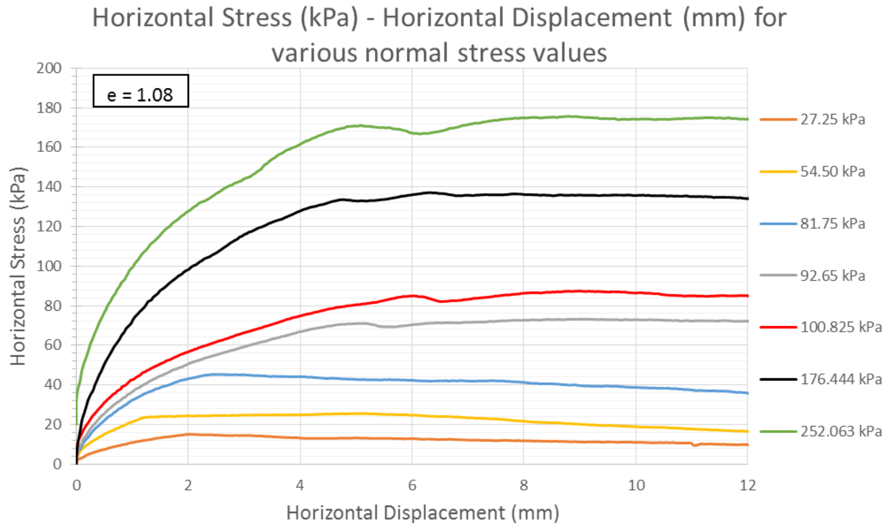

Figure 4b. Shear stresses of A50 silica for various normal stresses

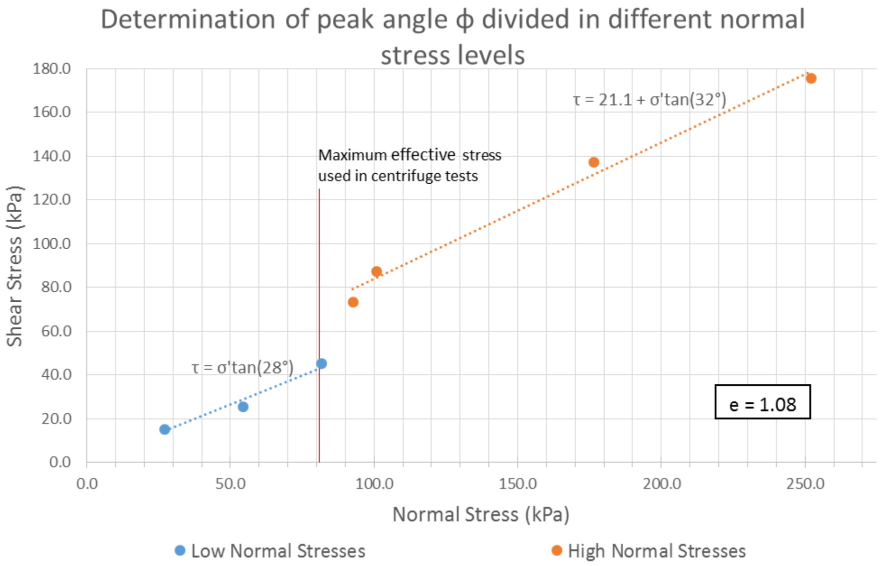

Figure 5. Peak friction angle φ of A50 silica for low and high stresses

Table 2. Soil properties of coarse silt-graded A50 silica

Soil Properties	**Value**
D_{10} *(µm)*	3.095
D_{50} *(µm)*	33.810
D_{90} *(µm)*	95.824
e_{max}	1.385
e_{min}	0.612
G_s (t/m^3)	2.65
Liquid Limit (LL)	24.60
peak friction angle φ	28.0° ~ 32.0°
Grain Shape	angular

Simple Shear Testing Behaviour

A number of cyclic simple shear tests were carried out to investigate the liquefiability of this material in cyclic loading. The equipment used for the tests was the GDS Variable Direction Dynamic Cyclic Simple Shear System. A cylindrical sample of 70.4 mm diameter is prepared on a base plate, by using a rubber membrane and a number of metal rings which allow the shearing displacement of the specimen (Fig. 6). Then, the sample is docked on the centre of the device, where it can be deformed in simple shear in any horizontal shearing direction. Undrained tests on the soil were not possible due to the lack of a cell pressure, so drained tests were carried out in order to assess the degree of contraction under cyclic simple shear, which may be interpreted as indicative of a drive to undergo liquefaction. Fig. 7 shows the results obtained by the simple shearing tests at four different ratios of shear stress to effective stress τ/σ΄. Results show that the material contracts under shear stress when cycling in a range of shear ratios and cycle numbers and should therefore be appropriate for behaving as liquefaction - susceptible material in the centrifuge tests.

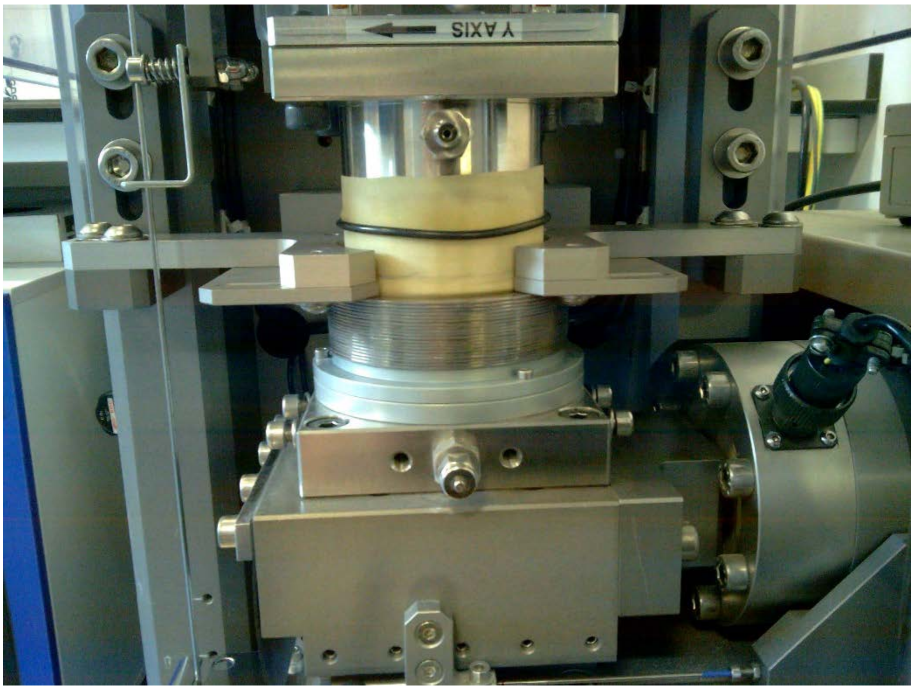

Figure 6. A50 silica sample preparation for simple shearing testing

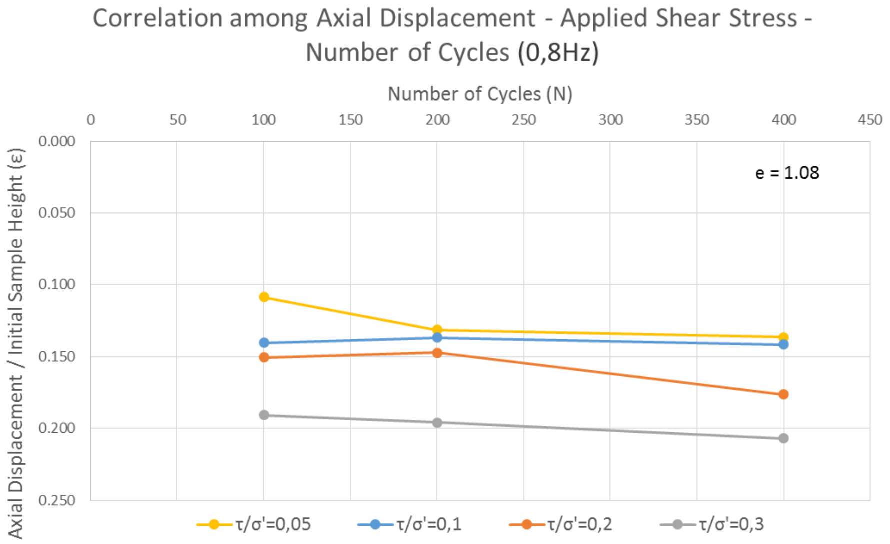

Figure 7. Axial displacement (contraction positive) as a function of number of stress cycles applied, for different shear stress ratios

LIQUEFIABILITY TEST OF A50 SILICA SILT ON CENTRIFUGE

Sample Preparation

Since the aforementioned laboratory tests indicated a preliminary observation that silt-graded A50 Silica could be liquefiable, the fine material was then tested in the geotechnical centrifuge of Dundee University, to confirm its behaviour during the desired dynamic loading of the application. The characteristics of Dundee University geotechnical centrifuge and the earthquake simulator were described by Brennan et al., 2014. The centrifuge test series included models with loose, saturated coarse silt and other saturated samples of the fine material in denser form, reinforced with model stone columns, which were filled with coarse sand aggregate. For the loose case, the silt was pluviated in the centrifuge box through a sieve with a diameter of 1.18 mm, with a target relative density D_r of 40% (initial void ratio e_o 1.08). In addition, instrumentation was installed in various positions throughout the samples, including accelerometers (ACC), linear variable differential transformers (LVDT) and pore pressure transducers (PPT), to measure the possible pore pressure elevation during shaking. The instrumentation ordinance in a typical test sample is given schematically in Fig. 8. The centrifuge soil models were tested in three different earthquake motions, with different peak ground acceleration values and time duration.

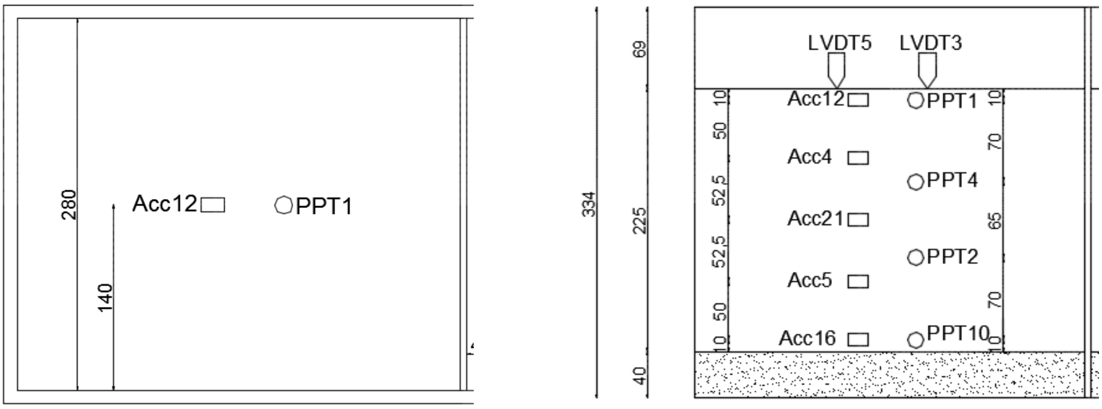

Figure 8. Instrumentation position for centrifuge test. Dimensions in mm at model scale. Test carried out at 40g.

Centrifuge Test Results

Fig. 9a and 9b show excess pore pressure recorded during the shaking event based on accelerations from the Maule earthquake in Chile, 2010 (PPT2, PPT4). Both graphs indicate the rapid increase of pore pressure for the silt sample. The input acceleration motion is given in Fig. 9c (ACC16). Fig. 9d shows acceleration on the model surface (ACC12). This shows significant alternation from the input (Fig. 9c), commensurate with that expected when soil softens as it reaches liquefaction.

Moreover, significant surface settlement was observed, which differed among the model cases. More particular, the unreinforced models had a total settlement of about 45 to 50 mm, while the reinforced had 20 mm. Both model cases were densified to a final void ratio e_f 0.69. In addition with silt soil densification which confirms that the coarse silt is a liquefiable soil.

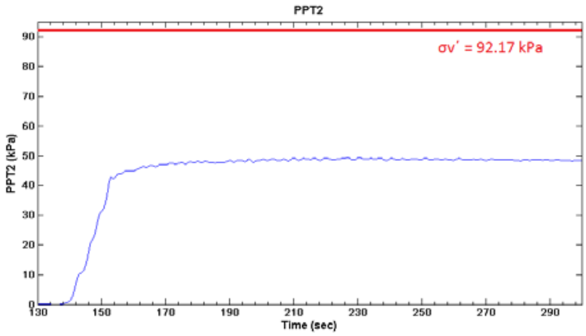

Figure 9a. Pore pressure graph for PPT2

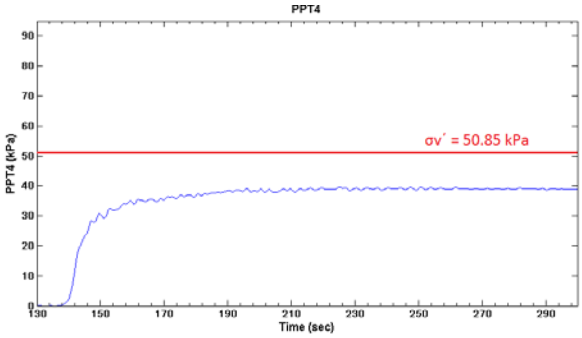

Figure 9b. Pore pressure graph for PPT4

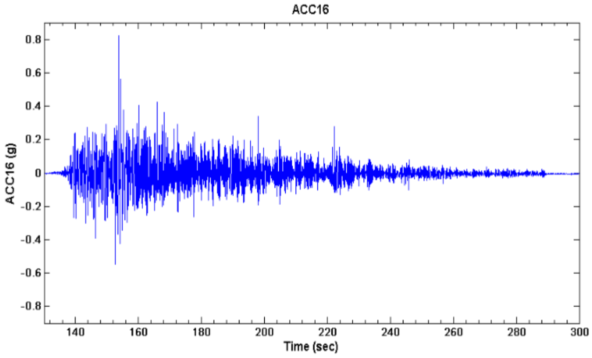

Figure 9c. Input acceleration motion (ACC 16)

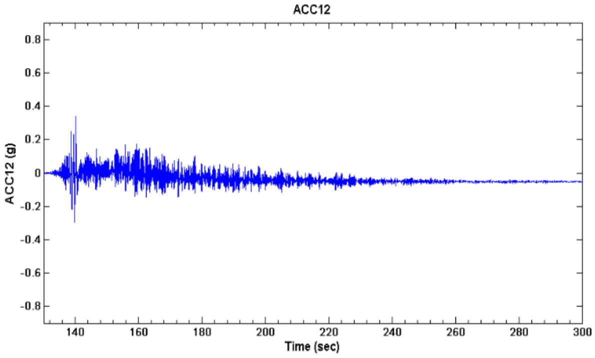

Figure 9d. Acceleration response on surface (ACC 12)

CONCLUSIONS

Various references and cases studies claim that silt soil can generate water pore pressure and show some liquefaction behaviour characteristics. Thus, coarse silt - graded A50 silica flour was tested in the laboratory to examine its possible liquefiability. The preliminary soil characterisation tests had shown that rockflour contracted under shear and therefore could be liquefiable under cyclic simple shearing. As a result, a series of centrifuge tests took place, to confirm the contractive behaviour of coarse silt material. The rockflour soil proved to be able of generating pore pressure during shaking. Further centrifuge tests are going to be performed, to evaluate the liquefiability of the soil. Finally, it can be concluded from the lab and centrifuge tests that coarse silt A50 Silica is a liquefiable soil and it can represent a coarser liquefiable soil for centrifuge modelling, particularly if particle sizes of other soils must be scaled.

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