On the undrained compressive behaviour of gassy sand



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ABSTRACT

Gassy soils contain both free gas as well as a large amount of gas dissolved in the pore fluids, which results in an increased compressibility as compared to their saturated counterparts. This paper presents some preliminary experimental results that indicate the loading behaviour of gassy soils is a time dependent process in which the soils will exhibit differing responses when loaded below and above the liquid gas saturation pressure. Shear and compression wave (S and P wave) velocities were measured throughout the tests. Although the S wave shows little response, the P wave velocity was confirmed to be sensitive to gas content. P wave responses throughout the test indicate that there may exist a link between total stress and the gas content.

RÉSUMÉ

Les sols gazeux contiennent du gas libre ainsi que des grandes quantites de gaz dissoux. Ces gaz dissoux augmentent la compressibilite des sols en comparaison avec les sols satures. Cet article presentent quelques resultats preliminaires indiquant que le comportement de chargement des sols gazeux est un processus dependant du temps, processus pour lequel les sols presenteront des reponses differentes selon que la charge est inferieure ou superieure a la pression de saturation des gas dissoux. Les vitesses de propagation des ondes de cisaillement et de compression (ondes P et S) ont été mesurées pour tous les tests. Bien que l'onde S montre peu de reponse, ces tests confirment que la vitesse de propagation des ondes P est sensible au contenu gazeux. Les reponses de des ondes P indiquent qu'il pourrait exister un lien entre la pression totale and le contenu gazeux.

1 INTRODUCTION

Classical soil mechanics often overlooks saturation by assuming the soil voids contain water only; however, degree of saturation can have an important role on soil behaviour. When soils contains a high concentration of gas inclusions, referred to as gassy soils, the saturation or gas content combined with the drainage conditions and loading path are crucial to understanding the resulting behaviour.

Under certain conditions the presence of gas can have a beneficial effect, for example Grozic et al. (2000) showed that the increased compressibility of gassy soils results in a substantial increase in resistance to cyclic liquefaction. Likewise, when sudden load is applied, it is possible that the gas inclusions within the soil formation will absorb the initial shock which results in short term stability. However, this stability will change with time as a result of partial drainage, gas compression, and gas solution.

In order to quantify the response of gassy soils to loading, an experimental program has been carried out. In addition to typical triaxial parameters, it is also necessary to determine the degree of saturation (or gas content) at each stage in the test. In this study, shear and compression waves were used to quantify the degree of saturation, which is an approach quite sensitive to the onset of bubble formation as identified by Ishihara et al. (1998); Yang (2002 and 2005); Yang and Sato (2000); Tsukamoto et al. (2002).

2 BACKGROUND

2.1 Gassy Soil

Gassy soil is a multi-phasic system which is composed of three phases namely, soil, water and air. These soils contain a relatively large amount of gas dissolved in the pore fluid compared to unsaturated soils (Sobkowicz and Morgenstern, 1984). Generally, gassy soils are found with a large number of small bubbles embedded in pore water (Figure 1a) or large bubbles of gas in the matrix of a fully saturated soil (Figure 1b).



Figure 1. Microstructure of gassy soil. (a) when bubble size smaller than pore space and (b) when bubble size is greater than soil particle size.

Sobkowicz (1982) investigated the response of gassy soil to undrained unloading and illustrated its differing behaviour as compared to classical soils such as unsaturated soils and saturated course and fine grained soils (Figure 2). According to Figure 2, for saturated and gassy soils above the liquid/gas saturation pressure $(u_{l/q})$, changes in pore fluid pressure (u) remain constant in response to decreases in total stress. However, when u reaches ul/g, gas begins to exsolve and u remains almost constant for further changes in total stress. As the effective stress becomes small, soil compressibility is increased and pore fluid pressure rapidly decreases. Eventually, the pore pressure (u) becomes equal to the total stress (σ) and the effective stress (σ ') reduces to zero. At this point B=1 and the change in pore pressure is equal to the change in total stress.



Figure 2. Undrained equilibrium behaviour of an element of soil on unloading: effect of amount of gas dissolved in pore fluid (after Sobkowicz and Morgenstern 1984)

Amaratunga (2006) conducted isotropic and anisotropic undrained-unloading gassy soils experiments on loose and dense sands. The isotropic tests illustrated behavior similar to Sobkowicz (1982) where the pore pressure initially dropped with as a result of a drop in cell pressure, then subsequently increased back to (or near) the liquid/gas saturation pressure, as a result of gas expansion and exsolution.

2.2 Compression (P wave) and Shear (S wave)

P-wave propagatation through a medium causes contraction and dilation in the longitudinal direction while S-waves cause displacement in the transverse direction (Figure 3).

Nishio (1987) demonstrated that the B value of a unsaturated sand specimen could be related to P and S wave velocities. More recent work by Naesgaard et al. (2007), Tamura et al. (2002) and Tsukamoto et al. (2002)

studied P-S wave propagation through saturated and unsaturated porous medium and found that P wave velocity will decrease with any decrease in saturation while S wave remains relatively unchanged.



Figure 3. P-S-wave propagation through porous media Source:http://www.seismo.unr.edu/ftp/pub/louie/class/100 /waves.GIF)

Sills et al. (1991) showed a correlation of gas content to compression wave velocity and attenuation. These gassy soils exhibited a rapid drop in compression wave velocity during the onset bubble formation (Figure 4). Amaratunga (2006) used P wave velocities to determine the onset of bubble formation during undrained unloading of gassy soils and observed similar compression wave behaviour.



Figure 4. Compression wave behaviour during onset bubble formation (after Sills et al. 1991)

The current research program aims at evaluating the transient behaviour of gassy soils during undrained loading while using the P and S wave velocities to garner information about the change in saturation.

3 LABORATORY PROGRAM

3.1 Experimental setup

3.1.1 Materials

Reconstituted Ottawa sand, a round to sub-rounded quartz, was used in the experimental program. Ottawa sand has a specific gravity of 2.65 and is graded in accordance to ASTM C-778 standards. The minimum and maximum void ratios (0.81 and 0.51) were determined using ASTM D2049 standards. Based on the particle distribution curve, it is noted that Ottawa sand has a uniform distribution with a mean grain size of 0.35 mm (i.e. D_{50}).

Naturally occurring gassy soils usually contain large concentrations of dissolved methane gas. However, compared to carbon dioxide, methane gas has a lower solubility in water and thus requires higher working pressures; hence carbon dioxide was selected as for this research. Carbon dioxide is also non-flammable whereas methane requires special procedures and equipment due to its explosive nature.

Membrane leakage experiments performed by Sobkowicz (1982) showed that a double membrane with glycerine cell fluid was the most reliable membrane/cell fluid combination to avoid gas diffusion from the sample into the cell fluid. However, previous experience (Grozic et al. 1999) has indicated that the total amount of gas diffusion from the sample can be managed with double latex membranes followed by thin overlapping aluminum foil layers adhered to the membranes with silicone grease, as long as the test duration is kept relatively short.

3.1.2 Testing Apparatus

The triaxial system used for the tests is modified from an unsaturated stress path triaxial system. A double walled cell construction enables precise specimen volume change measurements during undrained gassy soil testing. The cell pressure capabilities are 2000 kPa, higher than a conventional system. The system is servo controlled and capable of stress path or cyclic testing. A specialized circulation system enables replacement of the pore fluids under high back pressures.

The ultrasonic test system consists of two platens with diameter of 70 mm each. The platens are bonded with the transducers; one P-wave crystal surrounded by a circular array of S-wave crystals. When a voltage is applied, the crystals change shape and generate ultrasonic waves (GCTS, 2001). The crystals used in the ultrasonic system are ceramic and behave as a piezoelectric material. Prior to each series of tests the P and S waves are calibrated with Aluminum specimens, and before every test the face to face offset is checked.

3.1.3 Specimen Preparation

Reconstituted specimens were prepared using the moist tamping method. This technique consists of placing moist soil layers into a mold and tamping each layer with a specified force of tamping. Following assembly within the triaxial apparatus, carbon dioxide was percolated through the sample for a period of 20 to 30 minutes. Next de-aired distilled water is introduced to the specimen bottom port and collected from the specimen top. To ensure complete saturation, 2 to 3 times the pore volume of water is allowed to pass through the specimen. Cell and back pressures were then slowly increased to 800 kPa and 750 kPa, respectively. At this point, a B- test was performed to check saturation; B-values of 0.98 and greater were obtained. The P and S wave velocities of the saturated specimen were recorded.

The specimen pore water was then replaced with carbon dioxide saturated water (approximately three times the volume of voids was used) by circulating the gas dissolved water through the specimen under a pore pressure 750 kPa with a driving head of 0.5 m. In order to produce free gas bubbles, the cell and pore pressures were then quickly lowered to 700 kPa and 600 kPa, respectively. P wave measurements were taken to ensure that gas exsolution had occurred. Once this process was completed, the all valves to and from the specimen were closed, thus creating an undrained boundary condition.

3.2 Testing Procedures

Amaratunga (2006) captured the transient behaviour of gassy soils under isotropic and anisotropic undrained unloading. To determine the behaviour during loading, a similar testing procedure was used. The cell pressure was increased rapidly in increments of 25 kPa during which the pore pressure, axial and volumetric deformations were measured. Each increment lasted approximately 10 minutes where P and S wave measurements were taken near the end of the increment at equilibrium conditions.

4 LABORATORY RESULTS AND DISCUSSION

Figure 5 illustrates the results of one loading test. As the cell pressure is initially increased from 695 to 725 kPa, the pore pressure responds with an immediate 11 kPa increase but then decreases gradually with time. At the end of the increment, the pore pressure is almost back to its original value of 655 kPa. For comparison, an ideal saturated specimen would have shown an increase in pore pressure by 30 kPa, which would not have dissipated with time. In the second increment, an initial pore pressure response of 16 kPa is observed, yet the pressure dissipates over the increment to reach an equilibrium value of 695 kPa. Subsequent increments show a significantly damped pore pressure response to the increasing cell pressure. At the end of each increment, the pore pressure equilibrates close to the initial pore pressure value prior to testing.

The P and S wave at equilibrium conditions for each increment are shown in Figures 6 and 7, respectively. The P wave velocity for this specimen when it was saturated was 1700 m/s, this value reduced to just over 1200 m/s during the gas exsolution phase of pre-testing. During the experiment, the P wave velocity shows a sudden increase when the confining pressure reaches

750 kPa. It remains approximately constant then until the pressure passes 850 kPa where it begins to increase rapidly. The shear wave velocity shows no to little response to changes in degree of saturation.

This particular specimen has a liquid/gas saturation pressure of 750 kPa, the pressure at which carbon dioxide was dissolved into distilled water. Certainly, soil response shows differing behaviour above and below a confining pressure of 750 kPa and above 850 kPa. Below 750 kPa confining pressure, some pore pressure response is observed where the pore fluids initially sustain load but then it is believed that the high compressibility of the pore fluids results in a partial drainage or relief of pressure. The P wave velocity is showing little change indicating the gas content has not changed significantly. At approximately 750 kPa, an increase in P wave velocity is observed which indicates that the degree of saturation has increased probably due to gas compression. Between 750 and 850 kPa, the P wave remains essential constant and the pore pressure shows little response to changes in the cell pressure. At 850 kPa, the P wave increases significantly meaning that the specimen saturation has increased due to gas compression and solution.

One interesting aspect of these results is the concept that gas content, or degree of saturation, may be responsive to confining pressures (i.e. total stress) and not only pore pressures. Oedometer test results on gassy clays presented by Sills et al. (1991) also indicated a dependence of gas pressure on the total stress. Further testing is required to confirm and perhaps quasi-quantify this link.

Relative to a saturated soil response, where the effective stress would have remained at 50 kPa during

the duration of the test, the gassy specimen increased in effective stress from 50 kPa to 184 kPa, a change of 134 kPa, as a result of an overall increase in cell pressure of 151 kPa. These results illustrate the unique properties of gassy soils, namely the compressibility, can have a beneficial influence on stability provided the applied stresses do not substantially exceed the liquid gas saturation pressure.

5 CONCLUSIONS

Gassy soils are often thought of as a hazard, where the reduction of pressures could result in dramatic decreases in effective stress. However, gas can be beneficial in loading situations where the high compressibility of the pore fluids result in a more stable soil structure relative to a saturated undrained condition. Preliminary results of an experimental program investigating the loading behaviour of gassy soils highlights the transient nature of gassy soils due to gas compression and solution over time. The soils are sensitive to the liquid gas saturation pressure and early results indicate that gas content or gas pressure may be linked to total stresses. Ultrasonic velocity measurements enabled an indication of changing gas contents throughout the tests where the P wave velocity increased with decreasing gas content (i.e. increasing degree of saturation) while the S wave velocity showed no response to gas content. Further work is required to understand and quantify the behaviour of gassy soils in loading stress paths.



Figure 5. Pore pressure response due to isotropic step increases in cell pressure



Figure 6. P wave response during isotropic loading.



Figure 7. S wave response during isotropic loading.

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