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Effect of particle loss on soil behaviour

Darren KELLY[1], John McDOUGALL[1] and Daniel BARRETO[1]

[1]Edinburgh Napier University

10 Colinton Road, EH10 5DT, Scotland: - d.kelly@napier.ac.uk; j.mcdougall@napier.ac.uk; d.barreto@napier.ac.uk

Soil particle loss can result in strength and volume reductions which are difficult to predict. This paper investigates the influence of the removal of fractions of selected particle sizes under different confining pressures. The mass loss process was reproduced by the dissolution of selected salt particle sizes and fractions from uniform Leighton Buzzard sand. The dissolution tests were performed in a triaxial cell customised to allow circulation of pore-fluid thereby allowing the dissolution/removal of the salt fraction. Test results from previously conducted oedometric dissolution tests and subsequent triaxial dissolution tests all show increases in void ratio. From the triaxial tests, a reduction in shear strength with increasing ductility was observed. Volumetric and strength behaviour were found to be related to the particle size and fraction material removed while shear-wave measurements obtained pre- and post-particle removal indicate significant changes in small-strain stiffness.

Key words

Dissolution, triaxial, bender elements, particulate soil.

1 Introduction

Particle loss can occur through dissolution or suffusion, the latter being a key factor in embankment dam failures. Dissolution occurs in soils containing soluble minerals such as gypsum, anhydrite, calcite, dolomite, halite [James and Lupton, 1978; Craft *et al.,* 2006]; while suffusion is the transportation of particles small enough to pass through the pores of a cohesionless granular material and influenced by soil grading, density, and seepage flow [Kenny and Lau, 1984].

The dissolution of minerals in embankment dams is common place, especially in the western United States where dams have been constructed using soils containing gypsum, anhydrite and halite or are constructed on ground containing these readily soluble minerals. Erosion in embankment dams can lead to an overall structural weakening of the dam as indicated by emerging sinkholes and total settlements [Muir Wood, 2001].

Dissolution research has shown that both settlement and void increase accompany particle loss. Fam *et al*., (2002) considered the large and small-strain properties of sand-salt mixtures experiencing dissolution of a fine-grained salt (D_{50} = 0.35 mm). Focusing on various *percentages* of a single sized salt (0-10% by weight) they found a change in shearing behaviour from dilative to contractive as the percentage of salt removal increased. Shear-wave velocity was found to decrease by as much as 25% for the higher percentages during the dissolution stage.

Shin and Santamarina (2009), performing dissolution tests on salt-glass bead mixtures under the k_0 condition observed lateral stress changes during dissolution (salt-sand mixtures: D_{50} = 0.3 & 0.7 mm respectively; 5, 10 and 15% additions by volume salt). Truong *et al*., (2010) reported on dissolution tests in an oedometer using salt-sand mixtures (D_{50} = 0.25 & 0.36 mm respectively; percentages 2, 5, 7 and 10% by volume salt). Settlement strain, void ratio increase and shear-wave velocity decrease were found to occur for each dissolution test, with the magnitude of change directly related to the fraction of salt removed.

In erosion studies the post-suffusion stress-strain behaviour of a gap-graded soil tested under triaxial conditions was studied by Chang and Zhang (2011). Shearing behaviour was found to change from dilative to contractive with fine particle loss.

This study investigates the influence of the removal of a range of salt particle sizes at various percentages from a coarse-sand matrix (D_{50} = 0.85 mm) over a range of stresses. Dissolution studies performed to date have focused on mixtures of sand-salt with sand to salt particle size ratios (diameter ratio) of 1.4-2.3. This study examines the influence of dissolution tests performed on sand-salt samples with diameter ratios ranging 0.57-9. The smallest salt particle size simulates the particle sizes lost in unstable/suffusion-potential soils while the complete range of particle sizes provide insight into dissolution/degradation processes. The volumetric and mechanical consequences of particle removal, relating size and percentage effects are the subject of this research.

2 Modified triaxial apparatus

A triaxial cell with submersible load cell was modified to include bender elements and a solution circulatory system for the purpose of the dissolution stage (Fig. 1). Bender elements were installed in the top-cap and base-pedestal allowing wave propagation in the vertical direction during testing to monitor stiffness changes during dissolution and subsequent shear. A circulation system for the dissolution stage replaced the standard pore-water pressure function and consisted of a reservoir, stirrer, peristaltic pump and custom triaxial access ring. A standalone pressure/volume controller replaced the original pneumatic cell pressure control and volume change transducer to improve volume measure accuracy (resolution: +/- 0.001 cm^3).

Sample pore-water is traditionally used to measure sample volume change during triaxial tests. However the current experimental setup requires the circulation of pore-water for the dissolution stage. The use of cell water to measure sample volume change has been employed previously by researchers [Klotz and Coop, 2002] but its use can introduce a number of errors, e.g., cell pressure changes induce cell expansion/contraction, cell water is absorbed into the acrylic cell, temperature equalisation, dissolution of possible undetected air inclusions into the cell water, and the large volume of cell water in relation to the sample volume (≈ 10:1) thereby increasing the sensitivity to error overall.

Acrylic water absorption was limited by keeping the cell filled with water when not in use [Wheeler, 1988]. The cell water was drained prior to sample setup with efforts made to ensure internal surfaces did not dry completely to limit air-bubble adherence to internal cell surfaces, especially at cell seals and fittings. The apparatus was then ‘primed’ by applying the test cell-pressure for 24 hours prior to the dissolution test stage to allow rates of volume change due to the effects detailed earlier reach an acceptable value. Low compressibility high-density polyethylene (HDPE) dummy-sample tests demonstrated rates of volume change in the ‘primed’ cell of c. 0.02 cm^3/hr. This rate was insignificant in terms of the duration of the monitoring stages (c. 80 minutes) and the sample volume of approximately 196 cm^3. Furthermore, volume changes measured during dissolution and shearing stages were at least an order of magnitude greater than cell water volume change over that period.

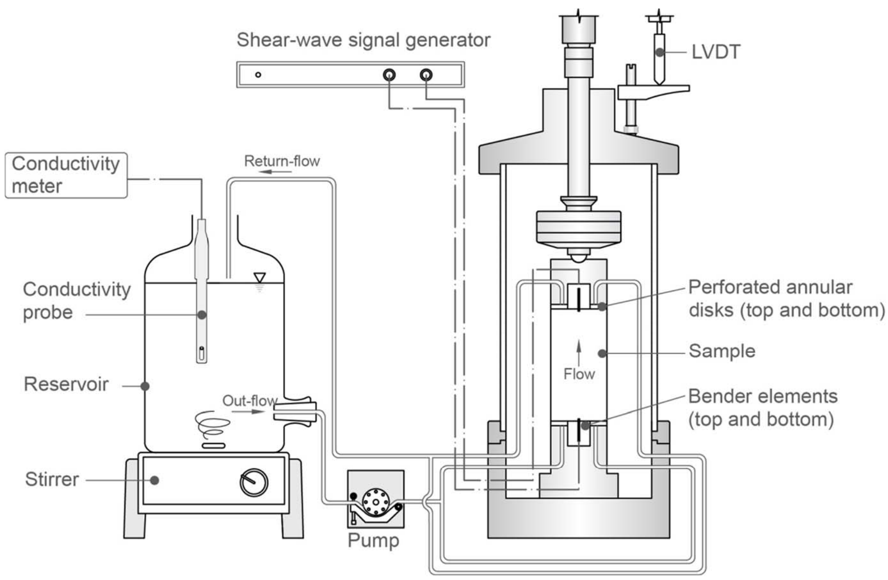

Fig. 1 Modifications to standard triaxial apparatus.

3 Experimental study

3.1 Sample material

Uniform sized, rounded to sub-rounded Leighton Buzzard sand (LB) formed the inert soil fraction (D_{50} = 0.85 mm; C_U = 1.4; G_S = 2.65). Sodium chloride salt particles (G_S = 2.16) formed the soluble soil fraction and were crushed to the required dimension (0.063, 0.125, 0.25, 0.5 & 1.0 mm) resulting in more angular shapes. The salt dimension refers to the sieve aperture size on which particles were retained.

Samples were prepared dry to prevent dissolution of salt particles prior to the dissolution stage. The dry sand-salt particles were mixed and riffled into 8 parts. Each part was deposited in the sample-former using a funnel to minimise drop height and avoid segregation of sand and salt particles, especially in samples with smaller salt particles. Each part was compacted in layers using a steel cylindrical weight, sized to fit into the sample former, and vibrated using an electric engraver to produce a dense packing.

The structural integrity of salt particles was investigated by applying increments of vertical stress to a sample of 1.0 mm sized salt particles under oedometric conditions with particle-size-distributions (PSD) performed after each stress increment. First signs of particle breakage occurred at 880 kPa, with 1.5% passing the 1.0 mm sieve, rising to 2.3% passing at 1760 kPa. This breakage occurred at stresses far in excess of the stresses applied in the test programme (42, 84 and 168 kPa) suggesting that salt particles maintained their structural integrity in the tests prior to the wetting/dissolution stage.

Fig. 2 presents the particle PSDs of the sand with 15% additions by mass of 0.063, 0.125, 0.25, 0.5 and 1.0mm salt particles. The 0.5mm salt was similar in grading to the Leighton Buzzard sand meaning 0.5mm salt additions did not alter the PSD of the predominant sand, described as uniformly graded, with additions of 15% of 0.25, 0.5, and 1.0 mm salt particles not greatly affecting this classification. Additions of 15% of 0.063 and 0.125 mm salt particles produced a gap-graded soil. However the aim of this study was not to replicate a specific soil grading but instead to produce quasi-binary mixtures as a first step to the interpretation of changes in a soil experiencing particle loss.

3.2 Dry isotropic compression

The cell pressures applied to the dry sample were chosen to allow comparison with previously conducted oedometric dissolution tests. Oedometric tests consisted of 40 salt dissolution tests performed at two vertical stresses of 62 and 250 kPa, with salt particle sizes of 0.063, 0.125, 0.25, 0.5 and 1.0 mm at percentage mass additions of 2, 5, 10 and 15%. Jaky's equation was used to approximate the mean effective stresses from the vertically applied loads of 62 and 250 kPa in the oedometric tests to 42 and 168 kPa respectively. Therefore, triaxial tests were performed at cell pressures of 42, 84 and 168 kPa.

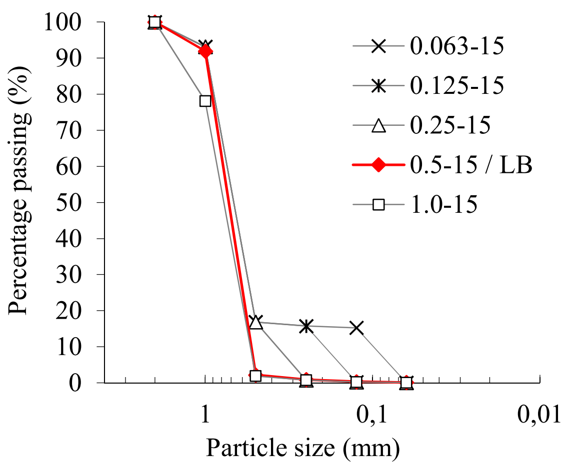

Fig. 2 Particle size distribution (PSD) for salt-sand mixtures.

3.3 Dissolution and post-dissolution shearing

Salt-solution (0.5 litre) was added to the reservoir and circulated to saturate the sample initially to allow a more gradual and uniform sample dissolution, followed by the addition of 1 litre increments of water to the reservoir (4 litres in total). The high solubility of sodium chloride salt in water ensured complete dissolution, indicated by the stabilisation of conductivity measure and simultaneous cessation of sample volume strain after a period of approximately 2 hours. Post-dissolution the loading piston was lowered to make contact with the sample to measure the vertical displacement during dissolution. Monotonic shearing was then applied at 0.25 mm/min to 20% axial strain.

4 Shear-wave velocity

Shear-wave velocity (V_s) is determined using $V_s = L/t$ where the shear-wave travel time (t) can be determined in the time-domain using a point picking method and the travel distance is taken as the bender element tip-to-tip distance (L). Shear-wave velocity is used to derive the small-strain shear modulus (G_{max}) using $G_{max} = \rho V_s^2$ where ρ is the bulk density of the soil. Pressure (compression) wave analysis in saturated soil is generally overlooked since the resulting calculated bulk modulus reflects that of the water rather than the soil.

Preliminary shear-wave tests demonstrated the optimum input amplitude voltage range as 4-10 volts (V) with 10V selected for the current tests. Input voltages less than 4V were found to result in weak received signals while voltages greater than 10V resulted in significant near field effects. An input wave frequency of 10 kHz was selected to minimise near-field effects [Salinero *et al*., 1986] based on the travel-distance to wavelength ratio value of 4 [Jovicic *et al*., 1996, Arulnathan *et al*., 1998, Brignoli *et al*., 1996]. Input shear-wave excitations were single sinusoidal pulses allowing wave travel times to be determined by picking points of similarity between input and received waves (Viggiani and Atkinson, 1995). The peak-to-peak method was initially chosen to avoid the near-field effects that interfere with the determination of the first-arrival time of the received wave. However, a flaw of this method was evident in Arulnathan *et al*., (1998) where the travel time was shown to be dependent on the input frequency; the period of the input wave varies with input frequency while the period of the received wave remains relatively unchanged. Therefore travel-time was taken as the start of the input wave to the first peak of the received wave.

5 Results and discussion

Volumetric strains with dissolution in oedometric and triaxial tests demonstrate sensitivity to both the amount and size of salt particles lost; larger amounts and larger particle sizes result in greater strains. However this paper focuses on the post-dissolution volumetric states that influence the mechanical behaviour of soil.

5.1 Initial volumetric states

To aid analysis of post-dissolution volumetric states, pre-dissolution void ratios for oedometric and triaxial tests are presented in Fig. 3. The 15% tests are presented in terms of particle size, revealing their influence on the initial state. The void ratio minimum and maximum for Leighton Buzzard sand, $e_{\min(LB)}$ and $e_{\max(LB)}$ respectively, are included.

The influence of salt particle size present in the dominant coarse sand matrix is apparent; smaller size salt particles lower the initial void ratios as demonstrated theoretically and experimentally by Lade *et al*., (1998). The smallest particle sizes at the percentages tested can be accommodated in the interparticle voids without affecting the total volume of the soil. As the salt particle size approaches that of the sand, the salt particles no longer nestle in the inter-particle voids of the sand, but assume a structural role within the dominant sand matrix. This interpretation is reflected in dissolution settlements where larger salt particles when removed lead to a rearrangement of the sand matrix resulting in greater settlements [McDougall *et al*., under review]. In terms of applied stress, initial void ratios are not influenced greatly over the stress range tested in either oedometer or triaxial tests (Fig. 3). In fact, striking is the correlation of initial void ratios in both apparatuses irrespective of applied stress.

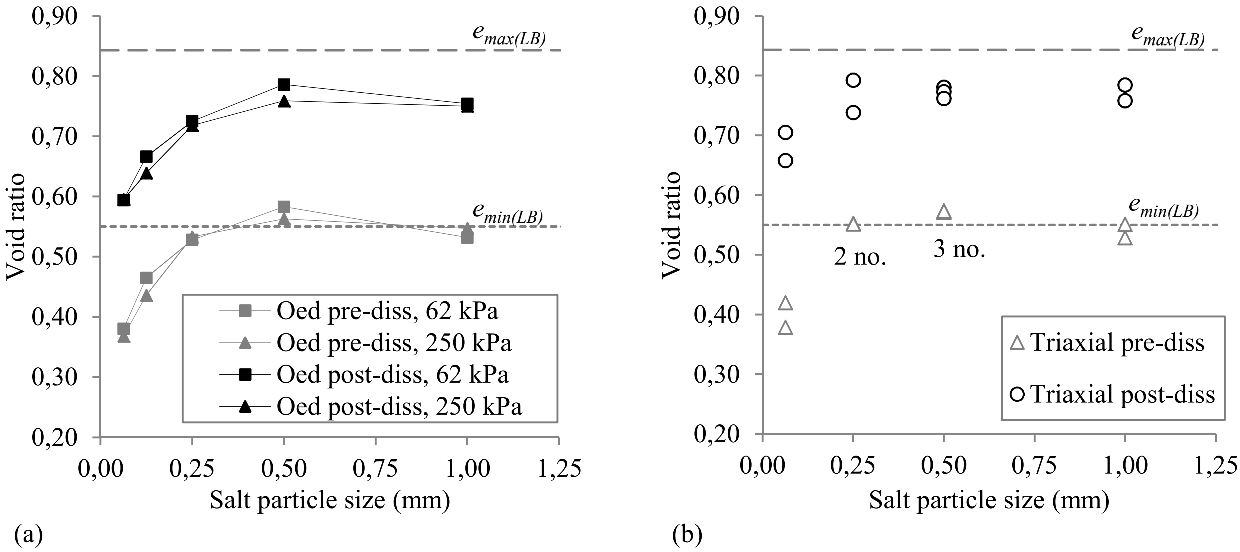

Fig. 3 Pre- and post-dissolution void ratios for 15% by mass salt with particle sizes ranging 0.063 to 1.0 mm for *(a)* oedometric tests (15% by mass salt; 62 & 250 kPa), and *(b)* Triaxial tests (15% by mass salt; 42, 84 and 168 kPa). Void ratio minimum and maximum for Leighton buzzard sand included.

5.2 Post-dissolution volumetric states

The volumetric state of the post particle loss soil is of importance since it influences the soils mechanical behaviour. Dissolution and suffusion tests have repeatedly shown that particle removal is accompanied by void ratio increase [Shin and Santamarina (2009), Truong *et al*., (2010), Chang and Zhang (2011), McDougall *et al*., (under review)]. McDougall *et al*., (under review) showed that the mass of material removed was the dominant influence in void ratio increase with near-proportional changes based on 2, 5, 10 and 15% by mass salt. Void ratio increase was found to be independent of the salt particle size removed (0.063, 0.125, 0.25, 0.5 and 1.0 mm), the initial void ratio or the applied stress.

5.3 Post-dissolution shearing

LB reference tests were performed under drained conditions and exhibited the typical behaviour associated with densely prepared sand at low stresses: the stress ratio plot shows peak strength development at low axial strain followed by strain softening to the critical state at high axial strains, while the volumetric strain plot exhibits an initial compression at low axial strain followed by dilation to high axial strains (Fig. 4(a) and Fig. 4(b)).

Dissolution tests performed on 15% by mass salt shows shearing behaviour varying from dilative to contractive with increasing particle size. The 0.063 mm tests exhibit pre-critical state peaks at large axial strains of 7-10%, but are not well defined and exhibit low rates of strain-softening to critical state. The loss of larger particles sizes demonstrate increasingly contractive behaviour by exhibiting a peak stress that coincides with the critical state stress at large axial strains of 10-20%. The volumetric strain behaviour reflects the volumetric state of the post-dissolution samples with each increment in particle size resulting in a more contractive response (Fig. 3(b)). Adopting the reasoning presented in McDougall *et al*., (under review) regarding the interaction of the different size salt particles with the sand matrix, it is appropriate that the 0.063 mm dissolution tests should be closest in behaviour to the LB reference tests, since their removal should cause least disruption to the dominant sand matrix. Each increment in salt particle size results in larger disruption of the sand matrix with dissolution, leaving the remaining sand in a looser state. This is demonstrated most vividly by the 0.5 mm tests where compression continues to exceptionally high axial strains of 20%. Such loose behaviour in silica sands generally requires a loose sample preparation technique such as moist tamping and high cell pressures in the region of 400-700 kPa to place the volumetric state of the sand above the critical state line [Klotz and Coop, 2002], while it was achieved in the dissolution tests at relatively low applied stresses ranging 42-168 kPa.

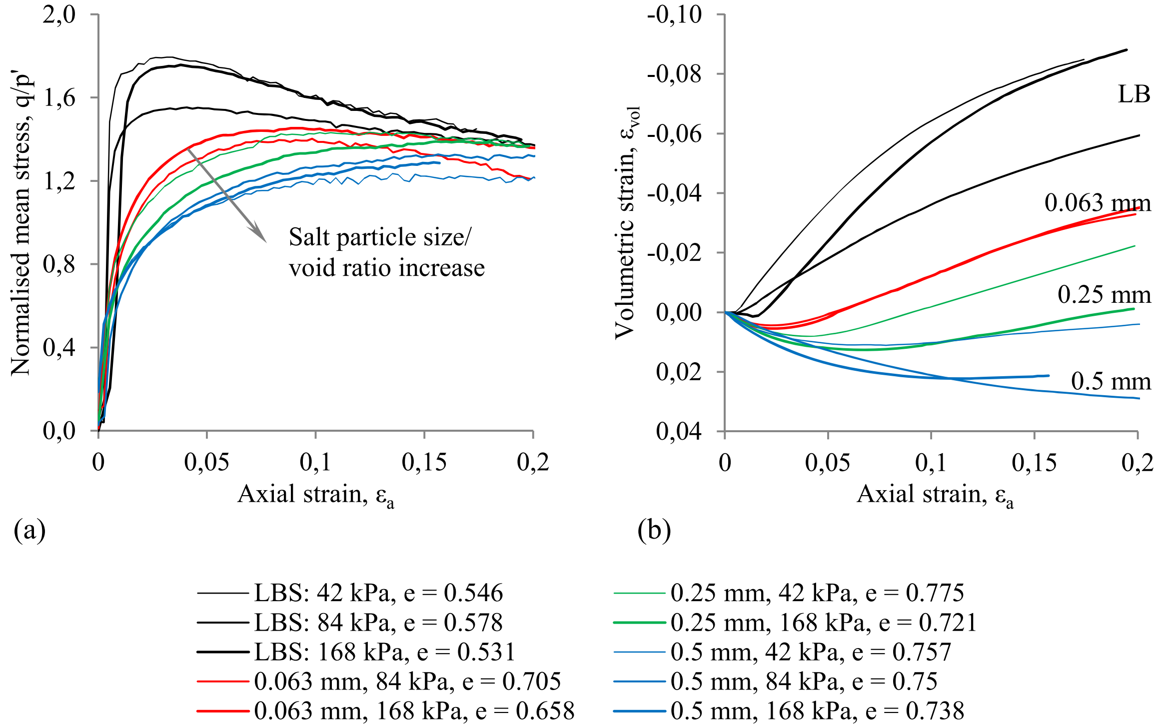

Fig. 4 Shear behaviour of LB reference tests and post-dissolution 15% salt by mass samples, (a) stress ratio vs axial strain (b) volumetric strain vs axial strain.

The shearing behaviour of soil experiencing particle loss consistently show increases in ductility. Erosion tests performed by Chang and Zhang (2011) on Leighton Buzzard sand with decomposed granite fines found a change in peak friction angle, ϕ'_{peak} from 43.4 to 41.1° with removal of fines. Dissolution tests performed by Fam *et al*., (2002) on coarse sand with percentages of salt of 0, 2, 5 and 10% showed increasing contractive behaviour with percentage of salt removed, demonstrated by decreasing ϕ'_{peak} values of 41.2, 39.8, 35.7 and 30.3° respectively. Dissolution tests performed here on various particle sizes of 0.063, 0.25 and 0.5 mm salt at a percentage of 15% demonstrated the influence of particle size on shearing behaviour. LB reference tests had the largest peak friction angles of 37.7 to 43.7°, while post-dissolution 0.063 and 0.25 mm salt particle tests demonstrated peak friction angles of 34.5 to 35.7°. The largest 0.5 mm salt particle tests had the lowest peak friction angles of 30.8 to 32.9° resembling the critical friction angle, ϕ'_{crit}, inherent of the Leighton Buzzard sand.

In each instance of particle loss reported in the research or documented here there was an accompanied increase in void ratio. This void ratio is consistently shown to determine the large-strain shearing behaviour of the soil. It appears that knowledge of the percentage and size of particles removed governs the void ratio and hence the large-strain response. This knowledge in turn can facilitate the determination of allowable limits of the particle size coupled with percentage of loss to prevent excessive losses of strength known to occur in soils susceptible to erosion and degradation processes.

5.4 Shear-wave data

Pre-dissolution shear-wave velocities appear to be related to salt particle size where smaller salt particles at a percentage mass of 15% give consistently higher velocities (fig. 5). Post-dissolution significant decreases in shear-wave velocity are observed with the majority of samples experiencing decreases of approximately 40% velocity, an approximately proportional decrease in terms of percentage removed when compared to the 26% decrease found by Truong *et al*., (2010) in 10% salt tests in an oedometer. However, two exceptions were noted in the 0.5 mm salt tests at 42 and 168 kPa with decreases of 7 and 14% respectively.

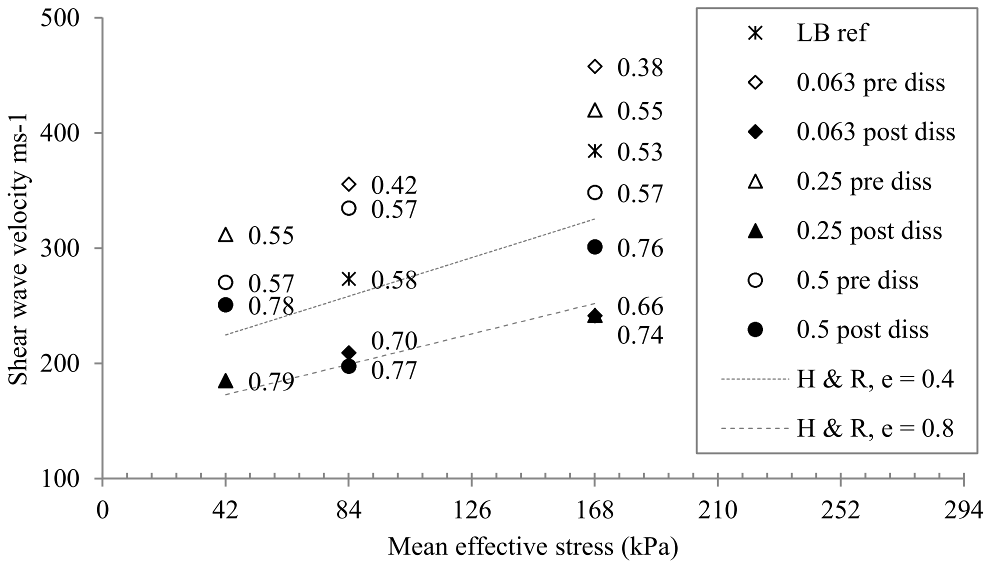

Fig. 5 Shear-wave velocity in pre- and post-dissolution 15% salt by mass samples. Symbol shapes represent the salt particle size with open and solid symbols representing pre- and post-dissolution measurements respectively. Leighton Buzzard reference test measurements are also shown. Void ratios are included alongside shear-wave velocity data points. Dotted and dashed lines represent empirical formulae for shear-wave velocity estimation with void ratios of 0.4 and 0.8 in Ottawa sand (Hardin and Richart (1963)).

Fig. 5 includes line plots based on the empirical formulae of Hardin and Richart (1963) that estimate shear-wave velocity in rotund quartzitic Ottawa sand and here are calculated for void ratios of 0.4 and 0.8. These plots demonstrate the considerable scatter between sand-only samples with respect to void ratio (sand-only refers to Leighton Buzzard reference tests and post-dissolution samples). Fam *et al*., (2002) found that void ratio in post-dissolution samples is a useful indicator of large-strain behaviour but unsuccessfully describes post-dissolution shear-wave velocity. They also cite difficulty relating void ratio to shear-wave velocity in dissolution tests where constant fabric is not maintained, perhaps explaining the spread in the current post-dissolution data.

6 Conclusions

A triaxial apparatus has been successfully modified to allow dissolution tests be performed followed by post-dissolution strength testing. Bender elements incorporated in the triaxial provide seismic wave data allowing the small strain stiffness of the soil be derived at all stages. An accompanying experimental procedure has been developed to enable successful dissolution tests.

Dissolution tests performed show the change in void ratio is influenced by percentage rather than particle size removed. However the salt particle size does affect the initial void ratio of the soil. This is demonstrated most clearly by the 0.063 mm salt particle where they fill the interparticle voids of the coarse sand matrix permitting a void ratio significantly less than the minimum void ratio of the Leighton Buzzard sand. The change in void ratio associated with 15% salt loss results in a medium-dense state while increments in salt particle size, with increasing initial void ratios, results in progressively looser states.

According to soil mechanics the post-dissolution volumetric state should determine the shearing behaviour of the soil and this is demonstrated here. The densely prepared Leighton Buzzard sand behaves as a dilative soil. Each increase in salt particle size at a percentage mass of 15% results in increasingly contractive behaviour, such that the 0.5 mm salt tests result in compressive strains to 20%.

Lastly, 15% salt dissolution resulted in reductions in shear-wave velocity of over 40% with post-dissolution void ratios not correlating well with shear-wave velocity measurements.

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