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Particle crushing and yield of clastic materials

Le broyage de particules et le fléchissement de materieaux clastiques

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ABSTRACT: High pressure one-dimensional compression tests on silica sand samples seeded with marked particles were carried out to examine the relationship between the slope and curvature of the compression line and the statistics of individual particle crushing. Five levels of damage were obtained from observations before and after testing. A statistical analysis was carried out of the variation of damage levels with increasing applied stress. For uniformly graded sand, there was a sudden catastrophic onset of major splitting between the yield stress and the maximum compression index. For well graded sand, there was a slow increase in the breakage of asperities for relatively large particles and major splitting of small particles. As the particle or structure variability increased so the curvature of the compression line decreased.

RÉSUMÉ:On a fait des essais a compression unidimensionelle sur des échantillons de sable silicieux ensemencés avec des particules marqués pour étudier le rapport entre la pente et la courbure de la ligne de compression et les statistiques du concassage des particules individuelles. On a défini cinque niveaux de dégats. La variation des niveaux de dégats avec l'effort a été analysée statistiquement. En ce qui concerne le sable uniforme entre la limite de fléchissement et le point maximume de l'indice de compression on a trouvé que les particules se sont fendus subitement. En ce qui concerne le sable bien calibré on trouvé que pour les particules grands le concassage des asperités a augmenté lentement et les particules petits se sont fendus. Au fur et à mesure que la variabilité soit des particules soit du structure augmentait, la courbure de la ligne de compression a diminué.

1 INTRODUCTION

It has been established in recent years that soil compressibility can be linked to particle crushing. But the relationship between these two factors is neither straightforward nor simple. One dimensional compression tests have therefore been conducted to examine the effects of initial void ratio and grain size distribution on soil crushability and consequently the soils compressibility. De Souza (1958) testing sands at stresses up to 138MPa first defined a yield point beyond which changes in grain size distribution showed substantial particle breakage. Many researchers have gone on to examine this yield point. De Souza (1958) and Hendron (1963) both suggested that the yield stress increased with increasing density. Later researchers such as Hagerty et al. (1993) have examined particle crushing in terms of initial void ratio, particle size, angularity and material composition. Particle crushing can be defined for increasing levels of damage such as grinding of the grain surface, breakage of an asperity and splitting of a particle. However no research to date has examined the relationship between the curvature of the compression line and the crushing of individual particles, and in particular the nature of particle crushing during yielding. A careful investigation of individual particle crushing would reward us with a greater understanding of the susceptibility of sands to crushing and the nature of the compression of granular materials.

Recent work by Nakata et al. (1999b) has related individual particle crushing in triaxial sand samples to the soil particle strength variability using a Weibull function. Using data from one dimensional compression tests on samples seeded with marked particles, this paper describes a continuation of this work by examining further the relationship between the slope and curvature of the compression line and the statistics of individual particle crushing taking into account particle size and overall grading.

Even though this data was obtained from high pressure one dimensional compression tests on silica sand, the findings will improve our understanding of the overall mechanical behaviour of all soils.

2 PARTICLE CRUSHING FOR 1-D COMPRESSION

2.1 *Materials and experimental methods*

One dimensional compression tests were carried out on a pure quartz silica sand with two different particle size distributions, shown in Figure 1, in order to examine the influence of particle size distribution on particle crushing. One was a single size uniformly graded sand with particle sizes between 1.4mm and 1.7mm. The other was a well graded material containing particle sizes from 0.25mm to 2.0mm. The oedometer specimens were 50mm in diameter and 10mm in height and the tests were carried

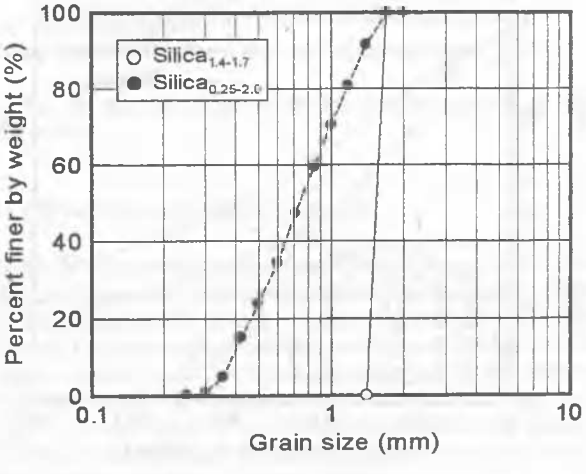


Figure 1 Grain size distribution curves for uniform and well graded sands

out at a constant displacement rate of 0.01mm/min. Twelve dyed particles were seeded in each sample. The digital images of each particle were recorded prior to placing in the oedometer. Following the compression test, the particles were removed and a new digital image recorded (Nakata et al., 1999b). The compression curves can be seen in Figure 2.

Samples were prepared in a dense state to similar void ratios e = 0.6±0.03. Having established the compression curves, a subsequent series of tests was carried out also seeded with dyed particles but these tests were each terminated at the different stress levels indicated by the data points on Figure 2. In these tests, point P corresponded to the yield stress and point A_1 the maximum compression index C_c. Observations of the nature of the crushing of dyed particles were carried out for all these tests apart from the test terminated at point P for the uniform sample.

2.2 *One dimensional compression behaviour*

Examination of Figure 2 shows that the yield stress given by the point of maximum curvature (point P) is larger, at 22 MPa, for the well graded material compared with 14 MPa for the uniform sand and that the maximum curvature was greater for the uniformly graded material. Researchers such as Hagerty et al., (1993) have already indicated that the steeper the curve after yield, the greater the degree of crushing that is occurring.

It can be seen in Figure 3 that following yield the rate of increase of vertical strain for a uniform material is initially greater than that for a well graded sand. There is a break point where the two curves in this figure diverge (Yoshida and Tatsuoka, 1997). It can be observed from Figures 2 and 3 that the value of the break point is the same as the yield stress for the uniform sand. Even for the same material the yielding characteristics are dependent on the grading curve although it can be seen that the gradients equalise and the consolidation curves tend to converge after about 30MPa. The variation of compression index with vertical stress has been plotted on a log-log scale and is shown in Figure 4. There is a marked peak value for C_c on this figure. This represents the increase in slope occurring immediately after yielding. The stress levels at yield and C_{cmax} are different for each sand. In the case of the uniform sand the gradient C_c decreases after the peak and approaches the same value as the well graded sand

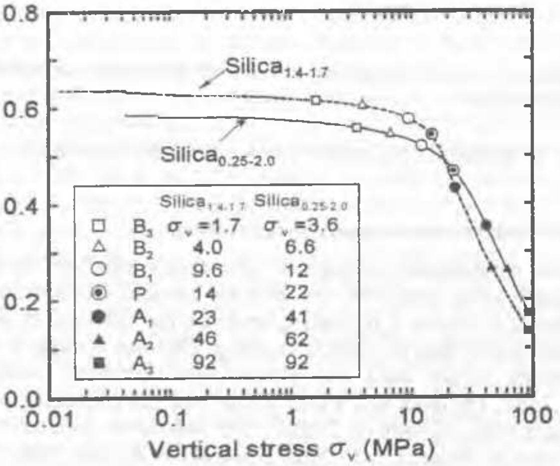


Figure 2 One-dimensional compression curves for uniform and well graded sands

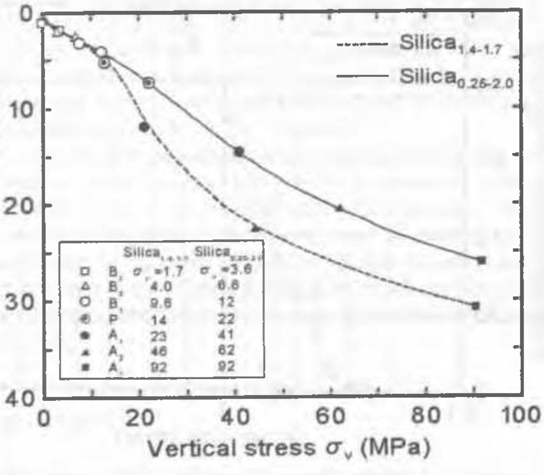


Figure 3 One-dimensional stress-strain curves for uniform and well graded sands

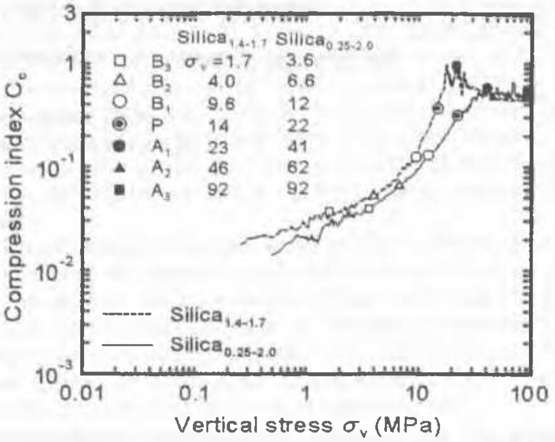


Figure 4 Variations of compression index with vertical stress for uniform and well graded sands

2.3 *Particle crushing for uniformly graded samples*

A number of objective levels of particle damage were defined. Type I damage was defined as no visible damage;. Type II damage as a single abrasion or breakage of an asperity; Type III, as more than one abrasion or asperity fracture. Type IV damage consisted of major splitting of the grains into two or more particles. Finally Type V damage was defined as further breakage of the Type IV sub-particles. In Type IV it was possible to remove all of the fragments of the original particle. But in Type V, it was not possible to completely recover all the sub-particles as any attempt at their removal resulted in fragments crumbling to powder.

A statistical analysis was carried out of the particle crushing data. Each category of particle damage was treated as a class and the frequency was defined as the number of particles in each class. The relative cumulative frequency of each class has been plotted against the vertical stress in Figure 5. The e-log p' consolidation curve has been imposed over the frequency data in this figure. Particle crushing can be seen to initiate after Point B_2 (4.0MPa). At Point B_1 (9.6MPa) approximately 80% of the particles are still undamaged (Type I). However when the yield point was passed at Point A_1 (23MPa) this reduced to less than 10%. Thus more than 90% of the particles had some kind of damage and about 50% of the particles had undergone splitting. After yielding occurred the relative cumulative frequency curves began to level out indicating that the rate of increase of particle crushing slowed down considerably. Major splitting of particles occurred mainly between the yield stress p_y and the point at which the compression index C_c reached a maximum. In the final stages 100% of the coloured particles had undergone some kind of crushing and about 60% had suffered major splitting of the grains. After the vertical stress reached 40MPa, the percentage by weight of the particles retained on the 1.4mm sieve became virtually constant as these large particles were largely protected by sitting in a matrix of smaller grains.

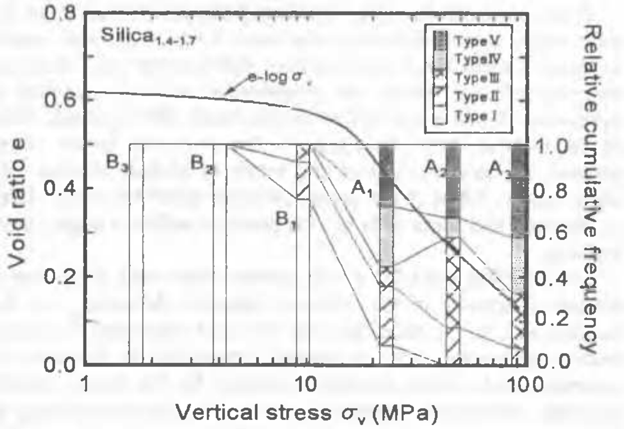


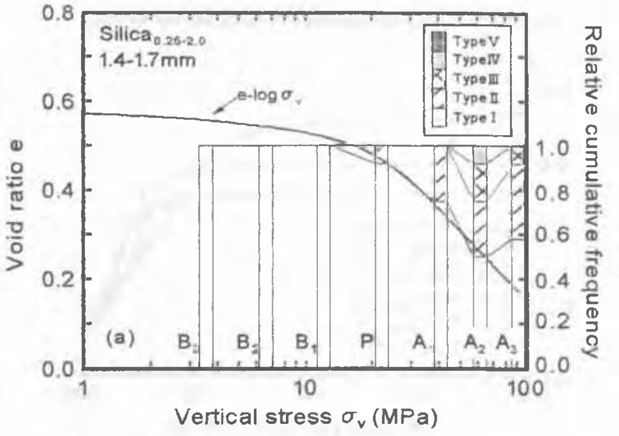
Figure 5 Relative cumulative frequency of damage in uniformly graded sand

2.4 *Particle crushing for well graded samples*

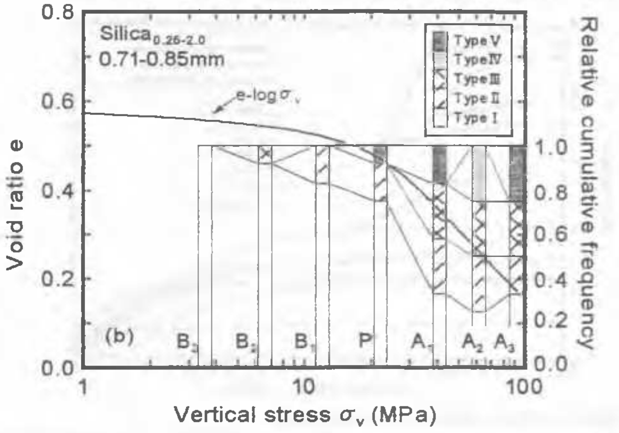
The sizes of the dyed particles which were inserted in this case were 1.4mm-1.7mm, 0.71mm-0.85mm, and 0.3mm-0.355mm and were defined by the sieve sizes used. So for example 1.4mm-1.7mm passed a 1.7mm sieve but was retained on a 1.4mm sieve.

The data in the tables for the largest, 1.4mm-1.7mm, intermediate, 0.71mm-0.85mm, and the smallest 0.3mm-0.355mm particles has been plotted as a relative cumulative frequency plot in Figures 7(a)-(c) respectively. Superimposed on each of these figures is the compression line for the sand. Considering Figure 6(a) for the largest observed particles, a small degree of damage was observed at the yield point but overall it can be seen that the worst damage that occurred was of Type II or Type III, with no splitting of grains occurring. Even at the highest stress levels 50%-60% of the particles remained undamaged. For the intermediate sized particles it can be seen in Figure 6(b) that some Type II damage commenced before the yield stress was reached. As the stress increased from the yield point P at 22MPa to point A_1 at maximum gradient C_c the degree of Type III and V damage increased. After this point the relative cumulative frequency for each degree of damage began to level out and remained almost constant, with approximately 70%-80% of particles undergoing some form of damage and 20% of the particles suffering Type V major splitting. The observed data for the smallest particles is shown in Figure 6(c). As for the intermediate particles, damage commenced before the yield point P was reached and major splitting of grains (Type IV and V) rapidly accelerated between the yield point P and the maximum compression index C_c at A_1. Damage continued to worsen after this point and finally more than 80% of the grains underwent major splitting and 100% of the particles underwent some form of damage.

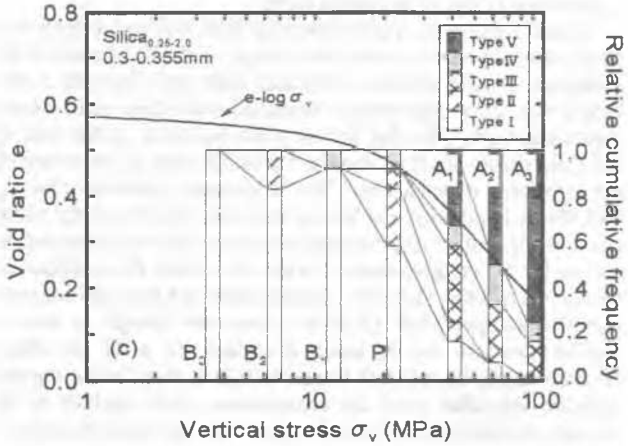
It is interesting to compare these data for well graded soils with that for uniform samples shown in Figure 5. In the case of the well graded sand the co-ordination number of large particles surrounded by large numbers of smaller particles will have been very high and the opposite will have been true for the smallest particles. In this case the tensile splitting stress for the large particles will have been relatively low while on the other hand that of the small particles with a low co-ordination number will have been much higher. So that even though larger particles are statistically weaker (Braddick, 1963, Billam, 1972, Lee, 1992, Nakata et al., 1999b, 1999c) their probability of survival in the matrix is much higher because of their higher co-ordination number. So it can be seen that the large particles, 1.4mm-1.7mm, in the well graded matrix were protected by the smaller particles which underwent splitting as a result of their low co-ordination numbers. Thus in Figure 6 (a) there was little damage to the 1.4mm-1.7mm particles compared to Figure 5 and the high degree of damage was reserved for the smaller particles as seen in Figure 6(c).



(a) 1.4-1.7mm particles



(b) 0.71-0.85mm particles



(c) 0.3-0.355mm particles

Figure 6 Relative cumulative frequency of damage in well graded sand

3 EFFECT OF PARTICLE VARIABILITY

Figure 8 shows compression curves for two types of single size glass particles with nominally identical particle sizes but with different degrees of particle variability. The particles labeled G.B.were spherical glass ballottini while those labeled AG were angular crushed glass sieved to the same size as the ballottini. The curvature in the yield zone for the ground glass with a higher particle variability is much less than that for the ballottini. The two curves merge as the spherical glass beads crush and become identical in texture to the angular glass.

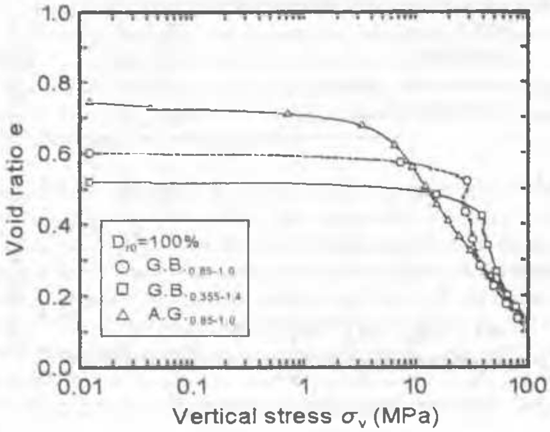


Figure 8 Yield of glass ballottini and angular glass

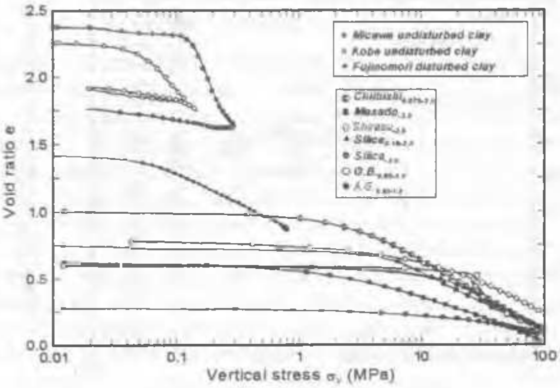


Figure 9 Yield curves for clays and sands

Thus particle variability as well as grading is an important factor in the shape of the compression curve

Figure 9 shows the yield curves for disturbed and undisturbed clays superimposed on those for a range of sands. Masado a decomposed granite, Shirasu a volcanic sand and Chiibishi a carbonate sand have high particle variabilities and their yield curves contrast strongly with that for the glass ballottini. In the case of the yield curves for the clays the variability lies in the nature of the structure of each clay. The Fujinomori disturbed clay (I_p =43.8%) is remoulded and has no structure. Thus the yield curve has a low curvature and becomes co-linear with the compression curves for the variable sands. On the other hand the undisturbed marine clays Kobe (I_p=60%, sample depth 4-4.8m) and Micawa (I_p=70%, sample depth 15-15.8m) clays are thought to have a regular structure due to aging processes. At yield the sharp breakdown of this structure is similar to that seen for the regular ballotini and after yield the compression curve appears to be moving towards those for the disturbed clay and variable sands.

4 CONCLUSIONS

High pressure one dimensional compression tests on silica sand samples seeded with marked particles were carried out in order to examine the relationship between the slope and curvature of the compression line and the statistics of individual particle crushing taking into account particle size and overall grading. Five levels of particle damage were defined and obtained from microscopic observations of the particles before and after testing. A statistical analysis was carried out on the data for the observed levels of damage to investigate their frequency variation with increasing applied stress. It was found that even for the same material the yielding characteristics were dependent on the grading curve with much more marked yielding occurring for uniformly graded sands in comparison with well graded sands. It was also observed that the compression indices equalised and the consolidation curves converged after about 30MPa.

From observations of the coloured particles inserted in an almost single size uniformly graded sand it was found that major splitting of particles occurred mainly between the yield stress p_y and the point at which the compression index C_c reached a maximum. It was observed that for this sand, after yielding, 50% of the particles were damaged. As the sand was further compressed, C_c became constant and levels of particle damage became steady. 100% of the seeded particles underwent some kind of crushing and about 60% of the particles suffered major grain splitting.

On the other hand for a well graded silica sand, there was a distinct difference in the crushing behavior depending on the particle size. In the zone between the yield stress and the maximum compression index, a marked increase in the breaking of asperities and surface grinding occurred for the larger seeded particles. For smaller particles however, the particle crushing in this region was characterised by a clear increase in major particle splitting rather than the breaking of asperities. The increase during yielding of the frequency of splitting of small particles was higher than that for the breaking of asperities on large particles but was slightly lower than that for the splitting of large particles inserted in a uniform material. As the particle size decreased so the frequency of occurrence of higher damage levels increased

As the coefficient of uniformity increased so the curvature of the e-logσ curve in the yield zone decreased. This was related to the nature of the microscopic particle crushing during yielding. As the material became more well graded, the nature of the breakage changed from the sudden catastrophic onset of splitting to the gradual splitting of smaller size particle, breaking of the smaller asperities and grinding of the surface.

Particle variability and soil structure as well as grading is an important factor in the shape of the compression curve, with the curvature in the yield zone decreasing with decreasing particle variability or removal of structure.

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