Laboratory testing issues related to crushable sands

Questions concernant des essais de laboratoire sur les sables écrasables

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ABSTRACT: Working with crushable sands, laboratory test issues arise related to their crushable nature and specific morphology. Complications occur already when determining the minimum and maximum density. The major issue is erosion of the sand during transportation and flow at testing, resulting in an ever increasing maximum density, affecting the definition of relative density, D_r. In addition, as with any other granular material at the initial stages of compression, a crushable sand densifies when interparticle voids decrease; yet when at a relatively low stress level particles also start to crush, their so-called intraparticle voids – typical for sands from bioclastic origin – gain importance. Other issues influencing the crushable sand matrix are: polishing of angular grains into more rounded particles; larger shells sheltering smaller grains; apparent cohesion due to interlocking of the angular particles, creating sandclusters with the appearance of larger particles; etc. During any kind of treatment of the crushable sand samples, attrition of the particles must be addressed with great care and granulometric properties should be closely monitored throughout.

RÉSUMÉ : Pendant les essais de laboratoire sur le sable écrasable, beaucoup de questions se posent liées à sa nature déformable et sa morphologie spécifique. Des complications surviennent déjà lors de la détermination de la densité minimale et maximale. Le problème majeur est l'érosion du sable pendant le transport, ce qui augmente continuellement la densité maximale, et influence la densité relative, D_r. En outre, comme dans autre sols granulaires dans les premières étapes de compression, un sable déformable densifie par diminution des vides interparticulaires; pourtant, à partir d'un niveau de contrainte relativement bas les particules commencent aussi à s'écraser, puis les vides dits intraparticulaires – trait des sables bioclastiques – rendent important. D'autres questions aussi influent la matrice des grains écrasables : le polissage des grains anguleux; grandes coquilles abritant des petits grains de sable; la cohésion apparente par l'emboîtement des particules angulaires, ainsi créant des clusters qui ressemblent à de grosses particules; etc. Pendant tout type de traitement des sables écrasables, l'attrition des particules doit être abordée avec soin et les propriétés granulométriques doivent être surveillés.

KEYWORDS: Crushable sands ; Relative density ; Sieving ; Breakage.

1 INTRODUCTION

At the Ghent University Laboratory of Geotechnics, an on-going research program focuses on the stress-strain behaviour of crushable sands. Several laboratory test issues inherent to the brittle nature and specific morphology of these grains complicate the performing and interpretation of experiments and the deduction of soil mechanical properties. Tests on crushable sands need an appropriate approach that differs from non-crushable, silica sands.

2 PREPARATION OF SAMPLES FOR LABORATORY TESTING

Since tests in soil mechanics laboratories represent geotechnical situations in the field, samples need to be prepared at a relevant density. Usually the minimum and maximum dry density of a sand are determined according to standard methods, and a sample is prepared at the density of interest, and possibly saturated if it is to resemble offshore conditions.

The minimum density in the research on crushable sands is determined following the ASTM D4254. Method A, herein described consists of pouring a mass of sand into a mould with known volume through a funnel. The pouring spout of the funnel has an inside diameter of either 12.7 mm or 25.4 mm, depending on the grain size of the sand. Should the grains be small enough, the small funnel can be used and this will yield the lowest density owing to blocking of the sand and a very slight sand stream. However, for a fine calcareous sand the small funnel gets blocked due to a cohesive arch formed by the angular particles. Jamming can only be avoided by gradually filling the funnel, along with the progression of the sand through the outlet. Therefore, contrary to what is normally the case, lower densities are obtained using the large funnel and pouring sprout.

For determining the maximum density of a crushable sand, the usual Proctor compaction is replaced by a less invasive vibratory table densification process as described in ASTM D4253. In this procedure a known mass and volume of sand is compacted by fixing the mould onto a table that vibrates at a frequency of 50 Hz for 12 minutes. A surcharge of 13.8 kPa keeps the sand grains from segregating. The test is repeated at different peak-to-peak amplitudes between 0.30 and 0.91 mm, where the optimal amplitude is the one where the energy transfer of vibration to compaction is most efficient, providing the maximum density by definition. This procedure only holds true as long as there is no crushing during vibration. Occurrence of crushing was evaluated by comparison of grain size distributions before and after the densification. Instead of having to divide the whole ±3.5 kg of sand into manageable portions to sieve, it was originally assumed that crushing would occur mostly in the top layer; hence a 120 g sample was taken from there. The granulometry then showed no evidence of crushing and the test could therefore be continued at higher

amplitude reusing the tested sand. It was noticed (as shown in Figure 1) that the density increased with higher amplitudes, however for every refill of the mould extra sand was needed, indicating that there had been erosion indeed. This had gone by unnoticed in the sand portion from the top because segregation during vibration had caused the crushed particles to flow downwards in the mould. When the entire ±3.5 kg sand mass was mixed and representative portions of 120 g were taken and sieved, crushing was eventually evidenced (Figure 2).

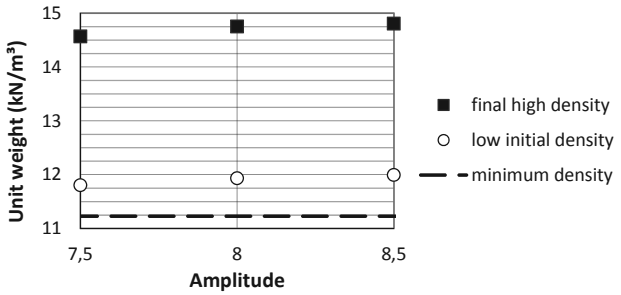

Figure 1. Vibratory table densification of S1-sand: Reusing the same sand causes crushing, which increases both minimum and maximum density. Note: The dimensionless "amplitudes" in this figure simply denote the positions (on a scale of 10) on the rheostat controlling the force of vibration, they are not the actual amplitudes.

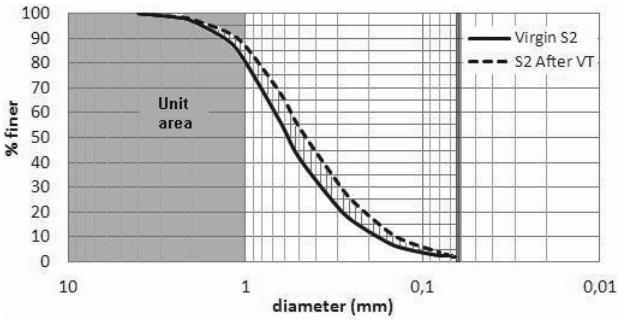

Figure 2. The granulometric distribution of S2-sand before and after vibratory table test at "amplitude" 6.5. Crushing can be quantified by Hardin's relative breakage factor, here $B_r = 0.1$ (see below).

High amplitude shaking causes crushing of the calcareous sand particles, altering the sand and leading to an ever increasing minimum and maximum density, the increase being greater with increasing amplitude. It is important to define single correct lower and upper values of the density in calculations of the relative density since the definition of $D_r = (e_{max}-e)/(e_{max}-e_{min})$ x 100 – a ratio of two small numbers – makes it vulnerable to errors. Moreover, e_{min} should be obtained without crushing since the interpretation of any geotechnical test on crushable sand is accompanied by the degree of crushing during the test, and during the test only; any crushing that occurs during preparation of the sample at a certain density is unwanted.

To some extent however, there is always a change in grain size distribution when handling crushable sands. Youd (1973) offers two determining factors by stating that a test has caused "no crushing" when the increase of particles passing the N°200 sieve (63 µm) is less than 1.5% of the total specimen weight, and the maximum increase of particles passing any sieve is less than 2%.

Still, even when there is no discernible change in grain size distribution, the densification process causes breaking of asperities of the angular sand grains. Particles become more rounded and very small dust particles are released. Both effects leave the granulometric distribution unchanged: the diameter (intermediate dimension) of a polished particle is still as before, and the fines lack substance to appear in the sieve fractions (especially when weighted with the total sample mass) or they get lost due to the electrostatic effect during dry sieving. Yet these small morphological and granulometrical alterations do affect the structure and the packing (Figure 3) – and hence the behaviour of the sand to a considerable degree.

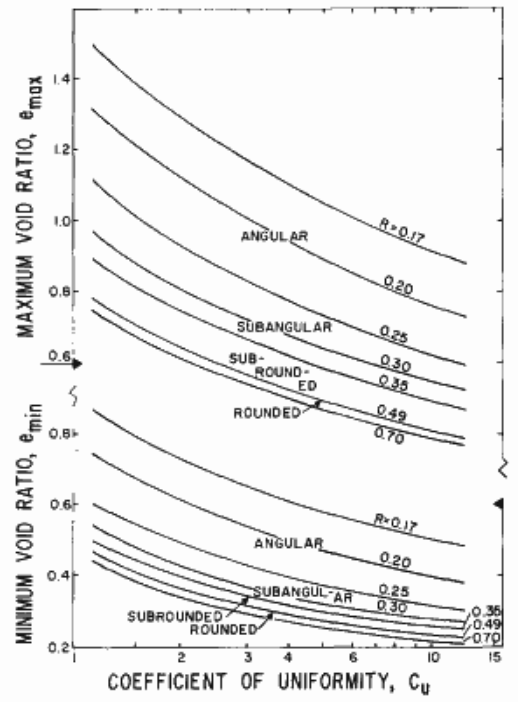

Figure 3. Gradation and particle shape control the possible packing configuration of sand (Youd 1973).

The ASTM D4253 notes that the sides of the mould may be struck a few times using a rubber hammer "to settle the soil so that the surcharge base plate can be easily placed into position and there is no surge of air from the mold when vibration is initiated". Although the amount and intensity of the hammerblows is not specified, a few (e.g. 3) strikes in small-scale densification tests on calcareous sand already prove effective for further densification. The impact of the hammer causes the initially unstable sand structure (with its many "bridges") to collapse into a more stable configuration that allows further settlement by vibration rather easily and without crushing. The standard method to obtain the maximum density of a sand according to the Japanese Geotechnical Society (1992) is based on this idea of densification by shear stress: a ∅40 mm mould is filled with sand in 10 layers. After pouring each layer, the mould is impacted sideways with 100 hammerblows. Some questions remain with this method: the boundaries of the small mould affect the densification process and the obtained maximum density value, and the absence of a top plate enables segregation of the sand grains.

The intent of the formulation of relative density D_r is to evaluate the potential for the assembly of sand particles to form a compressible structure. Yet when the maximum density increases due to crushing, the upper limit in D_r changes. The particular compaction behaviour of crushable sands (being totally different from that of silica sands) might call for a reviewed test method for e_{min}. Most papers disregard this problem of a correct determination of D_r of crushable soils. At best they urge to keep in mind that the real D_r-value can differ from the laboratory one, when using it for engineering purposes. Mostly the problem is avoided by using the natural void ratio e_0 as the primary variable and potential index to compressibility, without relating it to e_{max} and e_{min}. For example Semple (1988,

Figure 4) states that there is continuity of response of bioclastic and silica sands in their consolidation behaviour, with the initial void ratio as the controlling factor that differs only because of the increased grain angularity of the bioclastic soil. Crushing is therefore not perceived as a consequence of the mineralogy, but as a consequence of the higher stress concentrations at fewer interparticle contacts.

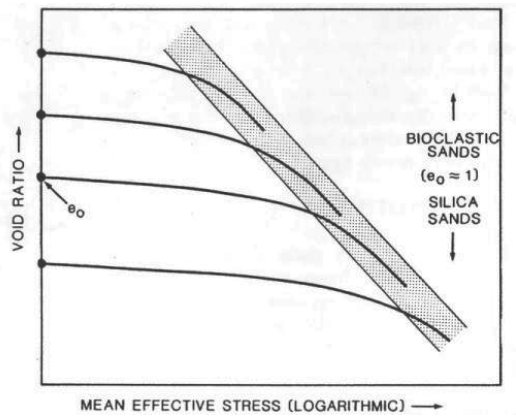

Figure 4. Schematic representation of the generalised compression behaviour of bioclastic and silica sands: virgin compression occurs in a diffuse band (Semple 1988).

In large-scale model testing, calibration chambers are filled with a homogeneous sand mass by pluvial deposition using a hopper and upward moving diffuser sieves. For calcareous sands this method has proved not useful (Nutt 1993), due to the irregularity of the grain shapes and the dependence of the method on a fluent sand rain for a homogeneous density. A small-scale variant of this method is therefore certainly not possible as a means of sample preparation.

Therefore, for the on-going study on crushable sand, homogeneous samples are prepared at the desired void ratio by sideways hammerblows using a small surcharge to avoid segregation. For triaxial specimen – where there are no sidewalls to blow against – satisfying homogeneity is obtained by pouring and tamping the sample in layers in accordance with the undercompaction method introduced by Ladd (1978).

In laboratory testing, not all densities can be obtained for crushable sand samples. A relative density of D_r = 60% seems both practical in the lab and relevant on site after deposition. Higher densities are hard to come by without crushing, lower values result in both structural collapse (obscuring the progression of the test) and irreproducible samples - two sand samples at the same high void ratio can have a different structure.

Especially when saturating the samples with water by means of flushing, a careful approach must assure that the grain structure remains intact. At low stresses this is of particular importance, since at low stress the sand structure is the controlling parameter of its behaviour.

Bioclastic sand samples contain the skeletal remains of marine organisms. Many of these shells are hollow, but in their complete state a high capillarity initially prevents water from penetrating the shells and reaching the enclosed "intraparticle voids". Yet, upon crushing of the particles the voids open up, introducing air in the once saturated sample. For S2-sand, the different specific gravities from pycnometer tests on complete sand grains and on grinded powder ($\rho_{s,grains}$ = 2.82 Mg/m³, $\rho_{s,powder}$ = 2.88 Mg/m³) are indicative of the amount of pores enclosed within the shells (2.4% on average).

Regarding the dimensions of small-scale test set-ups for calcareous sand, it is difficult to follow standard recommended ratios. For example, according to the ASTM D2435 standard for one-dimensional consolidation tests, the minimum initial height of the oedometer specimen shall not be less than ten times the maximum particle diameter. However, due to calcareous particles often being quite elongated, a presieved sample whose particles all passed the sieve with aperture size 4 mm will still contain particles measuring 10 mm and more, as is demonstrated in Figure 5. Although in this case a ∅40 mm mould would satisfy the dimensional requirements that were formulated in the standard, such a mould might influence the calcareous sand matrix beyond what is the case for more rounded sand particles.

Figure 5. Sieved S2-sand particles with D < 4 mm. From placement on millimeter-paper, it is clear that they have dimensions exceeding 4 mm.

3 INTERPRETATION OF LABORATORY TEST DATA

Sieving is an essential part of the research on crushable sands. Every test is accompanied by two sievings: one before and one after the test. From the shift in the granulometric distribution, the degree of crushing that occurred during the test is quantified by means of a certain "breakage factor", aiding the interpretation of the test data.

An alternative to sieving beforehand, is to assemble virgin samples following a preset granulometric distribution. Thus, there is no need to take statistical granulometrical variances into account, as the smallest shift in the grain size distribution will unquestionably indicate crushing. Additionally, when specimens share the same initial granulometry they have identical "breakage potential", defined by Hardin (1985) as the area above the virgin granulometric curve. This renders comparison of Hardin's "total breakage" after the test (the difference between the areas above the curve before and after testing) more straightforward, with Hardin's "relative breakage factor" (the ratio between the total breakage and the breakage potential) reserved for comparing different sands.

Such manual assembly of a sample is however not feasible for larger samples. Moreover, after testing of a large sample, only a small portion can be sieved, lest the sieves get clogged. How and where within the large specimen a representative sample must be taken depends on the interest of the research and the kind of test (e.g. after shearing in a shear box, one might want to sample near the shear plane whereas this wouldn't normally be achievable after a triaxial test; after vibratory table densification of sand, segregation has taken place within the mould, etc.).

After testing S2-sand under loads in the order of 1 – 8 MPa, recovering of the sand from the mould is problematic because of an apparent cementation. The only way to empty the mould without further damaging the sand is by wetting the sample, thus weakening the particle bonds. After drying the sample in the oven at 105°C, the sand mass is covered in a thin cemented crust made of salt crystals, sticking the small particles together (Figure 6a). Before sieving, the agglomerates must therefore be manually broken into separate particles (Figure 6b), otherwise they would create the illusion of larger particles. On the other hand, the impression of crushing would be formed when fine

particles that are initially hidden in larger shells come loose after manipulation.

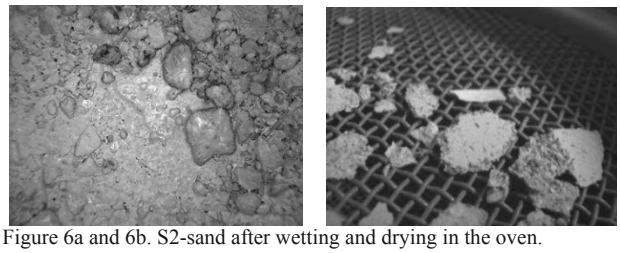

Figure 6a and 6b. S2-sand after wetting and drying in the oven.

Even though crushing is most often evaluated through granulometric distribution of equivalent grain diameters, microscopic analysis of the sand grains is a useful addition to fully quantify the effects of crushing as well as less invasive abrasion and polishing. Microscopy allows for exact measurement of grain dimensions, as opposed to a system of sieves that is based on the assumption that particles are perfectly spherical.

On a sample scale, Scanning Electron Microscopy might be a useful tool for viewing the sand matrix and the intergranular contacts, thus offering more insight in the effective stresses.

4 DEDUCTION OF SOIL MECHANICAL PROPERTIES

Findings from the laboratory tests must finally be translated to geotechnical situations with crushable sand. On site conditions are generally different from the laboratory: The very angular shape of the grains causes an anisotropic behaviour; water and temperature environment will be different; there is the scale effect of the small-scale samples; ageing can cause cementation that is hard to simulate in the lab. Crushing is a time effect and therefore has more time to establish in the field than in the lab. Corresponding to a continuous creep with time, the behaviour of crushable sands also depends on the strain rate (Nutt and Houlsby 1991), i.e. the possibility to form new structures without crushing.

Correlations between geotechnical parameters that are based on in situ experience with non-crushable sands, omit the specific behaviour of crushable materials. As a solution, Wehr (2005) links the differing best-fits between cone resistance and relative density for silica and calcareous sand, through a "shell correction factor" – without however revising the entire correlation.

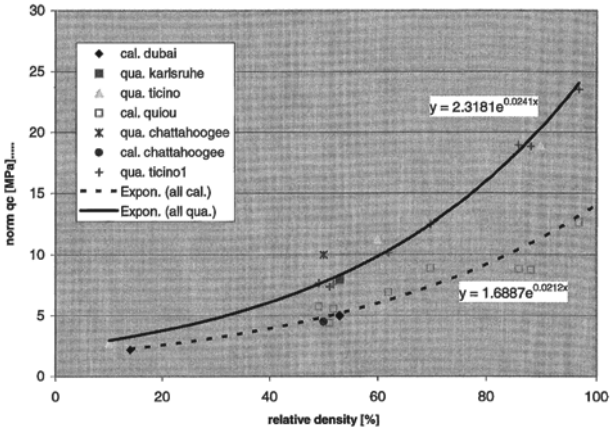

Figure 7. The correlations between relative density and cone resistance for quartz and calcareous sands can be related through a "shell correction factor" that depends on the relative density (Wehr 2005).

5 CONCLUSIONS

Just as research on sand differs from research on clay, crushable sands also need a different approach from non-crushable, cohesionless sands. Sample preparation, test procedure and interpretation need revising to accommodate for the crushability and the angularity of the grains. The phenomenon of crushing, which causes the sand-grains and sand-structure to alter significantly during a test, complicates testing and the used sand should be closely monitored throughout.

Usage of a crushable sand causes grain degradation, which manifests as erosion or breakage, anyhow altering the minimum and maximum density of the sand. Consequently, unlike silica sands, geotechnical parameters of crushable sands cannot be derived through correlations with the calculated "relative density", which is sensitive to errors in the limit density determinations and which has no real meaning for crushable sand. By the same token, crushing cannot be evaluated through sieving alone, a closer look at the grain morphology by means of microscopy is required to fully understand the structure and thus, the behaviour of crushable sands.

6 ACKNOWLEDGEMENTS

The authors acknowledge the Belgian Dredging company DEME, for providing the sands used in this study.

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