INFLUENCE OF GRAIN SIZE AND SHAPE ON THE DRY SAND SHEAR BEHAVIOUR

INFLUENCE DE LA MORPHOLOGIE DES GRAINS SUR LE COMPORTEMENT DES SABLES SECS

J. De Jaeger

Université catholique de Louvain, Louvain-la-Neuve, Belgium
Ecole centrale des arts et métiers (ECAM), Brussels, Belgium

SYNOPSIS : This paper describes an experimental study comparing 144 various sand samples which are pre-sieved to isolate the effects of mineralogy, grain size, uniformity, roundness and sphericity. After a direct determination of the morphometric factors, the results show that the maximum porosity is, for a given uniformity, the best global index of the grain shape. The analysis of comparative direct shear tests is oriented to the main strain-stress-dilatancy curve parameters. The grain morphology mainly influences the strain necessary to obtain the failure, the volume variation and the minimum thickness of the shear band. Each of these values increases with the grain size and angularity which act as a particle bulk.

INTRODUCTION

Particle size and shape influence the packing and the shear strength of granular materials. Their effects are qualitatively known, and the grain morphology is commonly admitted as a first importance parameter. Quantitatively, too few indications are available, particularly about the volume variation and the stress/strain curve before failure.

Excellent previous works by Frederick (1962), Mackey (1963), Zelasko (1966), Koerner (1970) and Dickin (1971) were achieved to quantify the grain shape influence, but comparisons between these studies are delicate because of the various parameters chosen to characterize the grain shape. They all find it difficult to separate the effects of mineralogy, grain size, uniformity, roundness and sphericity.

EXPERIMENTAL STUDY

This paper relates a part of Ph.D. thesis contributing to the knowledge of the grain morphology influence on the behaviour of sand materials. It uses the results of an extensive experimental work based on tests performed to compare the behaviour of 144 dry sand samples, varying by their nature, origin (natural and artificial), grain shape and size, but sieved to obtain the same uniformity ($C_U \approx 1.2$).

After a direct determination of the grain morphologic parameters (size, sphericity, roundness), the porosity limits and the flow velocity through an orifice have been studied as particle shape indicators. The shear strength has been comparatively investigated by direct shear tests starting at various initial densities. Special attention has been devoted to the analysis of the stress/strain curve and of the associated volume variation. The determination of the interparticle friction angle φ_μ has been performed, wich makes the test results interpretation easier. Other indications have been collected about any specific behavioural aspects : crushing, compressibility, sonic wave velocity ...

MORPHOLOGIC PARAMETERS

Grain size distribution is expressed using a multiplicity of parameters according to the disciplines concerned by the granular media. Four main points of view can be considered : the mean dimension (mode, median, ...), the dispersion around this value (uniformity, sorting, ...), the asymmetry of the distribution (skewness, ...), and the departure from a log-normal distribution (kurtosis). Practically, the first and second factors seem to be the most significant. In soil mechanics, they are expressed by the mean diameter d_{50} and uniformity coefficient C_U.

A multiplicity of parameters are also used to characterize the grain shape. They constitute two families.

The first approach is morphometric. It uses individual measurements performed on each grain. This processes is slow, difficult and expensive in order to obtain a statistically suitable number of 3D measurements on very little and irregular particles. However, this impediment decreases now with the use of computer-aided image analysis. Numerous shape parameters have been proposed, leading to confusion and lack of understanding. Three main facets can be observed : the grain silhouette (sphericity,...), their vertex acuity (roundness, ...) and their surface state (texture, ...). In Nature, these morphometric characteristics are correlated, influenced by the same causes, related by the stochastic genesis process. For natural sands, the roundness and the sphericity are concomitant, and the angularity generally increases when grain size decreases. Also for artificial granular media, the manufacturing process is prevaricated, resulting in interdependent shape parameters. Therefore it is difficult, perhaps illusory, to isolate the effects of each morphometric factor on the granular mass behaviour.

The second approach is behavioural. It does not determine the particle shape intrinsically, but it measures an "index" defined by the shape influence on one specific aspect of the granular mass behaviour : maximum porosity, flow velocity, sedimentation velocity, pivotability, ...

This process leads to a fast experimental determination integrating a good statistical signification. When examining the granular mass behaviour as a function of the particle shape, the second approach seems to be more precious. However, one must remember that, as when sorting the grains using a specific procedure (inclined rotating drum, vibrating table, sieve cascade, ...), one particular aspect of the behaviour is favoured.

POROSITY LIMITS

The porosity limits (n_{max} et n_{min}) must be known to appreciate correctly the sand behaviour as a function of its relative density. These limits are parameters only depending on its nature and turned out to be important to characterize the morphology. For identical grain shapes, the porosity limits are independent of the mean grain size. The porosity limits depend fundamentally on the grain shape and the coefficient of uniformity C_U. They decrease along with an increasing sphericity or roundness (Fig. 1.) and with the logarithm of C_U. The effects of the two first shape parameters cannot be isolated. The porosity limits n_{max} and n_{min} seems to be related by a difference equal to 9.4 % (for the test procedure used here), independently of the grain shape. As C_U influence is easily measured, and as n_{max} et n_{min} are correlated, the maximum porosity n_{max} (or the void index e_{max}) becomes a prime global shape index which must be included in each further study.

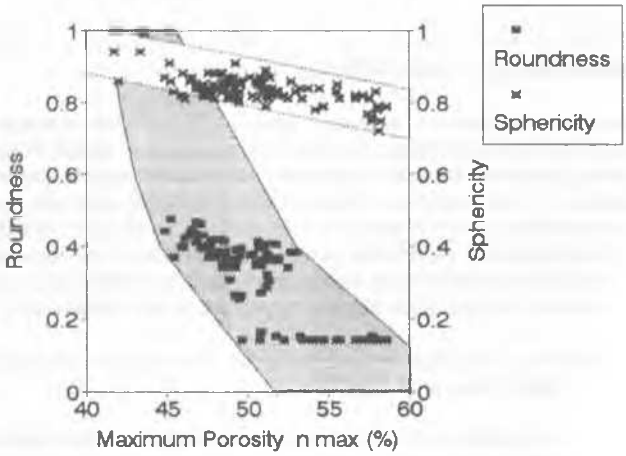

Fig. 1. Maximum porosity n_{max} as a shape indicator

FLOW-TEST

An other angularity index may be found measuring the sand flow velocity through a hopper orifice (De Jaeger, 1989). It is a fast, cheap and accurate comparison test. It is very reproducible with a given hopper, but a strong calibration is required. The flow time does not depend on the height of sand charge nor on its initial relative density. For a uniform granulometry, the flow velocity depends only on the grain size, the orifice diameter, the grain shape and the hopper characteristics. Fundamentally, the flow velocity is strongly controlled by the maximum porosity n_{max} which is a function of C_U and of the grain shape.

SHEAR TESTS

The research described in this paper has confirmed the strong connection between the particle morphology and the volume variation of the sheared sands.

Shear Strength

For a given initial relative density, the shear strength is higher for the angular sands than for the round ones, but this difference weakens when the mean stress level increases. Actually, at low stress levels, one mainly meets rollings with global volume variations ; this process is very sensitive to the moving grain shape and size. On the other hand, a more important stress level favours a granular mass shear with slidings, grain deformation and crushing ; the grain difference influence vanishes.

Along with its impact on the volume variation, the grain morphology influence has also a lower effect on the friction angle (Fig.2). A rise of the grain size d_{50} and/or of their angularity produces an increase of the residual angle of friction φ_{res} (taken as an estimate of φ_{cv}).

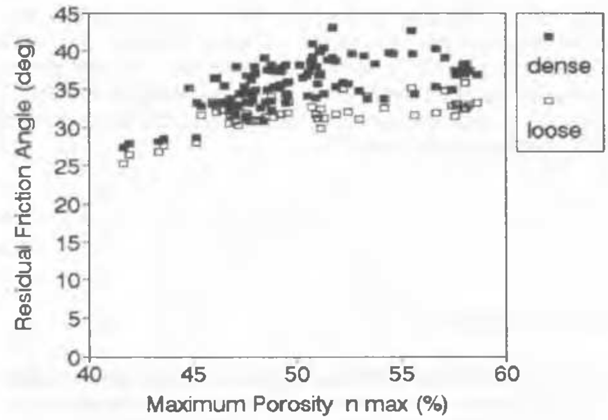

Fig. 2. Residual shear strength related to n_{max} as a shape indicator

Within the limits of this research, we don't find noticeable influence of the mineralogic nature on the angle of internal friction. Grain size and shape are the major factors influencing the rollings because the grain diameter and its shape irregularities are responsible for the grain *bulk* when moving. In this way, the influence is first on the dilatancy and on the failure strain, indirectly on the shear strength. This influence vanishes when the stress level increases because the rollings and the concomitant volume variations are essentially the result of the low mean stresses.

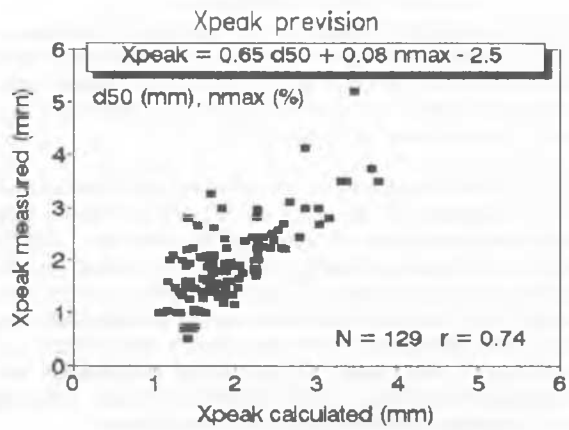

Fig. 3. Relative displacement at failure calculted from d_{50} and n_{max}

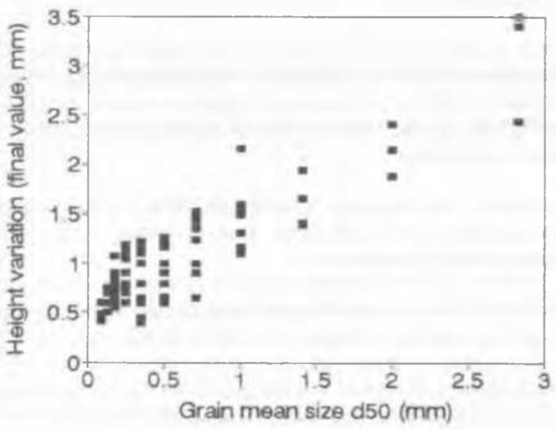

Fig. 4. Final value of the sample height variation ΔH_{rm} versus d_{50}

Shear Band Thickness

The behaviour analysis must consider that the main part of the dilatancy is localized in the shear band around the failure surface. The analysis must be done in terms of thickness variation along a direction which is normal to the failure surface, and might not be expressed using a volume variation calculated as an average on the whole sample.

When assuming that the whole volume variation is concentrated around the failure plane, one can compute the critical void ratio and the minimum thickness which is disturbed by shear (De Jaeger, 1978, 1991). Our experimental results show that the volume variation disturbs a shear band which has a minimal thickness from 5 to 10 mm for a fine sand and to 20 mm for a coarse one. The shear band thickness is a significant factor which is correlated with the strain necessary to obtain the failure. At low stress levels (normal stress equal to 0.1 MPa), our tests have shown that the relative displacement corresponding to the failure x_{peak} (Fig.3) and to the maximum dilatancy x_{Dmax}, the final value of the sample height variation ΔH_{rm} (Fig.4), and the shear band thickness H_f (Fig.5) are parameters varying in the same way. They increase with the particle angularity (the variation being more marked for the finer grains). They increase also with the grain size.

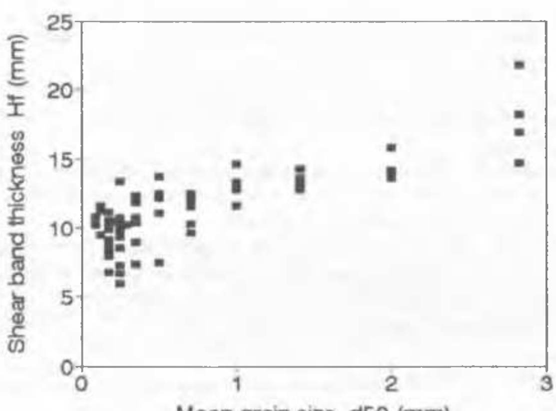

Fig. 5. Minimum shear band thickness H_f versus d_{50}

Stress Level

The total energy consumed to shear the granular media is used to
- produce the dilatancy,
- overcome the friction,
- bend the particles,
- crush the grains.

These partial works are distributed differently according to
- stress level,
- initial relative density,
- interparticle friction angle φ_μ ,
- grain modulus of elasticity,
- their strength,
- their shape and size.

The material favours the failure mode which requires the minimum of total energetic consumption. So, at high mean stress, the grain crushing requires less energy than sliding and rolling when volume increases; at a lower stress level, slidings (and perhaps rollings) are favoured; finally, at very low stresses, failure is achieved by rollings as soon as the interparticle friction exceeds a definite threshold.

For the same initial relative density, the shear strength is more important for the angular sands than for the round ones; this difference decreases when the stress level increases. Indeed, at low stress levels, rollings producing global volume variation are mostly encountered ; this process is very sensitive to the grain shape and size. On the other hand, a more important stress level gives greater place to mutual slidings, particle deformation and crushing, and erases the grain differences.

Therefore, the particle morphology factors are vital at the low stress levels, when the grain rollings dominate the failure process. But the mean stress rise favours interparticle friction influence, then particle strength and deformability; the failure occurs more by sliding, then by grain crushing. Thus, the relative importance of all the influence parameters must be related to the mean stress level; it is a point to remember when comparing sample behaviour. Any further research on the grain morphology influence should pay more attention to the particle rollings at the lowest stress level behaviour.

INTERPARTICLE FRICTION

The angle of interparticle friction has been measured using the Rowe method, replacing the box lower part with a plate of the same material as the grain. At the maximum density, a peak value ($\varphi_{\mu,pic}$) for a very low relative displacement (x_p< 1mm) can be observed. Then, after some lessening, the stress increases slightly again to a final residual value. The test shows no significant volume variation. For the loose samples, the stress increases quickly to obtain a peak value; next it diminishes to an asymptotic residual value. The peak relative displacement is low (< 1mm for the majority of the quartz samples). There is a correlated sample volume decreasing, mainly during the first test phase, which is much more important than for the corresponding box shear tests. The crushed lime sands require a peak relative displacement larger than for the quartz samples, crushed or not. It is true independently of the initial density, but especially at the loose state. For the interparticle friction, the stress-strain curve depends essentially on the mineral nature.

The angle of interparticle friction φ_μ decreases when the normal stress and/or the grain size increase(s). For φ_μ , the effect of the grain shape is not significant.

Many theoretical relations between the interparticle friction φ_μ and the angle of shearing resistance at constant volume (critical state) φ_{cv} were

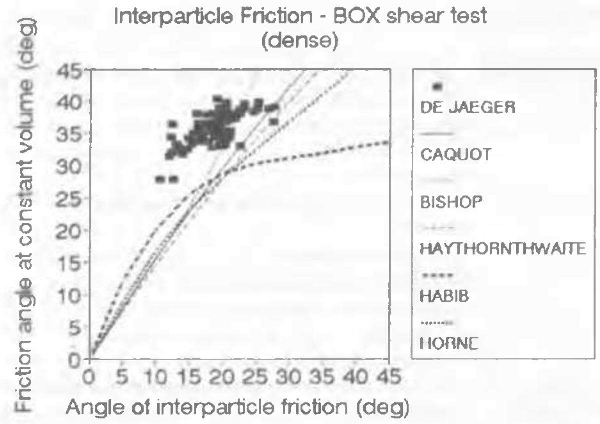

Fig. 6. Angle of shearing resistance at constant volume φ_{cv} versus angle of interparticle friction φ_μ

proposed in the literature (Fig.6). No one could approach the reality, even roughly. The method used to measure the interparticle friction is commonly questioned ; actually, granular media with very different angles of interparticle friction may have the same internal friction. This fact was first expressed by Skinner and Bishop (1969). We carried out their tests once again, and our results fully confirm their experiments and explanations. A correct analysis must abandon any one-to-one relation between φ_μ and φ_{cv} , because the rollings take the place of the slidings when the grains are rough and when the interparticle friction is too high.

The failure consists of slidings, rollings, grain crushing and volume variations. Its process is determined by the sample itself as a function of the grain characteristics, the initial density, the stress level and the boundary conditions in such a way as to minimize the energy consumption. Our analysis shows, quite obviously, that it is impossible to explain the phenomenon, even roughly, using a single univocal growing relation between φ_μ and φ_{cv} ; thus, such relations are incomplete without using other factors.

Effectively, these differences of failure process are essential, but they are generally forgotten when the relations between the parameters are expressed. The relation between the interparticle friction φ_μ and the angle of shearing resistance at constant volume (critical state) φ_{cv} is typical of these incomplete relations.

CRUSHING AND COMPRESSIBILITY

The particle deterioration is already present at relatively low mean stresses; with high stress levels, the crushing phenomenon might become determining and give reduced shear characteristics. Actually, the peak angle of friction decreases when the confining pressure rises, and the dilatancy disappears.

The bulk material compressibility varies globally in the same direction as the grain damaging probability. Along with obvious interference of the grain material deformability, the compressibility increases with

- grain size,
- grain size uniformity,
- grain angularity,
- deviatoric part of the stresses.

On the other hand, a rise of the mean normal stress produces a compressibility decrease but an increase of the particle crushing.

CONCLUSIONS

The grain morphology of dry sands is confirmed as a strong factor influencing the macroscopic behaviour, but it remains difficult to isolate the individual effects of roundness and sphericity which are generally correlated. For a given uniformity, the maximum porosity can be used as a global shape index.

In this research, the emphasis is on the fact that the failure process changes according to the mean stress level, according to the principle of minimum energy consumption.

An experimental study using comparative direct shear tests shows that the particle morphology influence is marked on the strain at failure point, the volume variation and the shear band thickness. These parameters increase with grain size and angularity. As far as behaviour is concerned, angularity and shape irregularity have the role of increasing the dimension and the particle bulk, especially when rolling.

ACKNOWLEDGMENTS

This research was supported by the Civil Engineering Department and carried out in the LGC Labs of the Université catholique de Louvain, Louvain-la-Neuve. The author wishes to thank Professor Lousberg for his interest and criticism. The assistance of J. Lecocq in preparing the manuscript is gratefully acknowledged.

REFERENCES

Bishop, A.W. (1969). Discussion, *Proc. 7th Inter. Conf. on Soil Mech. and Found. Eng.*, Mexico, p.182-186

De Jaeger, J. (1978). Epaisseur de la zone perturbée par le cisaillement, *Colloque International RILEM sur les Matériaux Granulaires*, Budapest 6-12 oct., p.185-196

De Jaeger, J. (1989). Determination of Sand Angularity from a Flow-Test, *Proc. Inter. Conf. on Micromechanics of Granular Media*, Clermont-Ferrand [F], 4-8 september 1989, p.397-404, Ed. Balkema

De Jaeger, J. (1991) Influence de la morphologie des sables sur leur comportement mécanique, *Ph. D. Thesis*, Université catholique de Louvain, Louvain-la-Neuve.

Dickin, E.A. (1971). The Influence of Grain Shape and Size Components of Quartz Grains, *Ph. D. Thesis*, Univ. Liverpool

Frederick, M.R. (1962). The Signifiance of Particle Shape in Sand Behaviour, *Ph. D. Thesis*, University of Birmingham

Koerner, R.M. (1970). Effect of Particle Characteristics on Soil Strength, *Proc. ASCE*, Vol.96, SM 4, Proc. Paper 7393, p.1221-1234

Mackey, R.D. (1963). An Investigation of the Factors Controlling the Shear Strength of Granular Materials, *Ph.D. Thesis*, University of Leeds

Skinner, A.E. (1969). A Note on the Influence of Interparticle Friction on the Shearing Strength of a Random Assembly of Spherical Particles, *Géotechnique*, p.150-157

Zelasko, J.S. (1966). An Investigation of the Influences of Particle Size, Size Gradation and Particle Shape on the Shear Strength and Packing Behaviour of Quartziferous Sands, *Ph. D. Thesis*, Northwestern University, Evanston, Ill.