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Stiffness of a calcareous sand under 1-D compression at medium-high stresses

La rigidité des sables calcaires en compression oedométrique sous contraintes moyen-hautes

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ABSTRACT: Results of an experimental research into the stiffness of calcareous bioclastic sands compressed under oedometric conditions at vertical stresses σ'_v up to 120 MPa are reported in the paper. The volume changes and the deformability of the investigated sands depend to a relevant extent on the crushing process of the sand grains. The stress-strain behaviour is highly non-linear. Three regions in the stiffness E_{ed} vs axial strain ε_a curve may be distinguished; within the first, up to strains of 2%, E_{ed} undergoes substantial decay with strain; within the second, from 2% to 18%, E_{ed} varies negligibly; within the third region E_{ed} dramatically increases with strains. The rebound coefficient k may increase with maximum previously experienced stress up to three times. At high stress the structure and the grain size distribution of the sand profoundly change so to give rise to a material which tends to behave elastically.

RÉSUMÉ: Cet article présente les résultats d'une recherche expérimentale effectuée sur la rigidité des sables calcaires bioclastiques soumis à compression oedométrique jusqu'à contraintes verticales σ'_v de 120 MPa. Les variations de volume et la déformabilité des sables utilisées par la recherche sont dépendent en façon remarquable du procès de broyage des grains. Le comportement contrainte - déformation du sable est fortement non-linéaire. Dans l'évolution du module oedométrique E_{ed} en fonction de la déformation axiale ε_a on peut distinguer trois régions. Dans la première, jusqu'à valeurs de la déformation axiale ε_a du 2%, le module oedométrique E_{ed} substantiellement est décroissant par rapport à ε_a ; dans la deuxième région, dans l'intervalle de déformations $\varepsilon_a=2-18\%$, le module oedométrique E_{ed} est approximativement constant; dans la troisième région E_{ed} il augmente fortement avec la déformation axiale. L'indice de gonflement k augmente avec la maxime contrainte vertical précédemment appliquée aussi jusqu'à valeurs trois fois supérieures. Aux hautes contraintes verticales la composition granulométrique et la structure du sable changent profondément de façon que le comportement du matériel tend à devenir semblable à celui d'un matériel élastique.

1 INTRODUCTION

The stress-strain behaviour of soils is highly non-linear over a wide range of strains, (e.g. Atkinson and Salfors, 1991; Jardine et al., 1984, 1986 and 1999; Pane and Burghignoli, 1988). Experimental research carried out in the last two decades (e.g. Géotechnique, 1997; Jamiolkowski et al. 1999) has shown that the soil stiffness may decrease by several orders of magnitude when strains increase from very small (10^{-3} or less) to large (10^{-2} or 1%) values. The implications of non-linearity for the prediction of soil movements are very important since strains are not uniform within the relevant ground volume (Atkinson, 2000).

For the great majority of geotechnical engineering problems strains fall within the above range (Burland, 1989; Mair, 1993).

However, strains may exceed the above upper limit in some instances such in the case of high earth dams, deep well shafts, under the tips of driven piles and in the case of projectile impacts or explosions (De Beer, 1963; Leung et al., 1996; Yamamuro et al., 1996; Day, 1997). In these cases stresses up to 350 MPa can be reached, involving very high strains.

Stiffness within the range of very large strains has not attracted as yet much research effort. As a matter of fact, the soil stiffness no longer decays at compressive strains larger than about 1%; on the contrary it steadily keeps rising since particles undergo crushing processes and the soil structure modifies thus improving its capability to resist deformation.

In this paper results of an experimental research into the stress and strain dependence of the stiffness of calcareous bioclastic sands compressed under 1-D deformation conditions at medium-high compressive stresses are reported.

2 PROPERTIES OF TESTED SANDS

The testing programme has been carried out on a natural sand recovered from a beach deposit located near Palermo.

The sand is almost entirely composed of small fragments of shells, partly worked out by the action of sea waves.

The sand is shortly termed "shell sand" or SH sand. The particles are from angular to subrounded, frequently concave and elongated. The sand was prolongedly – at least 48 hours – immersed in flowing tap water, to wash away salts from the surface of particles. Particles are essentially calcareous; the calcium content is 90%. The specific weight is 27 kNm^{-3} . The particles are uncemented. Different granulometric fractions were obtained from the natural sand by sieving.

Tests referred to in this paper were carried out on three almost monogranular fractions (a), b), c) and on a mixture (d) made in equal proportion by weight of a), b), and c). The grain size distribution of the sands is indicated in Table 1.

Table 1 – Initial grain size distribution of tested material

Sand	Range of particle diameter d (mm)
a)	$0.30 \leq d \leq 0.42$
b)	$0.42 \leq d \leq 0.60$
c)	$0.60 \leq d \leq 0.84$
d)	a) : 34% Mixture b) : 33% c) : 33%

3 TESTING PROCEDURE

A special oedometer was built capable of withstanding very high stresses. The oedometer is equipped with electrical strain gages, placed on the outer surface (Ziccarelli, 1999). Radial stresses acting on the lateral surface of the sand specimen were backcalculated from the readings of strain gages, through a FEM analysis. The latter was validated by filling the oedometer with mineral oil and subjecting it to known pressures. The diameter and the height of specimens were 73 mm and 20 mm, respectively.

The sand was placed dry in the oedometer in thin layers and then gently tamped. The sand was tested dry.

The initial void ratios vary according to Table 2.

Table 2 – Initial void ratio of tested sands.

Sand	Void ratio e_0
a)	0.56; 0.59; 0.64; 0.71; 0.76
b)	0.68; 0.71; 0.81; 0.88; 0.95
c)	0.77; 0.81; 0.95; 1.08
d)	0.62; 0.77; 0.81

A thin film of polyethylene terephthalate was placed on the inside surface of the oedometer in order to keep friction at a minimum.

The maximum applied vertical stress reached 120 MPa. The vertical load was applied by means of a hydraulic press. The test were run at almost constant rate axial deformation of 0.5 mm/min. The vertical settlement of the sand was measured by conventional millesimal micrometers. This type of measurement does not permit to investigate the very small and the small strain range. Test duration varied from 2 to 4 hours. After testing the specimens were removed from the oedometer and sieved.

Conventional incremental loading tests were also carried out with maximum applied stresses up to 19.5 MPa; the results of these tests are dealt with elsewhere.

4 TYPICAL RESULTS

More than 250 tests have been carried out, (Ziccarelli, 1999). Typical results are shown in figures 1 and 2.

5 GRAIN CRUSHING

Particle crushing starts at low applied stress σ'_v . The evolution of grain size distribution in function of σ'_v is exemplified in Fig. 3. The process of particle crushing is the most important mechanism of deformation and of volume change. The evolution of the grain-size distribution with σ'_v can effectively be portrayed by means of an analytic expression of the Verhulst type, expressing the variation ΔD of characteristic diameters (such as D_{85} , D_{50} , etc.) in function of $\log \sigma'_v$; this expression properly accounts for the existence of an upper limit for ΔD (Valore and Ziccarelli, 2000).

6 EVOLUTION OF STIFFNESS

The stiffness of the sand under one-dimensional – or oedometric – deformation conditions may be conveniently described by the constrained modulus $E_{ed} = d\sigma'_v/d\varepsilon_a$ where σ'_v is the vertical effective stress and ε_a the axial deformation.

The value of E_{ed} during loading depends on the initial grain – size distribution of the sand, on its initial void ratio e_0 , and on the applied effective stress σ'_v , as shown in Fig. 4.

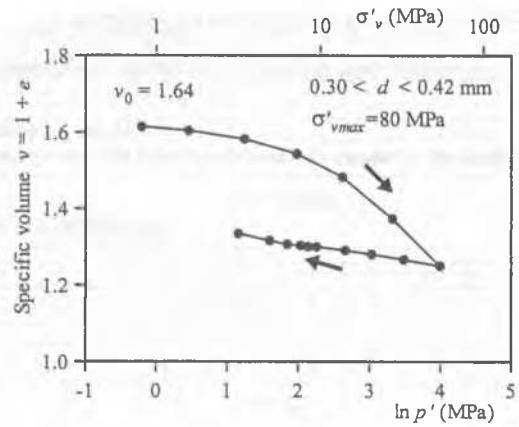


Fig. 1 - SH sand. Typical results of oedometer test with one loading-unloading cycle. v : specific volume; p' : mean effective stress (MPa); σ'_{vmax} : maximum applied vertical stress; d : particle diameter.

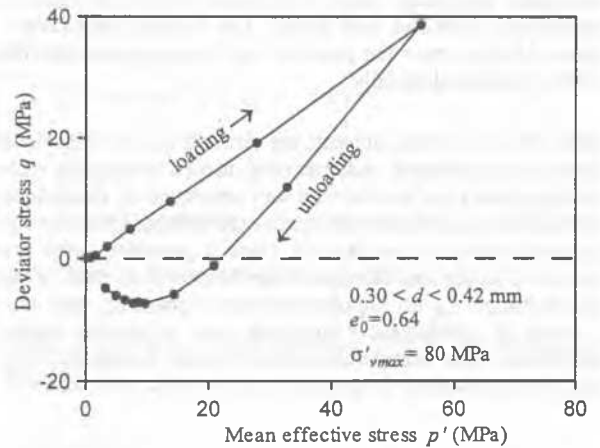


Fig. 2 - SH sand. Typical p' - q diagram. ($p' = (\sigma'_v + 2\sigma'_h)/3$; $q = (\sigma'_v - \sigma'_h)$).

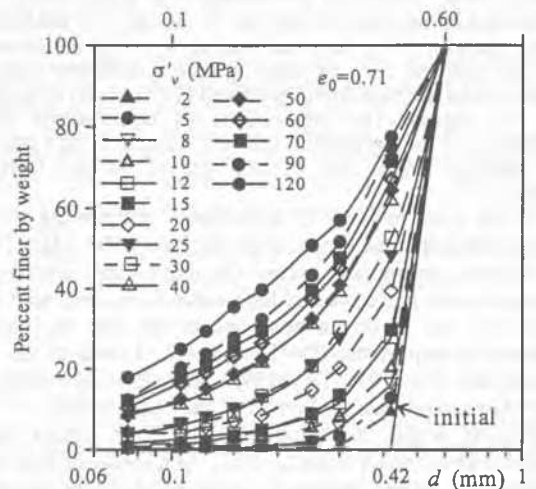


Fig. 3 - SH sands. Evolution under oedometric conditions of grain size distribution in function of the applied vertical stress σ'_v .

The influence on E_{ed} of e_0 and of the initial grading tends to diminish or even to disappear with increasing σ'_v . The relationship between E_{ed} and the axial deformation ε_a are shown in figures 5 a), b), c), d). Three regions can be identified in these diagrams. The first one refers to axial deformations up to about

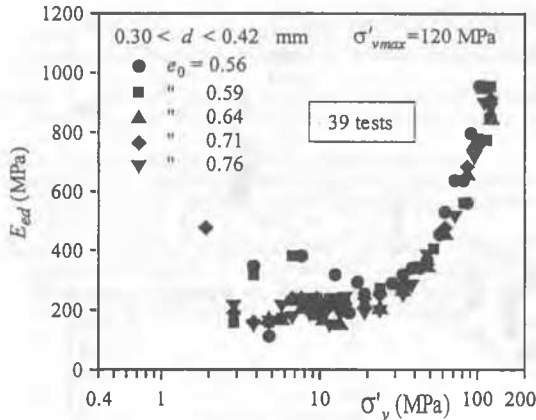


Fig. 4- SH sand. Constrained modulus E_{ed} in function of effective vertical stress σ'_v , for sand with different initial void ratios e_0 , d : particle diameter.

2%. Within this range the stiffness decays; the dispersion of experimental data is rather high as a consequence of the differences in the initial porosity of the sand. This region corresponds to stresses σ'_v up to 3 MPa. The second region extends over the interval of ε_a values from 2% to about 18%, irrespective of both the initial porosity and the initial grading of the sand. Within this region the stiffness displays remarkably small variations, as illustrated in Fig.5. The stiffness is relatively low. This region corresponds to values of σ'_v from 3 to 20 MPa. The third region extends beyond $\varepsilon_a=18\%$; it was investigated up to strains of about 40%, and up to values of σ'_v of 120 MPa. In this region the stiffness strongly increases with ε_a at progressively higher and higher rates.

The dependence of the stiffness on ε_a for different almost monogranular sands a), b), c) and for the mixture d) is remarkably similar, see Fig.6.

This is the general trend. However, it must be emphasised that the rate of E_{ed} increase does not vary steadily everywhere. On the contrary, there are intervals of ε_a over which the sand stiffness greatly increases, followed by intervals where E_{ed} undergoes only modest increases. This is to say that the $E_{ed} - \varepsilon_a$ curve is somewhat "steplike". This behaviour is coupled with the evolution of grain-size composition. It has been shown that characteristic diameters ΔD_{75} , ΔD_{60} , ΔD_{50} , ΔD_{25} , ΔD_{15} , ΔD_{10} varies with σ'_v according to a similar "steplike" pattern (Valore, 1994; Ziccarelli, 1999). It is worth noting that the compressibility index λ increases with applied stress σ'_v up to 25 MPa, while at higher σ'_v values it exhibits a standstill or slowly decreases.

It is possible to distinguish the reversible component of deformation, ε_{ar} , from the irreversible one, ε_{ai} .

The reversible component ε_{ar} starts to increase linearly with σ'_v beyond a total axial deformation of about 2%.

During unloading the relationship between σ'_v and ε_a appears to be fairly linear within the interval ranging from σ'_{vmax} (maximum applied stress during the loading phase) to about 20 MPa.

The rebound coefficient k increases with the maximum previously applied stress σ'_{vmax} ; the increase of k may be as high as 250% (see Fig. 7).

The evolution of stiffness with vertical effective stress depends on diverse factors, of which the most important are grain crushing, the progressive reduction of void ratio and the modification of the sand structure. The change of grain size with σ'_v is conspicuous as illustrated in Fig.3. Although the

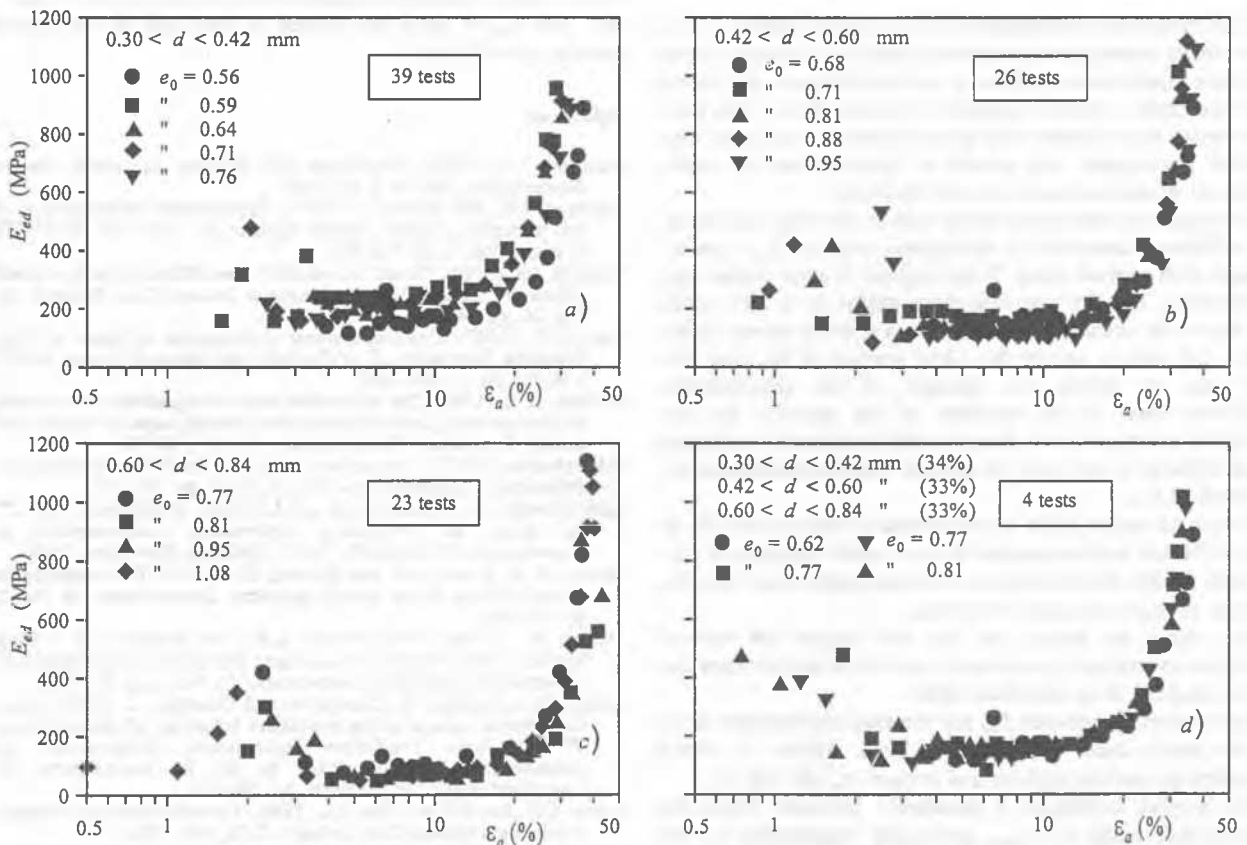


Fig. 5 -SH sand. Loading phase. Constrained modulus E_{ed} in function of axial deformation ε_a for sand with diverse initial grain-size distribution and different initial void ratio e_0 . a), b), c): almost monogranular sands; d):mixture of sands a), b), c). Vertical effective stress range: 1- 120 MPa; d : particle diameter.

coordination number of single grain does not vary appreciably with σ'_v as a consequence of grain crushing, the density of particle contacts (number of particle contacts per unit volume of sand) increases dramatically at medium-high stress.

The material becomes so densely packed that it resembles a sandstone rather than an assemblage of distinct grains. Accordingly, its behaviour tends to approach that of elastic materials, at least at high or very high stresses, both in loading and in unloading.

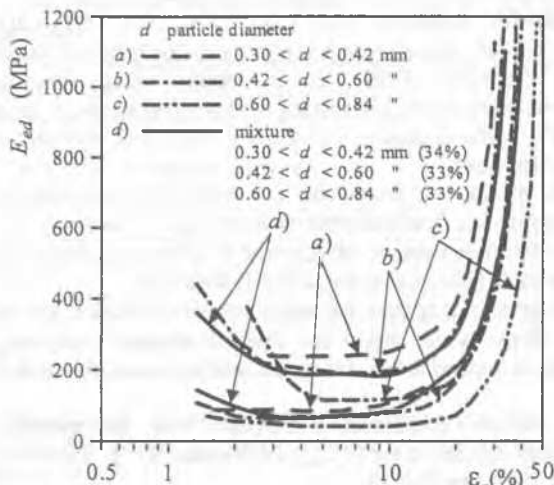


Fig. 6 - SH sand. Loading phase. Comparison of relationships between constrained modulus E_{ed} and axial deformation ϵ_a for different initial gradings of sand.

7 DISCUSSION AND CONCLUSIONS

One-dimensional compression tests have been carried out on three almost monogranular calcareous sands with diverse initial grain-size distributions and on a well-sorted sand. All tested sands are made of minute fragments of marine shells. Tests have been carried out by means of a special oedometer equipped with external strain-gages that permit to backcalculate the radial horizontal stresses acting on the sand specimen.

The stress-strain behaviour of the sand is definitely non-linear. The stiffness – described by constrained modulus E_{ed} – greatly changes with applied stress. Three regions of axial strains may be identified. The first one extends to strains up to 2%; within this region the stiffness is governed to a relevant extent by the initial void ratio e_0 and by the initial grading of the sand. For this range of strains the changes of the granulometric distribution and of the structure of the material are not negligible, nor regular, and thus give rise to noticeable scattering of the stiffness. In any case, the general trend is characterised by the decay of E_{ed} .

The second region refers to the interval of strains from 2% to about 18%, and is characterised by very small variations of the stiffness. Within the third region, at strains higher than 18%, the stiffness strongly increases with strain.

Both within the second and the third region the material undergoes so profound granulometric and structural changes that it loses memory of its antecedent state.

The relationship between E_{ed} and the axial deformation ϵ_a for all the sands under discussion is quite similar or almost coincident at medium-high vertical stresses σ'_v (cfr. Fig. 6).

The rebound coefficient k remarkably increases within the medium-high range of σ'_{vmax} previously experienced by the sand; the increase in k may attain 250 per cent.

The deformation process is markedly dissipative especially for low and medium vertical stresses. At high and very high stresses

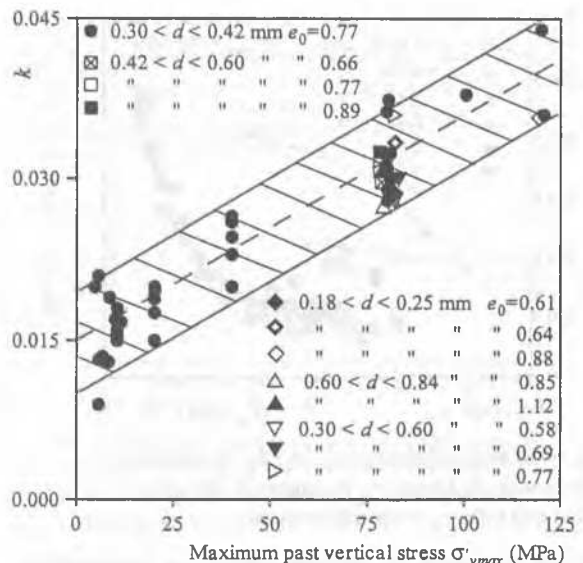


Fig. 7 - Dependence of the rebound coefficient k upon the maximum experienced effective stress σ'_{vmax} for SH sands.

the dissipated energy greatly reduces and the stress-strain behaviour tends to become reversible.

The reversible component of the deformation can be distinguished from the irreversible one. The irreversible component increase with σ'_v , but at decreasing rate; at very high stresses the stress-strain behaviour tends to approach that of elastic materials.

Tests on finer sands sieved out from the same natural sand sample confirm the above findings.

Analogous pattern of behaviour has been found for quartz sand, currently under investigation; in this case the curve E_{ed} vs σ'_v and E_{ed} vs $\log \epsilon_a$ are shifted to the right of the curves pertaining to SH sands.

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