REARRANGEMENT OF GRAINS BY SHEAR TESTS WITH SAND

REAJUSTEMENT DES GRAINS PAR ESSAIS DE CISAILLEMENT EN SABLE

ПЕРЕОРИЕНТАЦИЯ ЧАСТИЦ ПЕСКА ПРИ СДВИГЕ

H. BOROWICKA JUN., Dr. phil., Scientific Assistant, Laboratory for Soil Mechanics, Technical University of Vienna, Austria

SYNOPSIS. Samples of coarse sand were soaked with resin at loose, medium and compact density and plane-sections produced. In this way, number of points of contact and directions of tangent-perpendiculars could be evaluated. In diagrams, frequency of contacts was plotted against the angle of its direction. Additionally the same procedure was carried out for samples subjected to shearing. By comparison, changes in grain structure by shearing became apparant.

1. INTRODUCTION

Structure of grain accumulations was to be investigated within this research work. There are extensive investigations mainly dealing with sphere packings of certain geometric arrangement [1 - 10].

By contrast to those, intended tests were supposed to be carried out with material of natural origin and grain shape at casual arrangement of grains.

The present procedure consists of soaking grain mixture with polyesther resin after conclusion of respective tests. After solidification the sample was cut orientated, planely ground and finally photographed. Enlargements of the photographs of parallel plane-sections enabled determination of the number of points of contact, direction of tangents resp. tangent perpendiculars.

2. INVESTIGATIONS

2.1 SELECTION OF TEST MATERIAL

Different points of view, partly becoming apparant after lengthy series of tests had to be considered for the selection of test material as there are:

a) Sufficient test material
b) Degree of roundness of grain surface
c) Qualification for soaking
d) Grain size with regard to method of evaluation
e) Grain size with regard to laboratory tests using standard equipment.

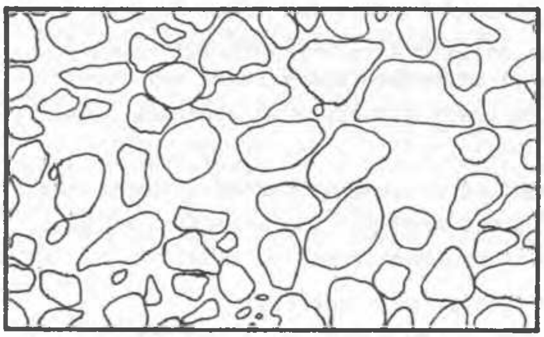
Coarse sand fraction, grain size 1 ÷ 2 mm of a filter material obtained from wet mechanical analysis turned out to be comparatively well suitable for intended investigations. It is a lime- and dolomite-rich quartz sand with specific gravity of 2,66 g / cm^3. The degree of roundness according to RUSSEL-TAYLOR-PETTIJOHN [11] differs from degree "subrounded" to "well rounded" and the average suits the degree "rounded" (original corners softly rounded, large sinus only slightly indicated, small sinus not existing any more at all).

Of great importance, especially for a certain part of tests were comparatively good results of soaking even at normal pressure - i. e. without producing vacuum.

2.2 TESTS

Two series of tests were carried out. By the first series of tests with three samples of loose, medium and compact density, influence of porosity upon grain structure should be investigated. Direct determination of porosity after soaking was impossible. For this reason, porosity was evaluated by parallel tests, on the one hand, and by computing relationship of the area of cut grains to that of the plâne-sections, on the other hand.

a) Loose density n = o,42



b) Compact density n = o,32

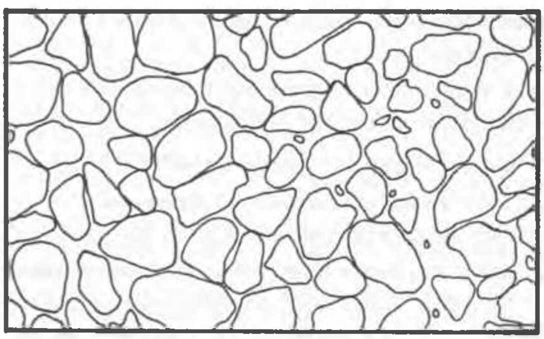


Fig. 1 Cross sections through samples of sand with different densities

Values for the three densities are:

Table 1

density	area porosity		volume porosity	
	n	ε	n	ε
loose	o,42	o,73	o,44	o,79
medium	o,36	o,57	o,37	o,59
compact	o,32	o,47	o,33	o,49

According to the principle of DELESSE area- and volume-porosity are supposed to coincide. As table 1 shows, differences are low and within limits of scattering to be expected.

For the second series of tests, three samples of the same kind were investigated, after they have been subiected to shear-deformation of approximately 6 mm in a direct shear apparatus. The density was subsequently evaluated from the area porosity.

The characteristics of carried out tests are:

Table 2

method of shearing	porosity	shear strain	shear angle
dimension	[n]	[mm]	[°]
a) const. vol.	o,4o	6,2	36
b) const. vol.	o,33	5,7	41
c) const. load	o,34	6,o	47

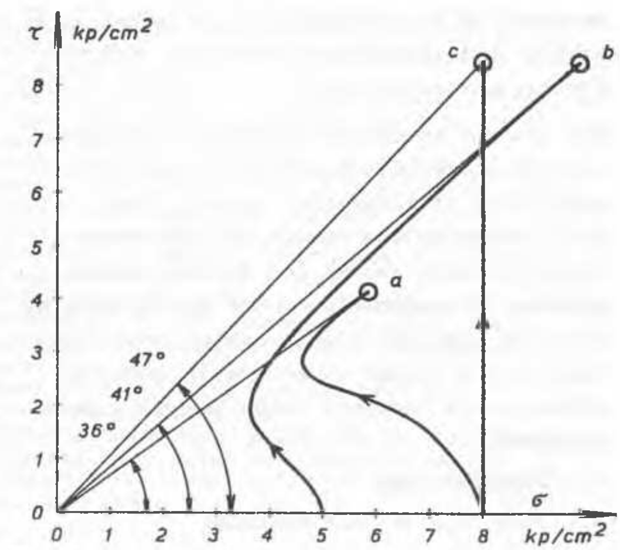


Fig. 2 Direct shear tests

2.3 METHOD OF SOAKING

After numerous series of tests polyesther resin VIAPAL H 24o S turned out to be suitable for the required purposes. The following ingredients were used:

Resin:	VIAPAL H 24o S
Diluting agent:	STYROL
Catalyst:	MEK 5o (5o % methyl-ethyl-ketone solution)
Accelerator:	Co 1 (1 % cobalt-naphthenate solution)
Colour:	Paste 261 (dark black, covering)

Above mentioned test soakings were of decisive influence for the selection of grain-size distribution of test material. Tests were carried out mostly using standard equipment (KREY shear box, compression test apparatus). In order to avoid sources of error - i. e. to preserve the structure of the sample as undisturbed as possible - soaking took place at normal pressure under continuance of stress conditions at the end of the test. Of great importance was to soak the sample thoroughly to avoid rearrangement of grains after solidification of resin. Approximately four days after soaking the load was removed and the sample extracted, cut to pieces and soaked again under vacuum (approx. o,1 kp/cm^2).

Dark black colour had to be added to resin in order to get exact outlines of grains in photographs being necessary for evaluation.

2.4 EVALUATION

In the undisturbed core of the sample, by repetitional grinding and photographing a series of cross sections was produced, the distance of which was about o,1 mm. In each photograph the points of contact and the directions of tangent-perpendiculars were determined and the frequency of contacts plotted against its directions in diagrams of fig. 3 and 4.

Determination of direction of tangent perpendicular resulted from measuring angle to the horizontal within the plane-sections.

Adding to the method of evaluation must be stated, that not the true angle of inclination of the tangent plane, nor the perpendicular could be obtained, but only angles apparent in the plane-sections. There also must be pointed out, that those points of contact could not be determined, whose tangent planes are parallel or almost parallel to the plane-section. Therefore the number of obtained contacts must be considered as a lower limit. But from certain considerations can be derived that the actual number of contacts should not be considerably larger than the obtained amount.

Despite those inaccuracies of evaluation the experiences made until now suggest that this method is well suitable to gain a survey over structure of the examined sand, to obtain preferential directions of tangent planes and compare different test series. Therefore, it was not aim of the investigations to get exact values for the number of contacts and their exact location within the sample - naturally differing within certain limits - but to recognize certain trends only. Trends could already be distinguished after having evaluated 5oo points ana, after 1ooo points, maxima and minima became clearly apparent. Altogether a couple of thousand points were evaluated for every test.

All subsequent diagrams are related to the same area of evaluation, so they can be compared to each another.

3. DENSITY AND NUMBER OF POINTS OF CONTACT

As generally known, limits of porosity for regularily arranged packings of spheres of equal size are o,476 and o,259. The possibly loosest disposition is represented by a cubic symmetry with centers of spheres at the corners of a cube. Each sphere touches six adjacent spheres. If the spheres are placed

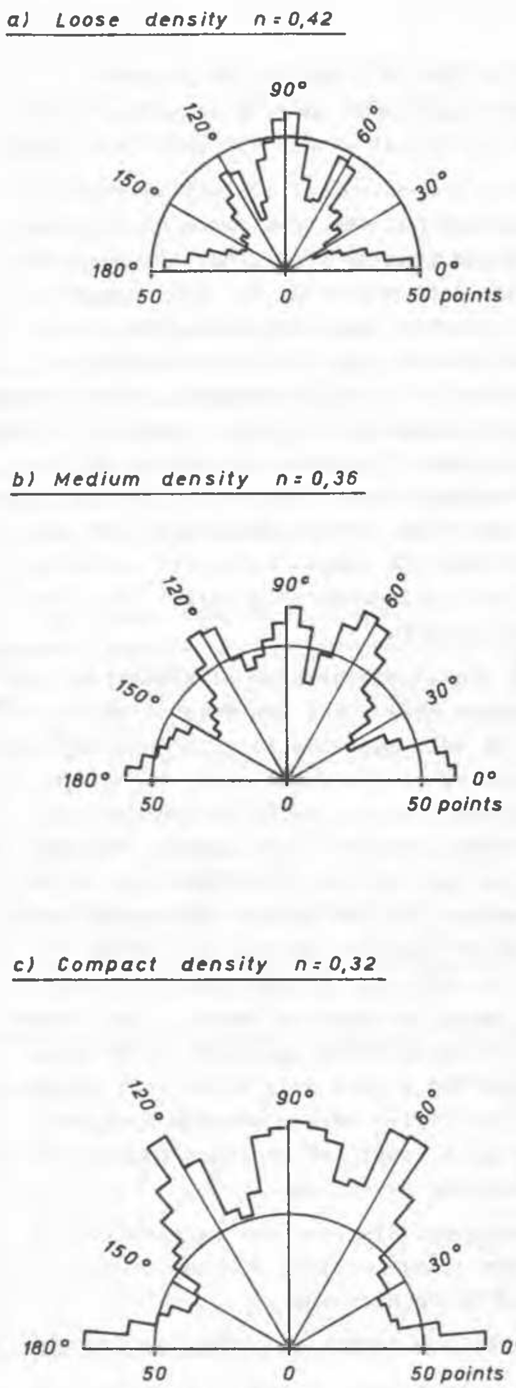


Fig. 3 Frequency – diagram of points of contact before shearing

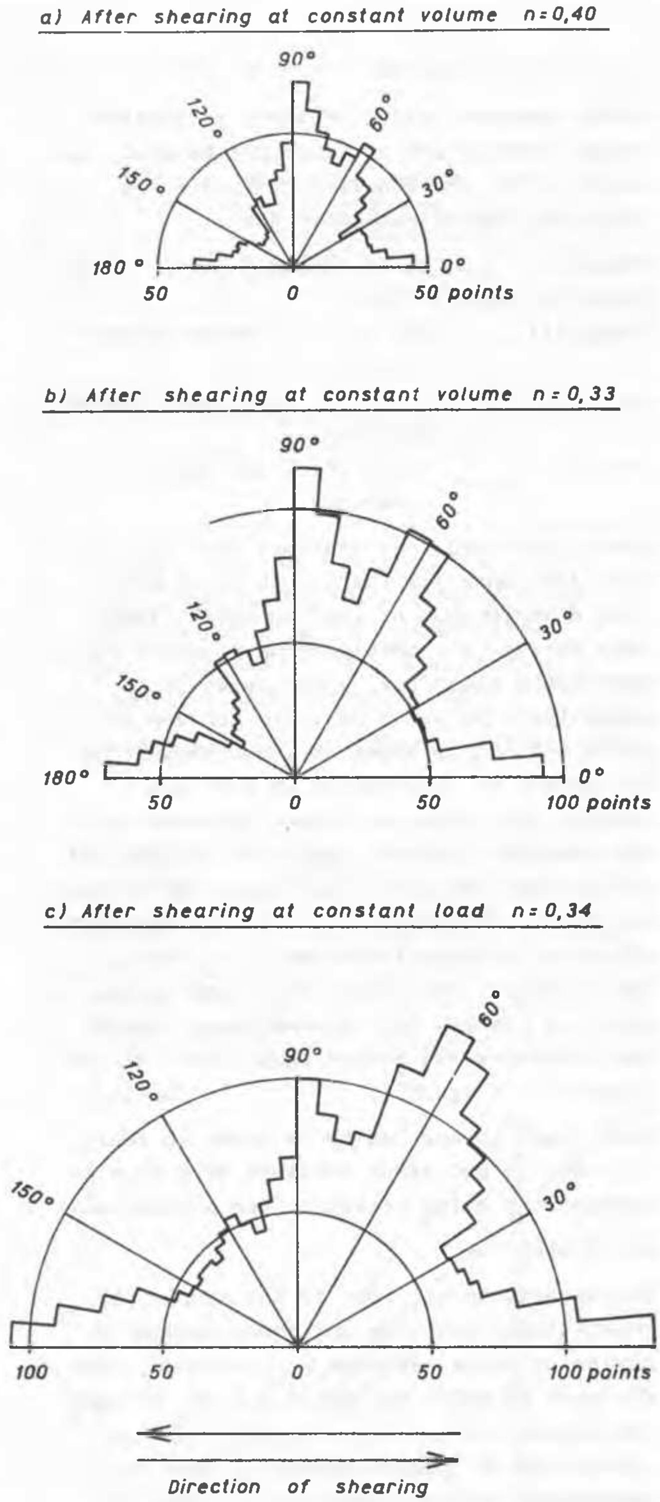


Fig. 4 Frequency – diagram of points of contact after shearing

in horizontal layers, cross sections will show only vertical and horizontal tangent perpendiculars. Highest compaction is obtained with centers of spheres shaping a tetrahedron. In this case, the number of mutual contacts for every sphere is N = 12. Also for this arrangement of spheres, only fixed directions of tangent perpendiculars appear. Between densest and loosest packing of spheres, there are different regular arrangements of spheres with number of contacts between 6 and 12.

There are fundamental differences between natural grain dispositions and geometrically arranged sphere packings. The latter have constant number of contacts and prefixed direction of tangents for every grain in any cross section. By contrast, in natural grain assemblies number of contacts will vary within certain limits and directions will not accur at certain prefixed inclinations.

With regard to the number of points of contact for one single particle of a grain structure following considerations can be made: Three volumetric forces in equilibrium have to pass through one point - therefore, the possibly lowest limit for contacts of a grain in equilibrium will be three. But a grain structure with an average of three points of contact must be considered extremely unstable, because change of loading conditions will cause movements of all grains more or less at the same time. Four points of contact on the average may be adequate for loose density because there still will be some grains with three contacts only that easily will move.

If a particle contacts six adjacent grains, any active resulting force can be induced at three points. The remaining three points can be considered to be supporting points. Therefore, grains with six points of contact mean quite stable bedding.

Under these circumstances movement of grains will not easily occur.

For this reason, grain assemblies up to an average of six contacts per grain should correspond to medium density and more than six in average to compact density.

In order to determine the number of points of contact for tested sand the number of grains per volume had to be calculated. The relation of number of grains for medium to loose density resulted 1,14 and for compact to loose density 1,2o. These values enabled the approximate calculation of the average number of contacts for one single grain: 4,4 contacts for loose, 5,7 for medium and 7,8 for compact density. These results are in suitable agreement to former mentioned considerations.

Generally, the number of points of contact is considerably below that of geometrically arranged sphere packings, for which the number is between 6 and 12.

The fact of fewer contacts with natural grain structures explains its greater compressibility, because individual grains can easier move.

In diagrams fig. 3 the number of evaluated points of contact is plotted from an origin against direction of tangent-perpendiculars, comprising a range of five degrees. According to the diagrams the shape of the frequency curves is qualitatively similar with all three densities. Maxima occur at the same inclination i. e. at o, 6o, 9o, 12o and 18o degrees. These results suggest that main directions are not essentially influenced by method of preparing and treating the sample, nor by the degree of density. Obviously, they are prefixed by geometric conditions like grain shape a.s.o.

Obtained main directions are, to a certain respect, connected with those of loose and compact density of sphere packings. Even if main directions of tangent-perpendiculars are identical with all three densities - certain differences in quantity appear.

The maximum at 9o degrees for loose density predominates, corresponding to spheres arranged in cubic symmetry. However, maxima at 6o and 12o degrees are more pronounced with compact density, as it is the case with sphere packings in hexagonal arrangement.

In photographs of cross sections, the directions of maxima and minima are not obvious by eye-sight. They were recognized by the evaluation. By contrast, differences in porosity of loose and compact density are clearly visible. As it can be seen from fig. 1, there are extensive pores and hollow spaces in loose sand as a main difference to compact sand. These pores are reduced upon an initiated load and are the main cause for greater compressibility of loose sand. Compressibility decreases to the same degree as great pores vanish. Unlike to this behaviour of compressibility and porosity, number of contacts increase clearly furthermore with increasing compaction.

4. REARRANGEMENT OF GRAINS BY SHEARING

Fig. 4 shows diagrams of frequency of points of contacts after imposed shear strain. Existing maximum at an inclination of 12o degrees has disappeared almost completely after shearing, while other maxima, especially the one at 6o degrees increased. The maximum at an inclination of 9o degrees is more or less preserved with constant volume test but it is considerably decreased at constant load test, according to fig. 4 c. Therefore, a rearrangement of contacts takes place during direct shear test in a way, that the number of contacts decreases in zones of smaller shear stress and increases in zones of greater shear stress. Tests shown in fig. 4 suggest that the degree of rearrangement into the directions relevant to shearing is of certain influence upon the magnitude of angle of shear.

However, it is in a certain way surprising that the inclination of maximum of frequency at 6o degrees is constant and does not depenc on angle of shear and density. In most cases, this inclination does not coincide to the plane of greatest shear stress forming an angle of 9o - φ to the horizontal. Therefore, the angle of 6o degrees seems to be prefixed by geometric conditions.

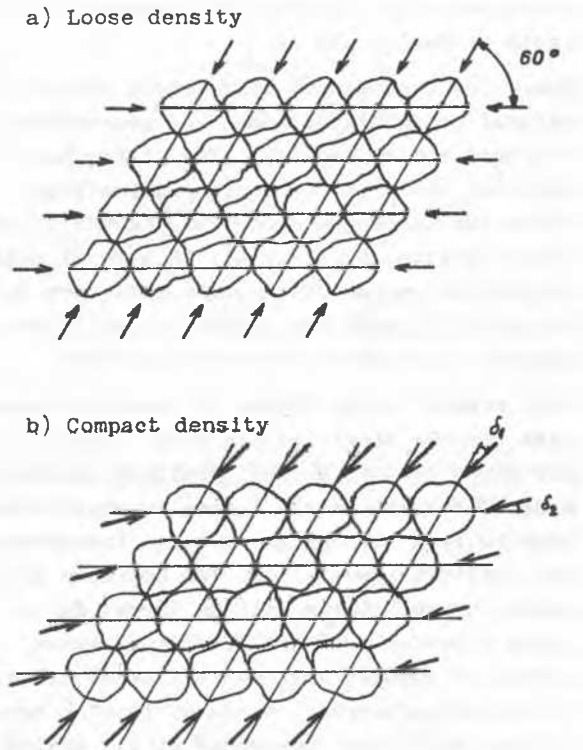


Fig. 5 Border-line cases for transmission of forces

Subsequently,for loose soil with an angle of shear of 3o degrees, main shear directions are equal to directions of maxima of contacts. For this reason, it is conceivable that shear forces in the shear plane are transmitted only by normal forces at the points of contact with loose soils, no friction occuring at all. A theoretic border-line case for such a trans-

mission of forces is shown in fig. 5 a. Therefore, shearing in loose sand does not occur by failure of the shearing resistance, but it is a kinetic procedure resulting from too great mobility of single grains caused by too few points of contact.
However, according to results shown in fig. 4, shearing of compacted soil is finally due to failure of friction at contact points. Shear forces in the shear plane cannot be transmitted by normal forces only. Frictional forces must occur at points of contact as soon as the angle of shear is exceeding 30 degrees. If friction reaches its critical point with increasing shear force, loosening and, as a consequence, failure results. A theoretic border-line case for transmission of forces at failure of compacted soil shows fig. 5 b.
In fig. 5 b different angles of friction δ_1 and δ_2 are indicated because test results in fig. 4 b and c suggest that these angles cannot be equal at failure.

Summarizing test results, shear failure in compact sand occur by overcoming of the frictional resistance at points of contact. Therefore, greater shear strength of compacted soil than that of loose soil may be attributed to a certain interlocking effect of the grains, not present in loose soils due to a too great mobility of grains.

5. REFERENCES

[1] WITTKE, W.: Über die Scherfestigkeit rolliger Erdstoffe. Rechnerische und experimentelle Untersuchungen von Kugelschüttungen.-
Veröffentl.Inst.Boden- u.Felsmech.T.H. Fridericiana Karlsruhe, H.11, 5-141, 58 Abb., 7 Taf., 23 Lit., Karlsruhe 1962

[2] FAROUKI, O.T. & WINTERKORN, H.F.: Mechanical Properties of Granular Systems.-
Res.Rep.Dep.Civ.Engng., 1-72, 19 Fig., 17 Tab., 1o5 Lit., Princeton 1964

[3] HERBST, T.F.: Shear Phenomena in Granular Random Packings.-
Ph.D.Thesis, 144 S., 65 Fig., 12 Tab., 2 App., 72 Lit., Princeton University 1964

[4] LEUSSINK, H. & WITTKE, W. & WESELOH, K.: Unterschiede im Scherverhalten rolliger Erdstoffe und Kugelschüttungen im Dreiaxial- und Biaxialversuch.-
Veröffentl.Inst.Boden- u.Felsmech.T.H. Fridericiana Karlsruhe, H.21, 1-7o, 28 Abb., 7 Taf., 16 Lit., Karlsruhe 1966

[5] MOGAMI, T.: On the Deformation of Granular Material.-
Reprint Journ.Jap.Soc.Civ. Engs., 39-44, 11 Fig., 2 Phot., 3 Lit., Tokyo 1966

[6] MOGAMI, T & IMAI, G.: On the Failure of Granular Material.-
Soil and Found.. 7, No. 3, 1-19, 13 Fig., 2 Tab., 5 Lit., Tokyo 1967

[7] RAJU, V.S.: Ruhedruck und eindimensionale Zusammendrückung von Kugelpackungen.-
Veröffentl.Inst. Boden- u.Felsmech.T.H. Fridericiana Karlsruhe, H.29, 1-112, 33 Abb., 4 Tab., 46 Lit., Karlsruhe 1967 a

[8] RAJU, V.S.: Über das Verhalten von regelmäßigen Kugelpackungen im eindimensionalen Verformungszustand.-
Veröffentl.Inst. Boden-.u.Felsmech. Univ. Karlsruhe, H.31, 9-29, 11 Abb. 11 Lit., Karlsruhe 1967 b

[9] WESELOH, K.: Scherverhalten regelmäßiger Kugelpackungen.-
Veröffentl.Inst.Boden- u.Felsmech.Univ. Karlsruhe, H.31, 61-88, 14 Abb., 1o Lit., Karlsruhe 1967

[1o] WESELOH, K.: Untersuchungen über Stabilitäts- und Spannungsverformungseigenschaften beim Abscheren regelmäßiger Kugelpackungen im Biaxialversuch.-
Veröffentl.Inst. Boden- u.Felsmech.Univ. Karlsruhe, H.34, 1-1o1, 78 Abb., 7 Taf., 28 Lit., Karlsruhe 1968

[11] MÜLLER, G.: Sediment - Petrologie. Teil I: Methoden der Sedimentuntersuchungen.-
1. Aufl., 3o3 S , 91 Abb., 31 Tab., 2 Taf., Stuttgart (Schweizerbart) 1964