Fabric Symmetry and Mechanical Anisotropy in Natural Soils

BY

D. LAFEBER, D.Sc.
(Assistant Chief, Division of Applied Geomechanics, C.S.I.R.O.)

AND

D. R. WILLOUGHBY, B.Sc.
(Experimental Officer, Division of Applied Geomechanics, C.S.I.R.O.)

SUMMARY.- Current opinion in soil mechanics considers mechanical anisotropy of natural soils as being primarily due to gravitational compaction and consolidation, and practically ignores all other patterns of anisotropy. This type of anisotropy ('cross-anisotropy') is characterized by a vertical n-fold axis of symmetry (n = m), and, consequently, a horizontal plane of isotropy. The present paper accepts the process of natural compaction and consolidation, but emphasizes that this process may be preceded by one or other depositional process possessing only a single vertical plane of symmetry. This single plane contains the usually near-horizontal transport direction of the depositional process involved, and is indicative of a much lower order of symmetry, namely monoclinal symmetry.

Fabric analyses and mechanical (triaxial) testing have been performed on several dozens of oriented undisturbed specimens of two commonly occurring soils (a recent beach sand, and a residual silty clay of uniform composition). The results of these studies indicate that both soils lack a vertical n-fold axis of symmetry (n = m) in their original, pre-testing geometrical fabric. They exhibit only a single vertical plane of symmetry, i.e. monoclinal symmetry, as a result of the geological process involved. It is further demonstrated that a vertical n-fold axis of symmetry (n = m) is absent in the two soils as far as such mechanical properties as the secant modulus are concerned. It is finally shown that the presently hypothetical symmetry elements of the secant modulus distribution pattern can be related in a simple and logical manner to those of the original, pre-testing geometrical fabric, and these in turn to the major terrain features such as the direction of the coastline, or the orientation of the terrain slope.

On the basis of these results it is suggested that current ideas on the frequency of occurrence of cross-anisotropy in natural soils need to be reviewed.

I.- INTRODUCTION

The need for a systematic study of the relationships between natural soil fabric or structure and soil mechanical properties has already been foreshadowed in Terzaghi's classical 'Erdbaumechanik' (Ref. 1). One of the major obstacles, however, in the development of a real engineering soil fabric analysis has been the fact that, particularly in soil mechanics, it has not been fully appreciated that many natural depositional processes are characterized by a directed, horizontal movement or transportation component. In nearly all anisotropy studies carried out by soils engineers, e.g. Bishop (Ref.2), and many others, the view has been adopted that soil anisotropy is primarily due to gravitationally controlled consolidation and compaction, and consequently characterized by the presence of a horizontal plane of isotropy and a vertical n-fold axis of symmetry (n = m).

In the present paper fabric and mechanical properties of undisturbed samples of two common types of soil will be described and their mutual relationship discussed. The two soils, although of Australian origin, have been chosen in such manner that they are comparable or similar to soils that are of common occurrence in many other parts of the world. It will be shown that in the two soils a horizontal plane of isotropy (or a vertical n-fold axis of symmetry, n = m) is absent as far as the fabric or the mechanical properties are concerned.

The fabric analysis techniques referred to in this paper are those developed by the senior author and his co-workers (Lafeber, Ref. 3, 4 and 5; Willoughby, Ref. 6; Walsh and Hollingsworth, Ref. 7; Willoughby and Walsh, Ref. 8). The mechanical testing techniques used are standard procedures, except where mentioned otherwise in the text.

II.-SOIL FABRIC CHARACTERISTICS

The first of the soils selected for this study is a recent beach sand from near Portsea, Victoria. The second soil is a red-coloured, Fe-rich, silty clay soil (krasnozem) from near Silvan, Victoria.

In contrast to common practice in many soil mechanics fabric studies, the relevant fabric or structural criterion in the present paper will not be the clay platelet or domain arrangement in the soil. The reasons for this approach are twofold:

(a) The beach sand does not contain any clay size-fraction at all.

(b) The major fabric characteristics of a natural soil are not necessarily or even generally expressed in the clay fabric only (Ref. 3, 5, 9, 10, 11 and 12), but also are usually
reflected in the arrangement patterns of the other major soil components. Often they can be determined more conveniently in the latter.

For the beach sand, therefore, the preferred orientation of the skeleton grains is the only 'micro' criterion that can be used to define the fabric (Ref. 5 and 13). In the krasnozem soil, although there is a small percentage of the clay material showing preferred orientation (associated with the planar pore pattern), the three-dimensional arrangement of the planar pores (Ref. 5) will be used as a criterion to define the fabric.

(a) Fabric Criteria of Portsea Beach Sand

The particular material is a fine to medium-grained, rather well-sorted beach sand with an average grain diameter of approximately 0.5 mm (Fig. 1). The major constituent is quartz with smaller amounts of rock fragments, a few well-worn shell fragments, and possibly a very minor quantity of other organic material (Fig. 2). The majority of grains is subangular to subrounded, and in thin-sections a substantial percentage of elongated grain cross-sections can be observed.

In undisturbed vertical cross-sections through the deposit a distinct bedding can usually be seen, dipping seaward at an angle of about 5 degrees. Closer inspection indicates that relatively small differences in average grain size, and possibly also small variations in the amount of darker coloured grains are responsible for the bedding (Fig. 3). A number of vertically and horizontally oriented thin-sections has been prepared from undisturbed specimens with known orientation (one series of sections vertical and parallel to the coastline, another series vertical but perpendicular to the coastline, and the third series horizontal). In each of these thin-sections the orientation of the long axes of elongated grain cross-sections has been measured for several hundreds of grains. The results are shown in Fig. 4, and indicate a distinct, preferred orientation of the long axes in all three instances. The simplest interpretation of the diagram is that in the particular beach sand a substantial number of more or less platy grains, i.e. grains in which the two longest of the three geometrical axes are of approximately the same magnitude, are oriented in such manner that one of these long axes is parallel to the coastline, whereas the other dips landward at an angle of approximately 10 degrees. In other words, these grains show a very distinct imbrication. In other samples, however, a preferred grain orientation corresponding to the bedding plane has also been observed.

In conclusion, it can be stated that the major fabric characteristics of the particular beach sand are the bedding plane and the plane of imbrication. These two plane surfaces are oriented in such way that their intersection line is horizontal and parallel to the coastline. Since it cannot be assumed a priori that the two planes are of identical significance in regard to the mechanical behaviour of the undisturbed sand, the fabric pattern must be considered as having only one plane of symmetry, namely a vertical plane perpendicular to the coastline. This single symmetry plane, that also contains the transport direction in the depositional phase (Ref. 14, 15, and 16) is the characteristic feature of a monoclinal fabric.

It should be pointed out and emphasized at this stage, that the determination of the critical fabric
features in many instances may not require the application of sophisticated research techniques, but can be based on an evaluation of purely geological factors instead (Ref. 13). In the present instance this would be only the bedding and the orientation of the coastline, where the strike of the bedding would be parallel to the coastline. In addition, the dip of the bedding is parallel to the transportation direction and to the vertical symmetry plane. Very obviously, this common type of beach deposit does not show a vertical n-fold axis of symmetry (n = 4) in its geometrical or morphological fabric, nor a horizontal plane of isotropy.

(b) Fabric Criteria of Silvan Krasnozem Silty Clay

The krasnozem silty clay is a partly saturated, red-coloured soil with 10-20 per cent (by volume) of silt-sized skeleton grains (Fig. 1), largely consisting of quartz, and a non-swelling member of the chlorite-group as the major clay mineral. The particular soil is associated with and possibly derived from a moderately acid to intermediate volcanic rock (dacite), and occurs mostly in deep, rather homogeneous and uniform profiles, frequently in rolling to hilly country. This is also the case at the particular sampling site near Silvan, Victoria, where the terrain slope strikes N 28° E with a northwesterly dip of 5 degrees (both determined by theodolite measurement).

Planar pore analysis techniques (Ref. 3) have been applied to three oriented (fabric-wise) undisturbed samples of the soil collected at the particular site. The results, amounting to a total of nearly 700 planar pore poles, have been combined in the compound fabric diagram shown in Fig. 5. It will be seen in this figure that the position and distribution of the maxima and of the areas of high pole density are clearly asymmetrical in regard to the primitive circle (Ref. 17). There is a very distinct indication of a 'girdle-like' arrangement along the margin of the projection area, but the width of this girdle is substantially less in the north-western quadrant of the projection area than in the south-eastern quadrant. This characteristic suggests immediately:

(i) the girdle axis is not vertical, but tilted, and

(ii) the girdle shows a close geometrical relationship with the actual terrain slope at the sampling site.

The simplest and most logical assumption then is that the girdle axis is located in the vertical symmetry plane of the local terrain configuration, i.e. the vertical plane perpendicular to the strike of the terrain slope. This plane also contains the transportation direction associated with local hill creep.

The appropriate outer boundary of the 'best-fitting' girdle has been indicated in Fig. 5, and appears to be characterized by an axis tilting 5 degrees 'backwards' or 'uphill' (G in Fig. 5), and making, therefore, an angle of approximately 10 degrees with the pole of the terrain slope (D in Fig. 5). The figure demonstrates clearly that the bulk of the maxima and of the areas of high pole density is contained within the annular zone between the boundary curve and the primitive circle. Expressed in quantitative terms in regard to the original pole diagram, it appears that the girdle annulus contains 55.4 per cent of all the poles in the diagram, whereas for a uniform dis-
III.-MECHANICAL ANISOTROPY

The initial purpose of the present investigation was to study the geometry of the deformation patterns and failure phenomena in the two previously mentioned types of soil. In view of this purpose, the triaxial testing arrangement has been chosen deliberately because of the 'high' initial symmetry, consisting of:

(i) a n-fold axis of symmetry \( (n = \pi) \) coinciding with the axis of the cylindrical test specimen and with the axis of loading in the triaxial testing machine, and

(ii) a plane of symmetry perpendicular to this axis.

Provided the soil is isotropic or 'cross-anisotropic' with the plane of isotropy parallel to the symmetry plane of the triaxial arrangement, the deformation patterns, the failure phenomena, and also the strength and elastic modulus patterns would be expected to show the same 'high' symmetry as the triaxial test itself.

If, however, the soil is neither isotropic nor 'cross-anisotropic', one or more of all these properties would be expected to show only those symmetry elements that are common to the triaxial testing arrangement and the soil. In the case of the two types of soil, discussed here, this would be only the single (vertical) monoclinic symmetry plane. It will be shown that this condition is indeed characteristic for the two soils examined.

(a) Sampling, Sample Preparation, and Testing Procedures

In view of the original purpose of the investigation the sampling technique and sample preparation have been rather different for the two types of soil. The main problems relating to the loose, non-indurated beach sand are: to obtain undisturbed, oriented samples of the appropriate size and shape, and to place these in the undisturbed state in the triaxial apparatus, and to recover the loaded and eventually failed specimens from the apparatus in such a manner that the least possible disturbance occurs, and the specimens or parts of them can be studied more closely by means of thin-sections, etc.

These problems have been solved satisfactorily by developing a special technique (Ref. 8) that can be briefly described as field sampling in the fully saturated state, i.e., close to the waterline, followed by a two-stage total replacement of the original seawater in the specimens by polyethylene glycol ('Carbowax 4000'). The triaxial testing of the specimens is performed while, as a result of heating, the polyethylene glycol is completely melted. After completion of the testing procedure, the polyethylene glycol is allowed to solidify before the specimens are taken out of the testing apparatus. The same sampling and preparation techniques have been used for vertically and horizontally oriented samples. It may finally be noted that all triaxial tests on the beach sand samples have been carried out as 'drained' tests and with standard ceramic endplates.

For the sampling of the krasnozem clay specimens, two different techniques have been used:

(i) all vertical specimens have been obtained by means of a three-inch auger core sampler, and
(ii) all horizontal specimens have been cut and shaped manually from oriented block samples. Furthermore, the krasnozem specimens have been tested at field moisture content, and under 'undisturbed' conditions. In a number of instances, low-friction, highly polished brass endplates have been used. In all other cases, however, these have been replaced by (high-friction) standard ceramic endplates.

(b) Test Results of Portsea Beach Sand

In the triaxial testing of the Portsea beach sand varying numbers, i.e. three or more, of specimens in each of a number of orientation groups have been used. One group consists of vertical cylindrical specimens, where the azimuth of the seaward direction has been marked on each individual specimen. Other groups consist of horizontal, cylindrical specimens enclosing angles of 0°, 30°, 60° and 90° respectively with the coastline, and where, in addition, the position of the bedding plane in each of the specimens is also known.

The most striking observations resulting from these tests are the following:

(i) the different but persistent failure patterns in the vertically oriented and in the horizontally oriented specimens,
(ii) the characteristic appearance of the stress-strain curves referring to all the tests on vertically and horizontally oriented specimens (unpublished data), and
(iii) the statistically significant differences in the magnitude of selected mechanical properties between vertically and horizontally oriented specimens.

In the present paper only the first and the last aspects will be discussed more thoroughly.

It appears now that almost all specimens show persistently* two inclined, intersecting, and practically plane failure surfaces. There are two specimens where there is only one plane failure surface, corresponding to either the one or the other failure plane in the other specimens. The difference between the vertical and horizontal cylinders, however, is due to the striking fact that these failure surfaces show consistently a completely different orientation with regard to the bedding and imbrication planes (Fig. 6). It will be noted that the orientation of the bedding and the imbrication planes is necessarily a horizontal straight line parallel to the coastline. In the group of horizontal cylinders perpendicular to the coastline the intersection of the two failure planes coincides with the intersection of the bedding and the imbrication planes, i.e. both lines of intersection are horizontal and parallel to the coastline. On the other hand, in the vertical cylinders and in the horizontal cylinders parallel to the coastline the intersection of the two failure planes is horizontal but perpendicular to the coastline. In all three instances, however, the presence of a single vertical symmetry plane, perpendicular to the coastline, is obvious. In other words, the deformation or failure pattern of the particular sand in the undisturbed or natural condition is also characterized by a monoclinic symmetry, corresponding with the identical symmetry of the pre-failure geometrical fabric features.

The features just discussed are shown in stereographic projection in Fig. 7. In the diagram representing the vertical cylinders the intersection of the two failure planes is represented by the vertical diameter of the primitive circle, and the intersection of the bedding and the imbrication planes, as well as the coastline, are represented by the horizontal diameter. The same arrangement will be observed in the diagram representing the horizontal cylinders parallel to the coastline. In the diagram representing the horizontal cylinders perpendicular to the coastline the two intersections and the coastline are coincident and represented by the horizontal diameter. Obviously the trace of the (vertical) symmetry plane is in all three instances given by the vertical circle diameter.

From the stress-strain data supplied by triaxial loading tests on vertical and horizontal cylinders the secant modulus has been determined in the conventional manner (Ref. 19). The mean secant moduli and their standard deviations for the five orientation groups are as follows.

1. Vertical cylinders; mean = 5.54 x 10^2 kg cm^-2, standard deviation = ± 0.28 x 10^2 kg cm^-2.
2. Horizontal cylinders, parallel with coastline; mean = 4.10 x 10^2 kg cm^-2, standard deviation = ± 0.24 x 10^2 kg cm^-2.
3. Horizontal cylinders, 30° with coastline; mean = 3.95 x 10^2 kg cm^-2, standard deviation = ± 0.18 x 10^2 kg cm^-2.
4. Horizontal cylinders, 60° with coastline; mean = 3.84 x 10^2 kg cm^-2.

---

* It should be noted that to obtain this persistency in behaviour, a very careful sampling technique and a near-perfect polyethylene-glycol impregnation are required.
on the particular soil have been performed with a standard type triaxial machine. Since there was some doubt initially about the possible influence of the type of endplates on strength and on deformation patterns, about half of the tests on vertical cylinders have been carried out with standard ('high-friction') ceramic endplates. The others were tested using highly polished ('low-friction') brass endplates that were lubricated and covered with a thin rubber membrane. The differences of the mean strengths and of the mean secant moduli, using 'high-friction' as compared with 'low-friction' endplates are clearly statistically insignificant at the 5 per cent confidence level. Consequently, as far as strength or secant modulus is concerned, the type of endplates used seems to be irrelevant.

A similar irrelevance of the types of endplates, used in testing, is suggested by the deformation patterns of loaded krasnozem cylinders of various orientations, shown in Figs. 8, 9, 10 and 11. It will be noted that the discontinuity or planar pore patterns in the four specimens are basically the same, irrespective of their orientation and the types of endplates used. All four specimens show a major 'horizontal' discontinuity perpendicular to the major axis of the cylinder, and dividing this axis into approximately equal parts. This major discontinuity, in a number of instances, approaches a plane surface; in other cases (Fig. 11) it may be somewhat curved. In addition to this major feature, other less evident discontinuities parallel to the edges of the cylinders may be present. The development of one or two intersecting failure planes inclined to the axis of the cylinder, like the Portsea beach sand, has not been observed to occur in the particular Silvan krasnozem silty clay. The discontinuity patterns demonstrated in Figs. 8 to 11 (inclusive) or observed in any other of the triaxially tested specimens of the particular soil do not show any clear evidence of a monoclinic symmetry. It could possibly be argued that, in this particular instance, the discontinuity patterns seem to reflect the 'higher' symmetry of the triaxial test itself. As there are no radial strain measurements available for the tested specimens, there is presently no evidence either to support or to invalidate the hypothesis of monoclinic symmetry of the deformation process available from the discontinuity patterns. The results of the corresponding secant modulus determinations to be discussed later, however, do support the hypothesis of monoclinic symmetry of the mechanical properties of the particular soil.

Apart from mutual differences in deviator stress, the stress-strain curves of the triaxially tested undisturbed krasnozem specimens do not show any unusual features (Fig. 12): the curves commence approximately linear with varying steepness, and, onwards from about 5 to 10 per cent axial strain tend to run horizontally or nearly so.

The stress-strain curves shown in Fig. 12 suggest in themselves differences in mechanical properties, e.g., peak strength, secant modulus, for the three orientation groups. Such differences, however, could possibly also result from significant differences in void ratio and/or moisture content in the original test specimens. To examine this possibility, data on both void ratio and moisture content have been arranged according to the three orientation groups with the following results.

\[ \text{standard deviation} = \pm 0.23 \times 10^2 \text{ kg cm}^{-2} \]

5. Horizontal cylinders, perpendicular to coastline; mean = 3.62 \times 10^2 \text{ kg cm}^{-2}.

\[ \text{standard deviation} = \pm 0.54 \times 10^2 \text{ kg cm}^{-2} \]

It has been stated elsewhere (Ref. 13) that:

(i) the mean secant modulus for the vertical cylinders is statistically significantly different at the 5 per cent confidence level from those for the horizontal cylinders.

(ii) the simplest 'best-fitting' curve to represent the data on the directional variation of the modulus in the horizontal plane is not a circle but an ellipse, where the major ellipse axis is parallel to the coastline, and the minor ellipse axis is parallel to the symmetry plane of the pre-testing geometrical fabric.

In other words, as far as the secant modulus is concerned the Portsea beach sand does not possess a horizontal plane of isotropy. Furthermore, the symmetry of the secant modulus distribution in the horizontal plane shows a logical and very simple relationship with the monoclinic symmetry of the original geometrical fabric pattern.

(c) Test Results of Silvan Krasnozem Silty Clay

In the triaxial loading tests on the Silvan krasnozem silty clay varying numbers (three or more) of specimens in each of three orientation groups have been used. The three orientation groups comprise one set of oriented, vertical cylinders, one set of oriented, horizontal cylinders where the major cylinder axis runs north-south, and, finally, one set of oriented, horizontal cylinders with the major cylinder axis running east-west.

As mentioned earlier, all triaxial loading tests
Fig. 8.- Stereopair of photographs of a transparent model showing the discontinuity pattern in a triaxially loaded vertical cylinder of Silvan krasnozem siltys clay. Low-friction endplates, 20% axial strain. The original dimensions of the cylinder are 75 x 150 mm.

Fig. 9.- Stereopair of photographs of a transparent model showing the discontinuity pattern in a triaxially loaded vertical cylinder of Silvan krasnozem siltys clay. High-friction (standard) endplates, 20% axial strain. The original dimensions of the cylinder are 75 x 150 mm.

Void Ratio:
1. Vertical cylinders:
   mean = 1.21, standard deviation = ± 0.029.
2. Horizontal NS-cylinders:
   mean = 1.30, standard deviation = ± 0.068.
3. Horizontal EW-cylinders:
   mean = 1.41, standard deviation = ± 0.050.

Moisture Content:
1. Vertical cylinders:
   mean = 38.8%, standard deviation = 0.70%.
2. Horizontal NS-cylinders:
   mean = 38.0%, standard deviation = ± 3.25%.
3. Horizontal EW-cylinders:
   mean = 39.7%, standard deviation = ± 2.94%.

Formal analysis of variance indicates that, for both void ratio and moisture content, the between-sample and within-sample variances for the three groups of specimens do not differ significantly at the 5 percent confidence level. All samples can be considered to have been drawn from the same population. If, however, the secant modulus is determined from the test data, the results are as follows.

Secant Modulus:
1. Vertical cylinders:
   mean = 0.97 x 10^2 kg cm^{-2},
   standard deviation = ± 0.25 x 10^2 kg cm^{-2}.
2. Horizontal NS-cylinders:
   mean = 0.73 x 10^2 kg cm^{-2},
   standard deviation = ± 0.11 x 10^2 kg cm^{-2}.
3. Horizontal EW-cylinders:
   mean = 0.44 x 10^2 kg cm^{-2},
   standard deviation = ± 0.07 x 10^2 kg cm^{-2}.

In this instance it appears that the difference between sample and within-sample variances is statistically significant at the 5 percent confidence level. Or, as far as the secant modulus is concerned, the values obtained from the three orientation groups can be considered as drawn from different populations. The most striking feature at present is the fact that the horizontal secant modulus in the N.S. direction is statistically significantly different at the...
5 per cent confidence level from that in the E.W. direction, i.e.
this particular Silvan krasnozem
silty clay does not possess a hori-
izontal plane of isotropy or a ver-
tical n-fold axis of symmetry (n =
1) in the particular soil as far
as the secant modulus is concerned.

IV.- CONCLUDING REMARKS

It has been pointed out in this paper that the anisotropy concept
in modern soil mechanics has been
restricted in general to one partic-
cular case where the anisotropy is
solely a result of gravitationally
controlled consolidation and com-
paction. These conditions lead
to the well-known concept of
'cross-anisotropy', where a ver-
tical or near-vertical n-fold axis
of symmetry (n = 1) and a plane of
isotropy perpendicular to this axis
are the only symmetry elements of
the physical system.

The evidence obtained from the
two natural soils discussed in the
present paper, however, indicates
that:

(i) Both soils lack a vertical
n-fold axis of symmetry
(n = 1) or horizontal plane
of isotropy in their origi-
nal, pre-testing geometric-
al or morphological fabric,
but they do possess a single
vertical plane of symmetry
(* monoclinic symmetry)
containing the horizontal
transportation component.

(ii) The beach sand shows in its
deformation pattern a strong
control by the original
monoclinic fabric symmetry.
There is not sufficient ex-
perimental evidence at this
stage, however, to demon-
strate a similar fabric
control for the deformation
of the silty clay.

(iii) Both soils show differences
in secant modulus between
horizontal specimens sam-
ped in variously oriented
directions, i.e. they seem
to lack a horizontal plane
of isotropy or a vertical
n-fold axis of symmetry
(n = 1) as far as this
mechanical property is con-
cerned.

(iv) The (presently hypothetical)
symmetry elements of the
three-dimensional secant
modulus distribution can be
related in a simple and log-
ical manner with those of
the original, pre-testing
V. ACKNOWLEDGEMENTS

The authors wish to acknowledge the very substantial assistance given by Mr. J.D. Walsh and Miss J. Hollingsworth in the field sampling, preparation, and testing of the soil specimens discussed in this study.

REFERENCES


