VOORDRUK UIT GEOLOGIE EN MIJNBOUW NW. SERIE. 16e JAARGANG. 1954 No.
SYMPOSIUM: KWARTAIRE NIVEAUVERANDERINGEN, IN HET BIJZONDER IN NEDERLAND

# SOIL COMPACTION IN RELATION TO QUATERNARY MOVEMENTS OF SEA-LEVEL AND SUBSIDENCE OF THE LAND, ESPECIALLY IN THE NETHERLANDS

## SOME CONCLUSIONS DRAWN FROM LECTURES TO THE CONFERENCE ON SOIL COMPACTION OF THE NETHERLANDS SOCIETY OF SOIL CIENCE. NOVEMBER 20th 1953 AT UTRECHT

J. BENNEMA, E. C. W. H. GEUZE, H. SMITS and A. J. WIGGERS

### INTRODUCTION

The problem of "subsidence and compaction of the soil had been under consideration as a suitable subject for a one- of two-day Conference by the Board of the Society for a few years already.

This project was cut across by a decision of the Board of the Geological Section of the Royal Netherlands Geological and Mining Society to organize a symposium on the subject of the quaternary movements of sea-level and subsidence of the land in the Netherlands.

After consultation with the organizers of the symposium, the Netherlands Society of Soil Science agreed to limit the subjects of the conference to problems of Soil Compaction. The conference took place on November 20th 1953 at Utrecht.

The organization of the conference and the discussions were led by Professor Dr. A. J. ZUUR.

The choice of subjects and speakers was also led by the consideration, that the conference had to be a preparation for the symposium.

The speakers and their subjects were as follows:

1. Prof. Ir. E. C. W. A. GEUZE: Compaction as a mechanical process.
2. Ir. H. SMITS: Compaction over short periods.
3. Ir. J. BENNEMA: Compaction over longer periods.
4. Drs. A. J. WIGGERS: Compaction over very long periods.

Though the lectures are intended to be published in due course in different suitable periodicals, summaries will be given below for the benefit of the participants of the symposium. They will be followed by some considerations related to the above-mentioned subjects and conclusions.

For the sake of completeness it should be stated, that apart from the lectures mentioned above, two others were given.

On the evening of November 20th, GEUZE lectured on: "Results of computations concerning soil compaction, based on laboratory tests and field observation". Next morning BENNEMA lectured on the "Use of compaction data in the analysis of quaternary changes of the sea-level and subsidence of the land".

The lecture by GEUZE cannot be reviewed here, but parts have been used as a basis for the general considerations and conclusions. Many elements of BENNEMA's lecture are encorporated in his paper for the present symposium. For this reason its contents will not be referred to here.

It should also be stated here that BENNEMA's method of applying compaction data met with general approval. A number of points from his conference have been introduced in the general considerations and conclusions.

### SUMMARIES OF THE LECTURES

(1) *Compaction as a mechanical process*

The causes of compaction are mainly threefold:

(i) the changes of hydrological conditions at the upper and lower limits of unconsolidated, compressible soil layers;

(ii) the consolidation of these layers, as a function of time, dus to their own weight;

(iii) compaction caused by an increase of thickness of soil layers (sedimentation and sedentation).

In case (i) the layers are subjected to increasing loads in the course of time (gradual lowering of the "polder" water-table, including the effects of capillarity and/or the lowering of water-pressures in the underlying, pervious soil layers).

In case (ii) the load remains constant (own weight of soil layers).

In case (iii) the load increases in the course of time, due to an increasing overburden.

These cases have been treated in soil mechanics litterature (see f.i. KEVERLING BUISMAN, "Grondmechanica", Hfdst. IV; and HUIZINGA, "Geologie en Mijnbouw", 2e Jrg., no. 5, pg. 94—106).

Some examples were given of the effects of hydrological changes on the consolidation process and which mechanical properties of the soil determine the magnitude of the settling.

It was also shown, that a prediction of this magnitude is largely determined by the experimental method followed in the laboratory, which has to satisfy certain conditions.

(2) *Compaction over short periods*

Short periods will be called those extending over 80 to a 100 years; the compaction over such periods is important, when dealing with reclaiming and draining works.

Some important consequences from the agricultural viewpoint are: the increasing differences of the local heights of the soil levels at short distances; increasing difficulties of drainage; modification of the soil profile; improvement of the trafficability and hampering of soil cultivation.

In connection with reclaiming and draining there are mainly the following three causes of settlement: the lowering of the water table; the drying out of the upper soil layer and the oxydation of organic matter.

Leaving the oxydation out of consideration, settlement is due to an increase of density of the soil layers. The density of soil may be expressed by its specific volume (i.e. the volume of 1 gram of dry soil in its natural condition). If no dry matter is lost by oxydation or in any other way, the settlement is proportional to the decrease of the specific volume.

This rule provides a method to compute compaction.

In order to apply this method, one has to know the thicknesses of the layers and their specific volumes under original conditions; on top of that the specific volumes should be known after the compaction has taken place. The thicknesses of the layers at this stage of the consolidation process then may be computed: the magnitude of the compaction is directly obtained from this result.

Soil layers below the water table may be supposed to be fully saturated with water. Their specific volumes may then be computed from the specific weight of the dry matter and the water content. It has been proved further, that mineral soils of about the same age with a normal content of organic matter, show a close relation between their water contents and their percentages of fines (according to Dutch nomenclature called: lutum i.e. percentage of particles smaller than 2 $\mu$) Specific volumes of these soils may thus be computed from their lutum contents.

In this way the determination of the specific volumes of soils from below the water table is a comparatively simple procedure, though the taking of undisturbed samples is a costly and laborious matter.

The computation of compaction however also asks for the knowledge of specific volumes in the state of "final" consolidation. These data are obtained from polder area's with identical soil profiles and soil composition approximately 80 to a 100 years old; other factors such as the initial circumstances and actual drainage conditions also should be closely comparable. It is then supposed that the specific volumes of the soil layers in the area's under consideration will attain the same values after a period of 80 tot a 100 years as those they have been compared with.

For the area of Eastern Flevoland the polders of "Waard en Groet" and "Anna Paulowna" have been taken as objects of comparison. The compaction of this area was discussed in detail.

Marsh sediments have lower specific volumes already at the time of reclamation than subaquatic layers with the same lutum content. Marsh soils therefore show a small compaction after reclamation, the more so as the subsoil usually is rather sandy.

Though the above-mentioned method of computing compaction in principle may be applied also to layers of the subsoil, which remain saturated after reclamation, the possibilities of application are extremely limited. Firstly the decrease of the specific volumes is rather small as compared to the scatter of the initial values; secondly a suitable object for comparison is hard to find.

Peat areas may settle through oxidation of the organic matter as well as by compression In English and American litterature oxydation is considered as an important factor; it may also occur in the Netherlands.

Several authors state amounts of compaction occurring in highmoor areas directly proportional to the thickness of the layers.

HALLAKORPI mentions the following compaction formula:

$$Z = a\ (0.08\ D + 0.066).$$

($Z$ = compaction; $D$ = thickness of layer; $a$ = factor depending on the density of the peat, varying between 1 and 4).

In our country the compaction of peat over short periods is especially of importance in draining and reclaiming of dug out peat lakes with remaining ridges.

The speed of compaction strongly depends on circumstances. The "final" value of compaction is computed on application of different percentages of the initial thickness, varying with the type of peat. Flatness of the soil surface after "final" settlement is aimed at by working the soil to higher or lower levels during reclamation, according to the amount of compaction to be expected afterwards.

(3) *Compaction over longer periods*

This subject was limited to the compaction of profiles, composed of peat- or heavy clay-layers. Phenomena observed in the Western part of the Netherlands were especially considered.

Usually the phenomenon of compaction is linked up with the cultivated area, though in natural alluvial areas it also plays an important role. The differences in height of the surface then remain rather small, as the low-lying parts often are filled up by a sediment or a sedentate (peat). Filling up however increases the load on the underlying layers and the subsequent compaction causes a deepening a.s.o. This continuous process may proceed till a temporary equilibrium is attained. Finally the soft layers will be hardened by this process. This is demonstrated in the soil profile by low-lying layers of older origin, having settled under the weight of layers of younger sediments, which are relatively thick by comparison. The consequences of the phenomenon may be observed everywhere in areas composed of soft layers and some idea of the magnitude of the compaction may be obtained. Some examples of this kind were discussed.

The magnitude of the compaction of cultivated areas depends, apart from time, especially on the depth of drainage and on the type of the profile.

In the forest-peat district to the west of Utrecht the depth of the water table in different polders strongly depends on the depth of the sand layers underlying the peat or, which amounts to the same, on the thickness of the peat-layer. As the mean value of depth of the water table below the surface in different polders does not vary to any large extent, this fact leads to the important conclusion, that the compaction at the same depth of drainage strongly depends on the thickness of the peat layers.

This can be confirmed only in those areas, where no clay layers occur in the peat mass. If clay and peat occur alternately in the profile, the levels of the water table are at greater heights over the sand layer, lying at the same depth. A comparison of the district to the West of Utrecht with the other peat areas in the Western part of the Netherlands shows, that besides these factors the kind of peat and probably the former hydrological conditions also play a part.

A quantitive view of the compaction of the drained polders of Holland on a landscape basis is hard to obtain, as the original levels of the different parts are not known. Qualitively speaking the effects of the compaction are easily observed. They depend mostly on the firmness of the clay and silt profiles. Considering the area between the "Oude Rijn" and the „IJ", is may be observed, that generally the soil profiles in the Western part are fairly firm becoming softer towards the east. The softest profiles are 2 metres lower than the firmer ones through consolidation, though their depths of drainage is less. This settlement occurred partly during the sedentation of the surface peat on top.

Having compared several polders, the effects inside one polder, consisting of soft peat and clay layers were treated.

The most striking compaction differences are to be observed in the "Oudeland-polders" in Zeeland, where the peat layers have been eroded by creeks. They have been filled up by silt and sand later on and now emerge up to 2 metres above the adjacent parts of the landscape through compaction of the peat and clay.

Compaction differences within the region of one polder in the peat area of the Western Netherlands are less evident. Though differences are seldom more than a few decimeters, their importance to grassland culture is considerable. They may be caused by a difference of thickness of the peat layers; local occurrences of silted up riverbeds or clay layers; or a greater depth of the water table by locally deeper draining or seepage; or a hollow shape of the water table between the ditches by strong exaporation during summer. Differences of types of peat in one polder may be the causes of compaction differences in exceptional cases.

A close relation between the differences in height of the surface and the depth of the sand layers was shown by polders with a soil profile consisting of a peat layer only, resting on sand. Some examples of this kind were discussed more in detail.

(4) *Compaction over very long periods*

In both preceding lectures compaction was considered extending over short periods (a 100 years) and over longer periods of a few thousand years.

It is desirable to consider the amount of compaction occurring at great depth (higher pressure) and over longer periods.

Data obtained from litterature on the subject mention compaction of clay layers loaded by sediments of thousands of metres thickness.

It is known f.i., that clay layers at a depth of 2000 metres have been compressed to 2/3 of the thickness at a depth of a 100 metres.

Volume changes were considered occurring during the transition from clay to shale, from sand to sandstone and from peat to coal. The processes involved were discussed briefly. Also the results of high pressure laboratory tests were compared with data obtained from nature.

A number of physical properties of Dutch sediments were mentioned in their relation to the problem considered, in order to procure a rough estimate of their contribution to the subsidence of the Netherlands.

It was shown that a.o. the factor of time practically excludes any prediction.

## GENERAL CONSIDERATIANS DERIVED FROM THE LECTURES AND DISCUSSIONS

In the following considerations the different aspects of the compaction problem, as advanced in the lectures, have been treated from a more general point of view.

The discussions during the conference, the lectures by GEUZE and BENNEMA, as mentioned in the introduction and the results of recent talks between the lecturers have also contributed to the general considerations.

According to the summaries of the lectures, compaction may be determined by the following methods:

(i) By using the theory of consolidation from the science of soil mechanics.

(ii) By comparison of the specific volume (i.e. volume of 1 gram of dry soil) of the sediment or sedentate considered and that of similar sediments or sedentates, not having been subjected to compression.

(iii) By a comparative analysis of profiles. In some cases a special expedient may be used in the form of deformations of rhizomes of Phragmites by the compression of peat layers.

These methods each have merits and shortcomings of their own. So far the method advanced by SMITS is mostly useful only for determining the compaction of the upper 1 to 2 metres. The consolidation theory on the other hand as advanced by GEUZE is especially suited to compute the compaction of saturated soil layers, whereas it can hardly be applied to the upper layers, subjected to drying out. It is apparent that combining both methods will be necessary in many cases, in order to determine the compaction of the entire soil profile.

Under favourable circumstances, the method of comparative profile analysis as advanced by BENNEMA may yield excellent results. The first condition is that the boundaries of the compressible soil layers should have been horizontal planes originally, or their differences in level at that time known.

The boundary of the firm subsoil further occur at different depths. In a few cases the compaction of layers below the water table only may be determined by this method. SMITS' method may then provide the missing data for the upper soil layers .

Comparative profile analysis can generally give us only the magnitudes of past compaction. In exceptional cases only has it been possible sofar to use these data for other areas. The methods advanced by GEUZE and SMITS may provide data about past and future compaction.

In many cases results are obtained only on the basis of a number suppositions. It is therefore advisable to use the methods simultaneously for comparison and checking of results.

The application of the consolidation theory so far has been seriously hampered by insufficient knowledge of the "layer thickness effect".

This important factor represents the retarding effect of the layer thickness on the compaction, which according to Terzaghi is represented by a quadratic law. Up till now it has therefore not been possible to determine the consolidation degree of a soil layer.

In the second place consolidation coefficients play an important part in the computation of compaction. It has been found by GEUZE, on the basis of a hypothesis for the consolidation process, that instantaneous loads produce a higher apparent compressibility, than gradually increasing loads.

This effect of the loading speed on the compressibility is especially important, when dealing with a gradual drawdown of the water table.

Compaction computations based on coefficients obtained from instantaneous loading tests yield higher values and should therefore be revised.

Comparison of compaction computations according to the consolidation theory, with results obtained by the other methods may give some indication of the maximum speed of loading to be used in consolidation tests, in order to obtain the correct compaction curve.

According to current views, the movement of the land surface in the deeper lying part of the Netherlands should be composed of the geological subsidence, changes of the sea-level and the compaction.

The resultant of the two first-mentioned effects combined is called the relative movement of the land and sea-level.

If these relative movements are to be determined on the basis of the actual level of older sediments or sedentates, or of geodetic precise level-points and tide gauge readings, the effect of compaction should be taken into account.

The compaction in the lower lying part of the Netherlands is not necessarily limited to the holocene sediments of (maximum) 20 metres thickness. As WIGGERS has pointed out, clay- and peat-layers at greater depth and of greater age may also contribute.

As it may be supposed that the compaction of the sand layers, even at great depth, is negligibly small, it is possible to find specific profiles in the Netherlands, of which the compression — even if layers of some hundreds of metres are involved — has scarcely contributed to the subsidence of the land.

On the other hand, pleistocene and older clay- and peat-layers may cause subsidence by compaction. Investigations in other countries have shown, that clay layers will obtain their maximum density under a load of thousands of metres of sediment. (pore volume = 0; specific volume = specific weight = 2.65). The speed of compaction at high pressure and of thick layers is however unknown.

Even if marine clayey "Eem" sediments are considered, the magnitudes of past and future compactions, the latter as a function of time, cannot be computed.

There are, however, some indications that both values are not important.

According to SMITS marine sands show but little compaction. We may therefore suppose, that the pure holocene sandlayers show negligible compaction. But some settlement may be expected from the effect of leaching f.i. decalcification.

According to BENNEMA, the maximum compaction of holocene sediments amounts to 85 % 90 % approx. of the original thickness after its sedimentation.

An extra amount of compaction by oxydation and decomposition of organic matter is not included in this estimate. The percentage mentioned above should be attained in peaty mud soils.

Earlier computations of the Delft Soil Mechanics Laboratory in this case resulted in even higher values. If these results are revised on the basis of new concepts, as advanced by GEUZE, lower figures should be expected.

Generally speaking, the compaction of the holocene soil layers will vary between 0 and 87.5 % of their original thickness after sedimentation. The compressibility strongly depends on the percentages of lutum and organic matter. Soils with a high content of lutum and/or organic matter will compress strongly.

Clay soils from the upper layer with a lutum content of 30 to 35 % of the "IJsselmeer" compress to about half their thickness after reclamation, over a period of a 100 years. At 20 % lutum content the compression is about 25 %.

An important point in determining the drop of a level by compression, is to distinguish between the part of the settlement during the building up of the soil below that level and the part which occurred after it had been attained. The former part is especially important in soil layers built fairly high above the water table (f.i. tidal marshes, levees, coastal barriers, river levees, etc.). The compaction after deposition then should be small as compared to that occurring during this process.

In silty marshes and river levees, with a silty or sandy subsoil, the settlement over the second period will not exceed 10 to 30 cm.

In clayey marshes 1 metre thick lying on silty or sandy subsoil it may amount to 30 or 40 cm. Clay or peat layers in the subsoil may increase these values, depending on the profile and the speed of formation of the layers.

The height of a soil level formed at approximately the height of the water table will be affected to a greater extent by compaction. In the Western part of the Netherlands the soil profiles will show strata which now lie at 3 to 4 metres below their original level.

The settlements of a western Netherlands peat landscape taken from the time it was reclaimed vary between 1 and 2.5 metres. The magnitudes seem to depend mainly on the layer thickness, as the depth of drainage everywhere is the same.

To the West of Utrecht the settlement was found to be about 23% of the original thickness of the peat.

An enormous settlement was found at some places in the IJ-polders. In an old tidal creek filled up with peat mud a settlement of 2.5 metres was measured over 75 years. Outside this creek the settlement in the IJ-polders amounts to 1 to 1.5 metres over the same period of time.