COMPACTION OF SEDIMENTS OLDER THAN HOLOCENE IN RELATION TO THE SUBSIDENCE OF THE NETHERLANDS

A. J. WIGGERS [1]

INTRODUCTION

The Netherlands Society of Soil Science organized a conference on the subject of soil compaction on November 20th 1953 at Utrecht. This conference had to be a preparation for the symposium of the Geological Section of the Royal Netherlands Geological and Mining Society, concerning the Quaternary subsidence of the Netherlands. Summaries of the lectures and some considerations and conclusions of the conference of the Society of Soil Science are published in this issue for the benefit of the participants of the symposium (BENNEMA, GEUZE et al, 1954).

The present writer lectured on "Compaction over very long periods" after preceding lectures on "Compaction over short periods" and "Compaction over longer periods". Short periods have been called those extending over 80 to 100 years, longer periods those extending over a few thousands of years.

The subsidence of the land in relation to mean sea-level can be due to three factors: eustatic rise of sea-level, geological subsidence of the land and compaction of unconsolidated strata. In the Netherlands compaction is generally thought to be restricted to the Holocene strata. These layers show a compaction varying between 0 and almost 90 per cent of their original thickness. In the western part of our country the compressible Holocene layers have a thickness of 10 to 20 metres. Compaction of these sediments plays an important part in the subsidence of the land, as follows from the lectures by SMITS and BENNEMA (BENNEMA, GEUZE et al, 1954).

For the sake of completeness it was desirable to consider also the amount of compaction occurring at greater depth and over longer periods. Investigations in other countries have shown that clay layers will obtain their maximum density only under a load of thousands of metres of sediments.

Geodetic marks and tide gauges are general-

ly foundated on the Pleistocene sand, this base being considered not to be liable to any compaction. However, in most cases the Pleistocene sand is underlain by Pleistocene or Tertiary compressible clay layers. So the study of the compressibility of these strata has also a more practical aim.

In the Netherlands hardly any study has been made about compaction of sediments older than Holocene. So the lecture comprised a brief review of literature and its application to Dutch circumstances.

SOME DEFINITIONS

For a good understanding of the graphs it is necessary to know some terms and definitions, the latter mainly according to HEDBERG (1936).

Grain density (mineral density, absolute density) is the density of the constituent particles of a rock, that is, the rock substance free from pore space.

Bulk density (rock density, lumb density) is the density of the thoroughly dry rock, that is, the rock with the pore space free of liquids.

Natural density is the density of the rock with all pore space filled with water.

Porosity is the percentage of total rock volume occupied by pores or voids. The porosity is calculated by use of the formula:

$$\text{per cent porosity} = 100 \left(1 - \frac{\text{bulk density}}{\text{grain density}}\right).$$

Void ratio is the ratio of the volume of voids to the volume of solid particles in a rock.

Hence, if the porosity is p and the void-ratio is ε, then $\varepsilon = \dfrac{p}{100-p}$ and $p = \dfrac{100\,\varepsilon}{1+\varepsilon}$.

Compaction is expressed as the percentage reduction of rock volume. Compaction is measured by $\dfrac{\varepsilon_1 - \varepsilon_2}{1 + \varepsilon_1}$ or by $\dfrac{p_1 - p_2}{100 - p_2}$, if ε_1 is the initial void-ratio, ε_2 the final void-ratio, p_1 the initial porosity and p_2 the final porosity.

If the grain density shows only slight differences compaction can be computed directly

[1] Research Department Noordoostpolder Authority, Kampen.

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from the decrease of bulk volume (specific volume). *Bulk volume* is the volume of 1 g thoroughly dry rock with pore space.

Often compaction is demonstrated by the decrease of porosity (ATHY, 1930; HEDBERG, 1936). It may be useful to emphasize that the relation between compaction and porosity is not linear; e.g. a decrease of porosity from 90 to 80 means a compaction of 50 per cent, a decrease from 40 to 30 means a compaction of only 14 per cent (fig. 1).

Lower liquid limit is the water content at
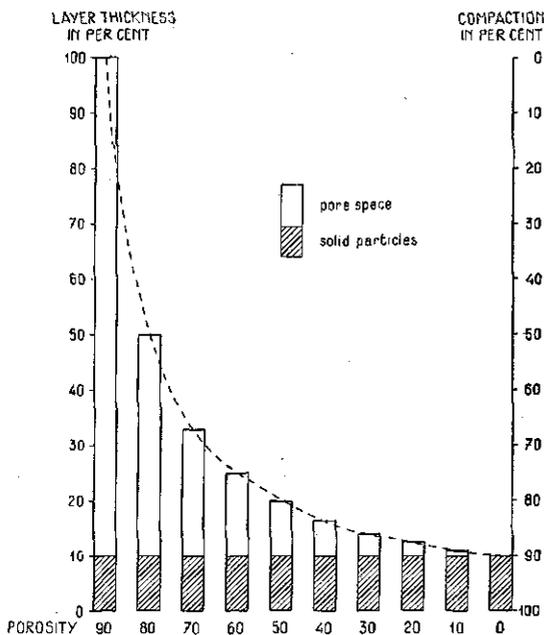
Fig. 1 — The relation between compaction and porosity (initial porosity 90 per cent).

which a mud or clay changes from the liquid to the plastic state.

Lower plastic limit is the minimum water content at which a clay changes from plastic to the semi-solid state.

Shrinkage limit is the minimum water content at which a clay changes from the semi-solid to the solid state, defined by TERZAGHI (1926) on the minimum water content at which volume ceases to diminish by evaporation.

HISTORICAL REVIEW

HEDBERG (1936) and JONES (1944) gave a historical review of ideas on pressure-volume relations in clay and shales. The following is borrowed from these papers.

In 1908 SORBY published the results of his experiments on various sediments. He suggested

that 'the amount of interspaces varies in some way inversely as the pressure'. The paper of SORBY shows that he had a very clear conception of the process of compaction. SORBY's paper received little recognition.

In 1920 BLACKWELDER called attention to the possible origin of the Kansas domes as a result of compaction of the Pennsylvanian shales and limestones, deposited over an uneven erosion surface of granite or Palaeozoic limestones. Already before 1920 (SHAW, 1918) but mainly in the years succeeding 1920 the influence of compaction in the origin of oil field structures have been discussed.

In 1926 HEDBERG attempted a quantitative evaluation of the compaction of sediments, based principally on porosity data from the Ransom well of Kansas.

In 1927 HEDBERG and RUBEY discussed the most suitable formula to represent the porosity/depth data.

In 1930 ATHY presented his famous and often cited paper on the determination of the density of some 2200 specimens and of the
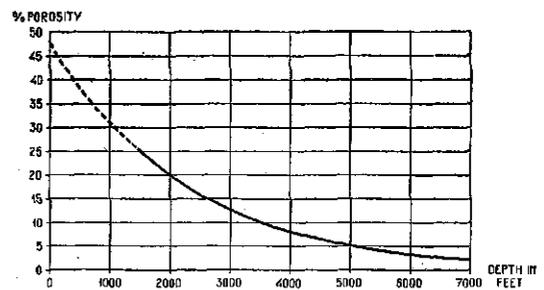
Fig. 2 — Porosity-depth curve (after ATHY, 1930).

porosity of 200 samples from oil wells in Oklahoma and Texas. ATHY plotted the density and porosity values against the depth. The curve of figure 2 represents the porosity-depth relation. The broken part of the curve is hypothetical and represents this relation in younger beds, which were removed by erosion in the area studied.

Figure 3 represents the compaction-depth relation calculated from the increase in bulk density or the decrease in porosity, the initial density taken as 1.4 and the porosity as 48 per cent.

For depths exceeding 2000 feet ATHY's results showed a considerable divergence from those, set forth by HEDBERG in 1926.

In 1936 HEDBERG published new data of samples of Tertiary shales from wells drilled in Venezuela. He believes that the data from well AB are particularly suited for determining
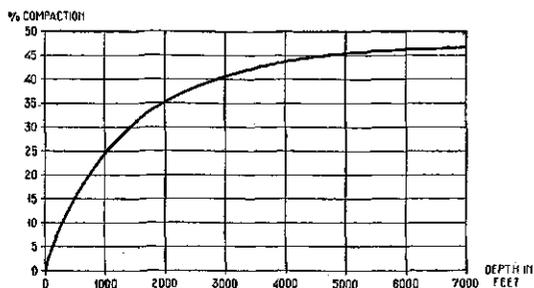
Fig. 3 — Compaction-depth curve (after ATHY, 1930).

the relation between pressure or depth and porosity or density of shale for the following reasons:

"1. It was a deep test in undisturbed and essentially horizontal Tertiary strata far removed from areas of major tectonic disturbance.

2. There is an excellent core record.

3. The strata consisted in large part of shale and there was little difficulty in procuring shale samples that were free from appreciable sand impurity.

4. Absence of major unconformities in the section makes it possible to assume that existing overburdens are essentially maximum overburdens.

5. Approximate density determinations were made by the samples at the well for every important change in lithology throughout the greater part of the section, so that the approximate conversion of depth to pressure has been possible".

In two figures HEDBERG plotted density and porosity against depth of overburden. However the fundamental relation is between pressure and porosity, so depth must be converted to pressure. As the natural density of shale overburden increases with depth and as overburdens rarely are made up entirely of pure shale, pressure of overburden is not equivalent to depth of overburden. HEDBERG was able to convert depth into pressure in the
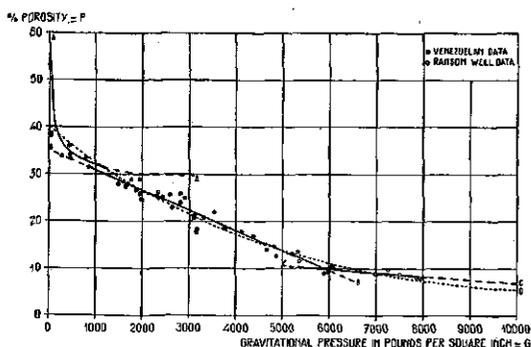
Fig. 4 — Relation of pressure to the porosity of clays and shales (after HEDBERG, 1936).

case of well AB. In this conversion he assumed that the interstitial water in the rock is held by adsorption and does not exert a hydrostatic uplift on the mineral particles.

The relation between pressure and porosity in Venezuela wells is shown in figure 4 (curve B-B). The curve C-C is based on data from the Ransom well. As little information was available on pressure-porosity relation under slight overburdens, curve A-A was based on experimental data from TERZAGHI (1925).

It is the great merit of HEDBERG that he tried to show in diagram the relative importance of the different processes involved in the compaction of clays and shales (fig. 5).
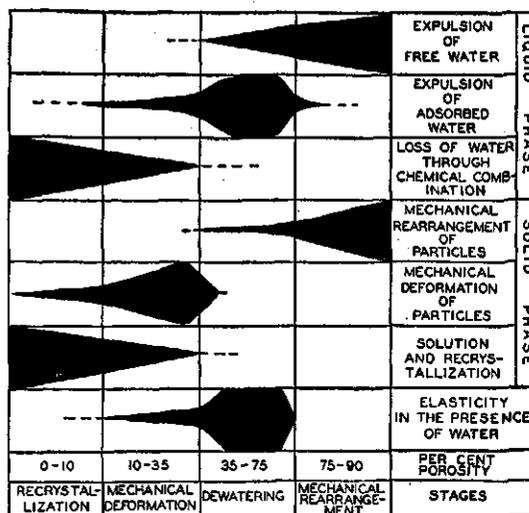
Fig. 5 — Relative importance of different processes in the compaction of clay and shale (after HEDBERG, 1936).

In the summary and conclusions HEDBERG writes: "In conclusion, it may be said that our knowledge both of the actual quantitative relations of pressure to volume in clays and shales, and the processes involved in compaction is still very incomplete".

"More data are needed on the porosities of natural sediments under known pressure and problems such as the bearing of time on compaction, the manner in which the water is removed from dense and extremely fine-grained sediments, and the course of recrystallization in argillaceous rocks urgently call for investigation".

In 1944 SKEMPTON published a paper on the compressibility of clays. He examined the compaction of different types of clay, as demonstrated in consolidation tests in the laboratory and compared those with the true compressibility of clays in nature. Sedimenta-

tion compression curves (relation between void-ratio and increasing pressure for a clay in nature, due to an increasing thickness of overlying sediment) are given in figure 6, compared with two laboratory compression curves. The void-ratios have been calculated from the water content and the grain density, the pressure from the depth of overburden.
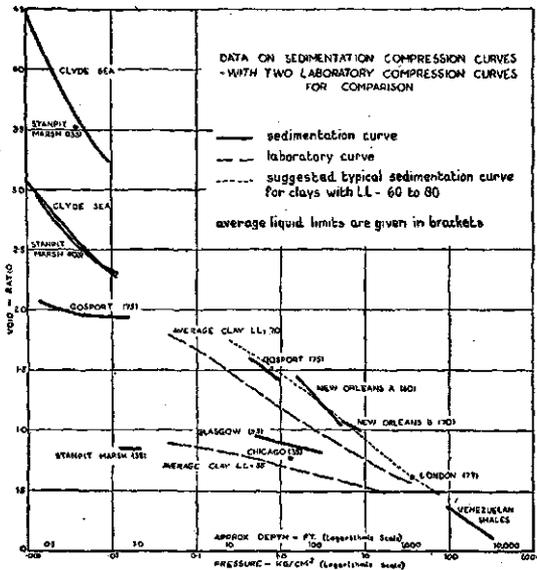

Fig. 6 — Data on sedimentation compression curves with two laboratory compression curves for comparison (after SKEMPTON, 1944).

There is a considerable difference between pressure calculated from depth of overburden whether hydrostatic uplift is taken into account or not. JONES (1944) showed that in calculation of pressure from depth of overburden the rule of TERZAGHI (full allowance for hydrostatic uplift for the layers below ground-water table) can be assumed for sediments with high void-ratios and HEDBERG's rule (no reduction for hydrostatic uplift) for low or very low void-ratios.

Figure 6 shows that the laboratory compression curve for a certain type of clay falls below the sedimentation curve. SKEMPTON proved that laboratory curves for undisturbed samples lie closer to the sedimentation curves than do these for slurries. But even the laboratory curves for undisturbed samples show a discrepancy from the sedimentation curves, probably due to the rate of loading which in laboratory tests is uncomparably more rapid than in nature. As mentioned in the general considerations (BENNEMA, GEUZE et al, 1954), GEUZE stated that instantaneous loads (as used by SKEMPTON) produce a higher compressibili-

ty than gradually increasing loads. Compaction computations based on coefficients obtained from instantaneous loading yield higher values. It seems probable that the discrepancy, mentioned by SKEMPTON, between laboratory compression curves and sedimentation compression curves, may be partly explained by the instantaneous loading in the laboratory.

In 1950 JOHNSON wrote about shale density analysis. He gives a graph, reproduced from a private report of SKEELS, in which a great number of density/depth curves have been combined. After elimination of two curves and shifting of two others SKEELS got a number of curves which agree fairly well. SKEELS' average shale density/depth curve, published by JOHNSON, can be consedered as the best curve available. This average curve agrees fairly will with the curve of HEDBERG (1936).

The foregoing dealt with the compaction of clay to shale. As ATHY pointed out, changes in density in sand caused by pressure are small compared with those caused by other agencies. Especially the amount of cementation greatly influences the porosity of sand, so it is impossible to plot density or porosity to depth or to pressure. Moreover the initial porosity of sand shows a great variability.

ATHY mentioned a laboratory test with sand which showed only a compaction of 2 per cent if placed under 4000 pounds pressure after settling of the sand in water under continuous jarring.

THIADENS and HAITES (1944), regarding the genesis of coal measures, emphasized the differences in compaction of the various sediments, which may play an important part in the understanding of the related phenomena. They concluded that hardly anything is known about the magnitude of original peat, needed to yield one ultimate foot of coal.

ASHLEY (1907) gives the following figures: 3½ feet of hard, dense peat correspond to 1 foot of coal and to 14 feet of original vegetable matter. KENDALL (1916) assumes that peat is reduced to coal in a ratio of 20 : 1. The other authors (e.g. ATHY, HEDBERG) do not deal with the compaction of peat.

THE FACTOR TIME IN COMPACTION

As mentioned by GEUZE (BENNEMA, GEUZE et al, 1954) the application of the consolidation theory has been hampered by insufficient knowledge of the factor time in compaction. HEDBERG mentioned that the bearing of time on compaction urgently calls for investigation.

JONES (1944) remarks that it is generally agreed that the degree of consolidation is independent of time. This would implie that recent sediments show the same degree of consolidation as older (e.g. Palaeozoic of Tertiary) sediments of the same type and subjected to the same load of overlying sediments.

According to TERZAGHI (1925) it is found that the rate of compaction decreases with increasing time after loading. For a thickness of a sample of clay of 2 cm equilibrium is approximately reached after some hours. The retarding effect of the thickness of the layer on compaction is represented by a quadratic law. BUISMAN (1940) pointed out that it is necessary to distinguish between direct consolidation and secular consolidation. He proved that in extreme cases no retarding effect of the thickness of the layer can be expected. It may be clear that laboratory tests hardly can contribute to the knowledge of the influence of time on compaction when dealing with geological periods.

HUIZINGA (1940) used laboratory data of Holocene sediments in order to estimate the compaction of these strata over longer periods. He dealt with the influence of time on compaction, but his periods are too short for our considerations.

In literature we could not find any further investigation concerning the influence of the fartor time. All investigators determine a porosity or a density at a given depth, calculate the pressure from the depth of overburden, estimate the initial stage of porosity and plot the decrease of porosity against depth of overburden. They suppose that at every depth equilibrium has been reached.

In the summaries of the lectures on compaction (BENNEMA, GEUZE et al, 1954) three causes of compaction are mentioned: changes of hydrological conditions, increasing load due to increasing overburden and consolidation as a function of time, due to the own weight of the layers.

This points to the fact that we are of opinion that it is not allowed to suppose that at every depth a real equilibrium has been reached. Older, e.g. Pleistocene and Tertiary clay and peat layers may show compaction, even when the hydrological conditions are not changed and the thickness of the overburden does not increase. The speed of compaction at high pressure and of thick layers is, however, unknown.

SOME DATA ON POROSITY OF DUTCH PLEISTOCENE CLAYS

Recent mud in the IJselmeer with a clay content of 40 per cent shows a porosity of about 85 per cent. At a depth of some decimetres beneath the surface porosity has been reduced to 75—80 per cent. Marsh sediments lying above normal high tide and with the same clay content show porosities of about 65 per cent. So these soils undergo a small compaction after reclamation, compared with the mud soils in the IJselmeer. After drying out by evaporation and transpiration during some centuries the porosity may decrease to 50 per cent. This value is found in the top layers in Dutch polders, reclaimed some centuries ago. In the porosity/depth curves a porosity of about 50 per cent generally is taken as the initial value.

We collected data on the porosity of marine clayey Eem sediments at a depth of about 20 metres, in order to establish the rate of decrease of porosity. The average porosity of the clays amounted to 50 per cent. From this figure we may conclude to a compaction of 50 per cent of the original thickness, supposing an initial porosity of 75 per cent, or to no compaction at all, supposing an initial porosity of 50 per cent.

The Eem layers have a thickness of some metres. After the deposition of these strata the geological subsidence in the coastal area of the Netherlands amounted to 30 metres. So it may be concluded that subsidence of the land, due to compaction of the marine clays of the last Interglacial did not play an important part, although the magnitudes of past and future compactions, the latter as a function of time, cannot be computed.

A great number of data on the porosity of clays, deposited in the northern part of our country before the advance of the Riss ice sheet, were available. This clay is an overconsolidated clay, as it was subjected to the load of the ice sheet during the Riss glaciation. Notwithstanding this, the porosity still amounts to 55 per cent. Perhaps it will be possible to calculate the pre-consolidation load by a consolidation test (HUIZINGA, 1940; SKEMPTON, 1944) The factor time, however, will hamper the application of this part of the consolidation theory, as the 'layer thickness effect' also plays a role in these considerations. Uptill now it is impossible to determine the degree of consolidation nor the degree in which a pre-consolidated sediment has achieved its

new porosity or density after removal of the load.

Pleistocene, probably Reuverian clays at a depth of 20—25 metres have a porosity of 40—45 per cent.

Tertiary, over-consolidated clays at a depth of 0—10 metres show porosities of about 45 per cent.

In the clays mentioned the clay content amounted to 40 per cent. SKEMPTON (1944) pointed out that the constants of compressibility show a fairly close correlation to the clay content. Exceptions were provided e.g. by the boulder clays. The Dutch boulder clay, occurring in two types which differ e.g. in clay content, show porosities not related to the clay content. The porosity amounts to 30—35 per cent.

It would be possible to give still more data on the porosity of Dutch clays. The variation in porosity of clays at a depth between 0 and 30 metres is fairly large. The porosities found also occur in recent layers at the surface. The pressure at the depth of about 30 metres is however not high and certainly not in comparison with the capillary forces, caused by evaporation.

CONCLUSION

Applying the foregoing considerations to Dutch circumstances it may be stated that the subsidence of the Dutch coastal area during the Holocene, due to compaction of older sediments is not important.

Although the Tertiary clayey sediments may amount to several hundreds of metres (PANNEKOEK, 1954) it is unlikely that these layers would not have reached fairly a state of equilibrium at the beginning of the Holocene. The same conclusion may be drawn for the Lower and Middle Pleistocene sediments; moreover these sediments are mainly sandy.

We have shown that even the compaction of the Eem sediments cannot be estimated. Their total compaction may lay between 0 and 50 per cent. Even in the most unfavourable case — linear relation between compaction and time and a total compaction of 50 per cent — the share of the compaction of these layers in the total subsidence of the Netherlands is very small. Apart from these Eem sediments the Upper Pleistocene consists almost entirely of sand.

Therefore in our opinion the entire compaction of the Tertiary and Pleistocene sediments during the Holocene although principally not negligible, must be very small and it can be left out of consideration compared with the geological subsidence of the land and the eustatic movements of sea-level.

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