would be no choice between the methods. However, on jobs where 3 or 4 soil compaction (dry weight and moisture content) curves were run every day on what appeared to be the same soil there was several pounds variation in dry weight but the indicated saturated penetration resistance of the compacted soil was about the same for all samples, indicating that a control based on soil dry weight alone would not be of much value. A direct check method involving ft lb per cu ft would be better but this would check only the roller efficiency. The indicated saturated penetration resistance checks not only the performance of the field methods but also checks whether or not the prescribed field methods are adequate to meet the design conditions. Hence, its continued use.

CONCLUSION

The foregoing discussion is intended to outline methods that can be used for the safe construcion of a 400 ft, or more, high earth-fill dam that will have its designed shear strength, without the customary unknown extent of weakening from pore pressure. The actual values given are believed correct for the two soils used as examples; however, they would not apply to any other soils and considerable testing, along the lines indicated herein, should be done before such a dam is designed and constructed in accordance with these methods.

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SUB-SECTION IV c

EXCAVATIONS AND SLOPES

IV c 13

COASTAL FLOW SLIDES IN THE DUTCH PROVINCE OF ZEELAND

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INTRODUCTION

The Dutch province of Zeeland consists, apart from the strip of mainland adjoining Belgium (Zeeuwsch-Vlaanderen), of a group of islands, separated by wide estuaries. The huge masses of water, propelled by tidal streams, especially during spring tides combined with gales, exert a considerable influence on the banks, even far into the estuaries. The average tidal range in the Wester-Schelde is 3.8 to 4,6 m, dependent upon the distance from the open sea, in the Ooster-Schelde 2.8 to 3.7 m. Throughout the ages the ingenuity and the tenacity of man have struggled here against the water to retain some scraps of soil acquired with great pains. Accordingly Zeeland's coat of arms shows a lion, emerging above the waves, bearing the device "Luctor et emergo" (I struggle and emerge).

As early as the 7th and 8th century the inhabitants of the islands started to protect themselves against high water by constructing dikes and in the course of time many small islands were united to a few large ones after the silting-up of the intervening channels. These changes in the configuration of Zeeland are illustrated by fig. 1 and 2, fig. 1 showing the situation in the 12th century and fig. 2 the present state of affairs.

Fig. 2 shows that the large estuaries consist of various stream channels, separated by

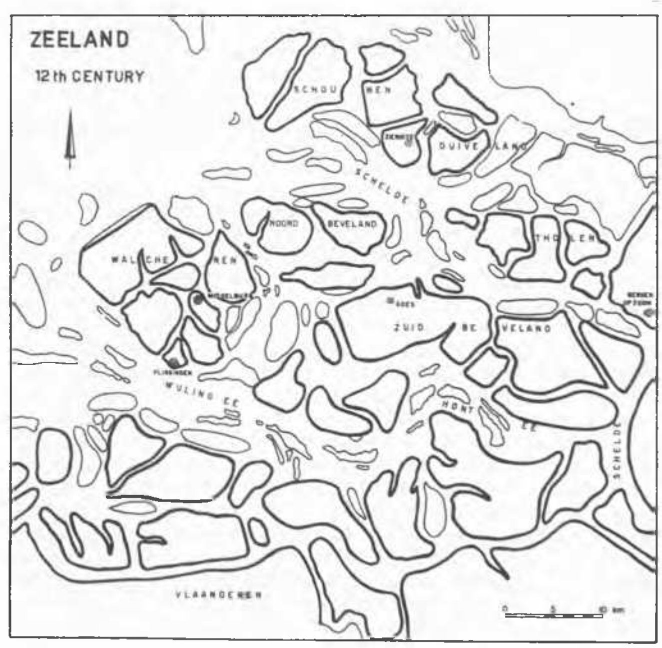

FIG.1

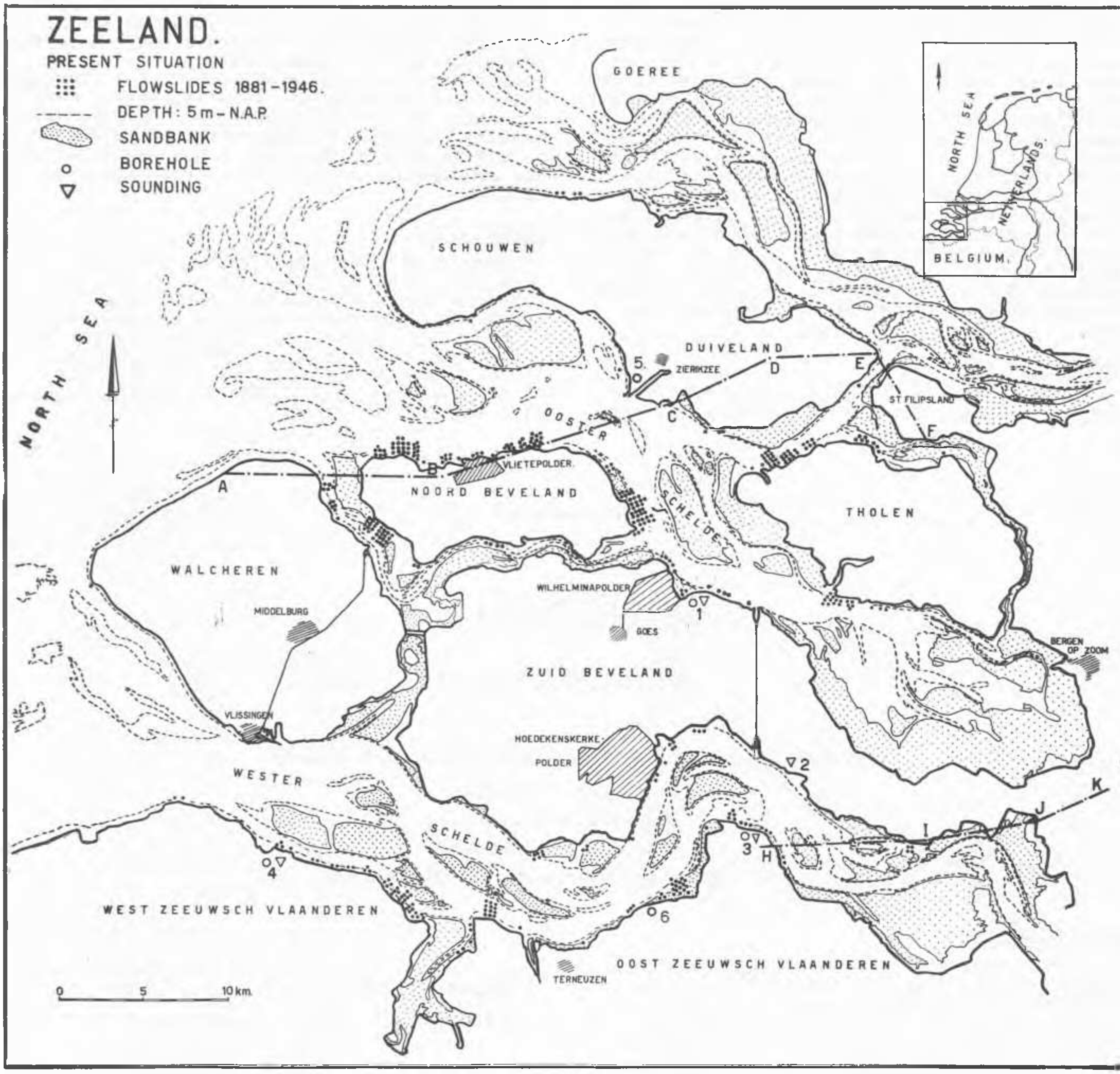

FIG. 2

sand-banks emerging at low tide. For simplicity's sake only the contour line of 5 m below mean sea level (designated as N.A.P. in the Netherlands) is indicated. The depth of some of these channels however is very great (40 to 60 m). Various influences cause a continuous and sometimes fairly rapid shifting of shoals and channels. This may result in an attack by the tidal currents on a certain stretch of the shore, so that the foreshore below the dike is scoured out. The stream channel tends to approach the dike more and more, necessitating the construction of protection works to check the shoreward movement of the channel. On the other hand the same influences may cause a gradual extension of the foreshore below the dike, which new land in its turn might be surrounded by a dike as a protection against high tides. It is also possible that a foreshore, that has been known to grow for years, will be attacked as a result of the shifting-back of the stream channel and from then onward will decrease.

Apart from being directly attacked by waves and tidal streams, the shores of the islands of Zeeland suffer from the notorious flow slides inflicting sudden heavy losses of soil These flow slides occur frequently; between the years 1881 and 1946 no fewer than 229 have been registered (in fig. 2 indicated by dots). The areas above the low water mark thus disappearing varied from 100 to 200,000 m^2 and the soil masses displaced from 75 to 3,000,000 m^3. The total area lost by flow slides during the said period amounted to 2.65 millions m^2 (660 acres) and the volume displaced to 25 millions m^3.

It is evident from these figures that flow slides are constantly damaging the shorelines of the islands of Zeeland. It is clear that grave damage is done when not only part of the foreshore but also part of the dike itself slides away, in which case the polders behind

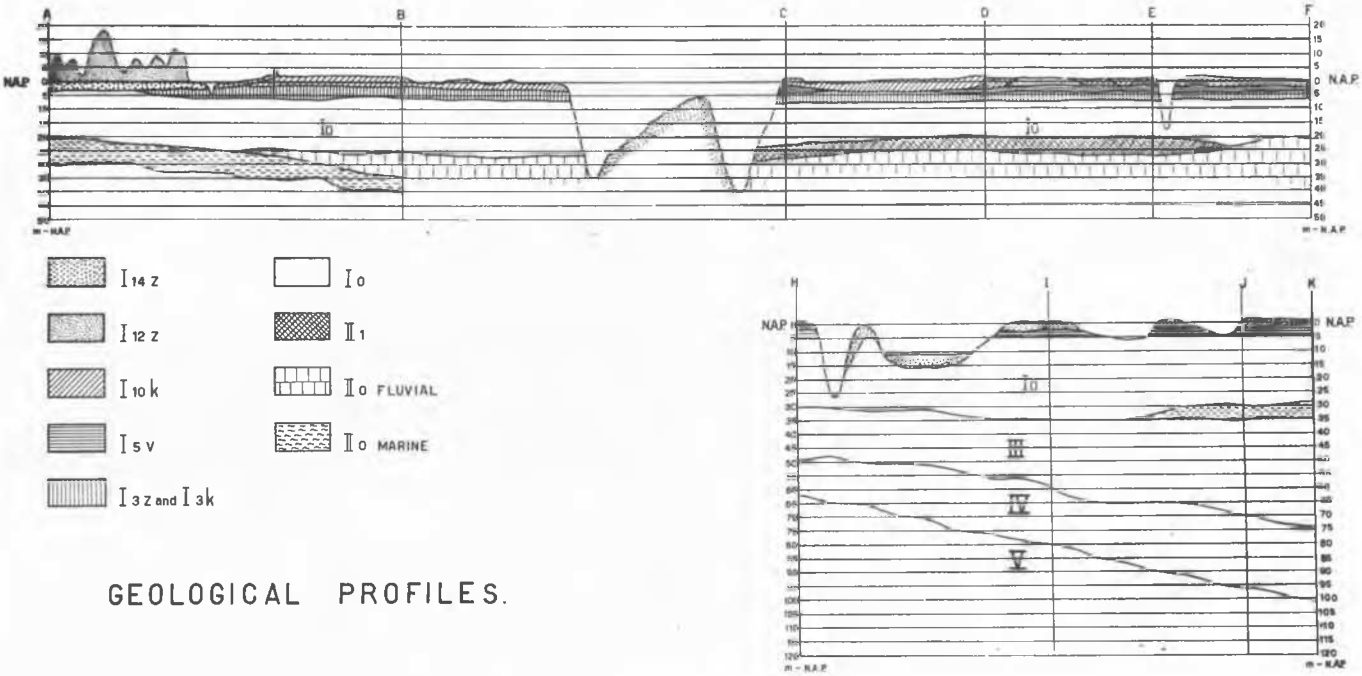

FIG. 3

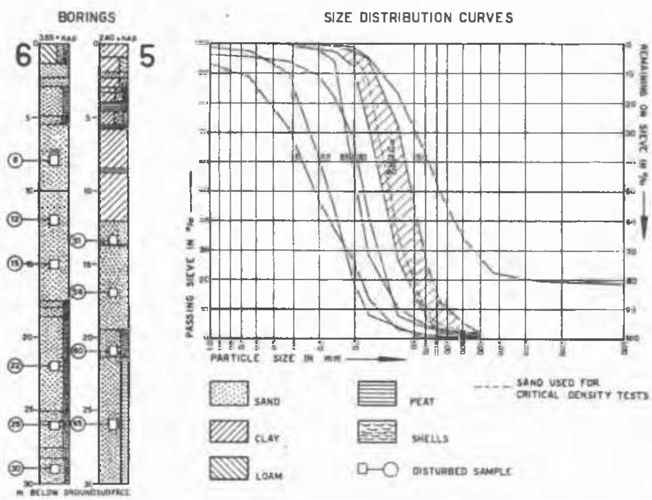

FIG. 4

it are flooded, these lying below high water level. Before entering further into these phenomena a description will be given of the soil conditions in Zeeland.

SOIL CONDITIONS

The geological formation of the soil in Zeeland 1) is indicated in the profiles shown in fig. 3, the location of which is shown in fig. 2. The sediments of the Tertiary Period can be divided into the Eocene, consisting of fine green sands, the Oligocene (symbol V), consisting of greengrey clay, the Miocene (IV), consisting of green-grey silts, and the Pliocene (III) built up of sands. The depth at which these marine Tertiary deposits are found increases considerably from South to North. They are overlain with Pleistocene sediments (II 0 and II 1), consisting of coarse and fine sands with clay layers. Their upper surface is fairly horizontal and it follows that the thickness of these layers increases towards the North.

After the Pleistocene glaciations a peat layer has been formed at the beginning of the Holocene Period, which is now found locally as a thin strongly compressed layer, although in Zeeland it has mostly been carried away again. The formation of this peat came to an end when the land was flooded by the continuously rising sea. In the shallows then formed fine sands (Older Holocene I 0) were deposited, carried along by the rivers Rhine, Meuse and Scheldt. At present their base lies on the whole at 20 to 30 m below N.A.P. Gradually sandbanks were formed in this sea along the present coast line and on these sandbanks dunes were modelled. Behind the thus formed shore-bar the inland sea was gradually filled with clay and sand; thus the older marine clay (I 3k) came into being, sometimes rather sandy in composition (I 3z), its base nowadays lying at 5 to 8 m - N.A.P. Subsequently peat (I 5v), younger marine clay (I 10k) and youngest marine sands (I 14z) were formed, while in the meantime the shore-bar had partly been swept away. Lastly younger coastal dunes (I 12z) were developing locally.

In fig. 4 two borings are shown, made on the outer berm of the dike at places where flow slides have occurred (for location see fig. 2). Particle size diagrams for a number of samples from these borings are also given. It is apparent that the Older Holocene sands (samples 8, 12, 15, 56 and 60) are fine and uniform in composition, 90% of the particles having diameters between 0.2 and 0.07 mm. An exception is sample 51, containing 20% clay. The sand samples from the deeper layers (samples 22, 26, 30 and 65) are apparently coarser.

In order to give an insight into the shearing resistance in the Older Holocene sand-layers, fig. 5 shows the results of four soundings and also of the borings made in close proximity (for location see fig. 2). At a sounding the penetration or sounding resistance of a cone with a basis area of 10 cm^2 is measured at increasing depths under the surface 2) from which the shearing resistance may be derived.

DESCRIPTION OF THE FLOW SLIDES. 3) 4) 5)

A coastal flow slide in Zeeland means an

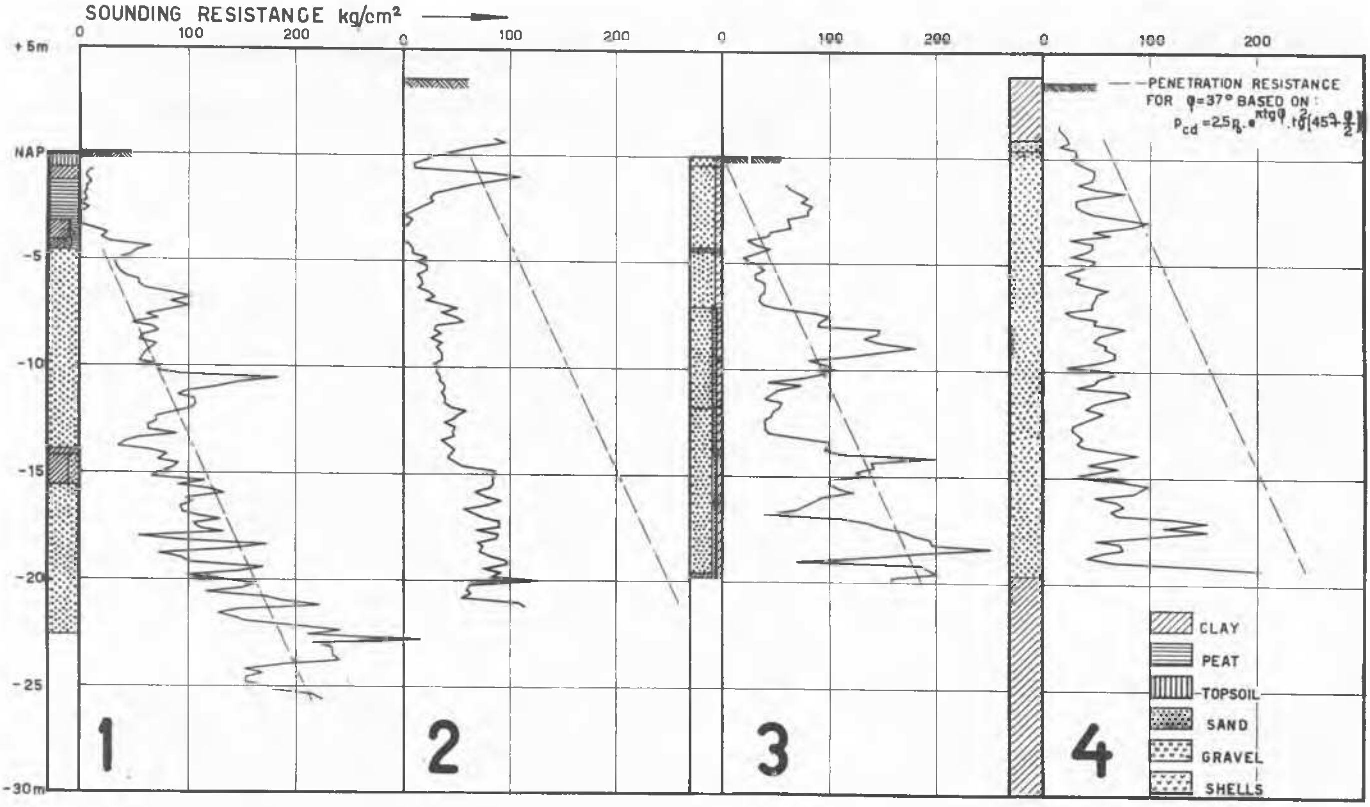

FIG. 5

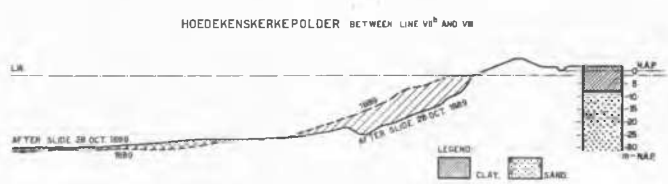

FIG. 6

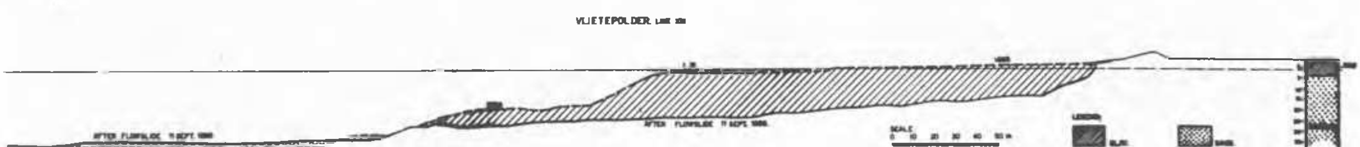

FIG. 7

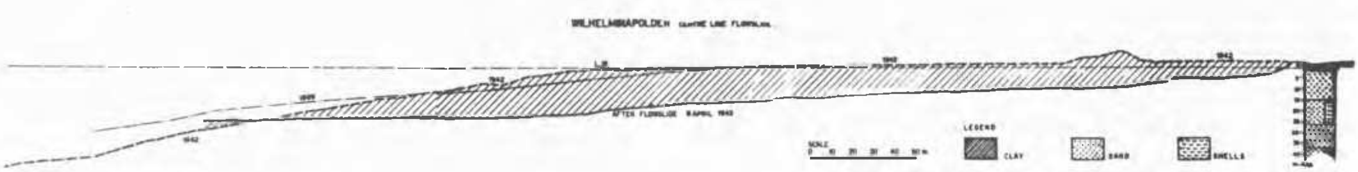

FIG. 8

Flow slide Oud Bevelandpolder 29 Januari 1937

FIG. 9

unexpected downward sliding of a large portion of the foreshore below the dike, sometimes causing disappearance of part of the dike as well; it is further characterized by the soil mass flowing out to a very flat slope e.g. to an angle of 3° to 4° with the horizon. However, ordinary landslides are also known on these shores, the soil not flowing out to a flat slope and only restoring the lost equilibrium of a slope scoured-out too steep, thus having a smaller extent. On the whole these phenomena occur only where the shore is receding as a result of the scouring action of the streams, whereas no danger exists when the foreland is growing. In several instances flow slides have been observed on shores where the last previous survey showed an average slope of less than 15° Normal routine surveys however are only done once a year and on lines 50 to 100 m apart, so that it is just possible that shortly before the moment of sliding the shore has locally been scoured out.

As an example of an ordinary landslide fig. 6 shows a section through the dike of the polder of Hoedekenskerke, where on 28 October 1889 a slide occurred, displacing 20,000 m^3 soil, although also here possibly some flowing may have taken place. The outside slope of the sand after the slide was about 22°, whereas the overlying, clay-layers showed a steeper slope. At the time of the last previous measurements an average slope of about 23° had been observed.

Fig. 7 and 8 show cross sections of two flow slides, viz. of the Vlietepolder where on 11 September 1889 935,000 m^3 was displaced and an area of 58,000 m^2 land above the low water mark disappeared, and of the Wilhelminapolder where on 9 April 1943, 2,000,000 m^3 was displaced and a loss of 200,000 m^2 land incurred. At the latter also part of the dike disappeared which caused flooding of the polder behind it. The last survey at the Vlietepolder previous to the slide in 1889 showed a steepest slope of 27°, whereas after the slide a slope of 4° was measured. The figures for the Wilhelminapolder before and after the slide averaged resp. 10° (steepest slope 20°) and 3° In fig. 3 some regression of the shoreline during the years 1899 to 1942 can also be seen.

A Zeeland flow slide is a gradual process where at intervals of a few minutes soil masses slide downward and flow out. Observation however is only possible after the disturbance has progressed to above the water line and a steep wall has been formed there. Then at a place one or more meters landwards cracks appear about 10 m long, after which the soil mass in front starts to slide. In this way the slides go on, progressing about 50 m per hour On the landward end of the slide the soil above and a little below the waterline may keep a very steep slope (fig. 9a and b). The duration of the complete process varies from a few hours to a day.

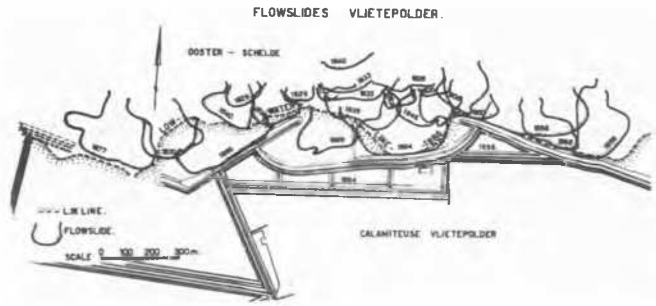

FIG. 10

In plan flow slides have a typical fan or shell shape, the width increasing towards the land-side (fig. 10). After a flow slide has occurred, a fairly rapid sedimentation can be expected in the deepening that has been brought about. A remarkable feature is that on the whole in these sedimentation no new flow slides occur, from which fact a saying in Zeeland originates "no slide within a slide". This is illustrated in fig. 10 by the limits of flow slides on the shore of the Vlietepolder, which are marked with their years of occurrence.This proves that several slides have been checked in their progress by earlier slides which had been silted up again. However, in case the depth in front of the shore has increased, a new slide may have its origin deeper and may embrace the whole of some previous ones. After 1889 the shore of the Vlietepolder has not suffered from slides any more, which may be due to a contiguous row of previous slides or to the sturdy shore protection works constructed since then.

EXPLANATION OF THE FLOW SLIDES

Flow slides occur chiefly in the Older Holocene sand layers. Fig. 4 indicates that these sands are fine and uniform of size, and it will be shown below that their density is on the whole below the critical density. The fact that after a flow slide another subsequent flow slide is seldom observed in the same newly silted-up area, may find its explanation in the greater density of the new deposits and possibly in a different particle size distribution as well.

For the primary cause of the slides we must in the first place look toward the harmful effect of tidal streams on the shore causing a steeper slope than the original safe one, and next toward seepage pressures during falling water diminishing the angle of the safe slope. In case the density of the sand is greater than the critical density, a normal loss of equilibrium results and the new slope will be determined by the angle of internal friction and the prevailing seepage pressures. However in loose sands with a density smaller than the critical a local loss of equilibrium may, as is well known, lead to an ever further spreading flow slide.

It is notable that flow slides occur mostly during periods of excessive tide differences e.g. at spring tides, sometimes coinciding with gales. Admittedly these cause an unfavourable situation, since, as the tide differences increase , so do the velocities in the channels and the seepage pressures. We obviously do not know the exact moment between high and low water when flow slides start under water. In the few cases however where the rate of progress of the slide landward has been evaluated, the assumption that this velocity under water has been the same leads to the conclusion that these phenomena have all started during ebb-tide between half tide and low water. This conclusion seems acceptable, since velocities of the current in the channels (scouring-out) are largest at half tide and seepage pressures are largest at a certain moment during the second half of the ebb-tide, the seepage flow being unsteady.

The relatively slow rate of progress of a slide can possibly be explained in the following way, assuming at first that also under water it proceeds in slices. When a slice has flowed out, it may be imagined that in fine sand with a relatively low permeability the thus formed very steep slope stands during a short time. For, as a result of the falling away of lateral support the soil will tend to expand slightly, while the necessary replenishing of the pore water will take some time. Consequentlv pore pressures will drop and the system of solid particles is temporarily supported by a seepage pressure directed inward. As the water flows in, the shearing stresses grow. Not until then will sand with a density below the critical density show a tendency toward a volume decrease. The pore pressures will consequently rise above their original value and the shearing resistances will decrease accordingly. More especially fine loose sands may acquire in this way temporarily the properties of a liquid and may flow out at a very flat slope. This process may repeat itself continuously, causing the intermittent flowing-out of more and more slices, resulting in the observed delayed action.

Therefore the course of affairs may be visualized as follows (fig. 11). A portion of the shore (a), which at the last previous survey was found to be already fairly close to the limit of equilibrium, be since then scoured out further (shaded portion). If now as a result of a large tidal fluctuation a strong current scours the shore e.g. up to plane b, then it is possible that, the momentary seepage pressures concurring, after a short delay such an increase of the shearing stresses or even loss of equilibrium is brought about that the sand with a density below the critical is liquified up to plane c, flows out and settles down over a large area in the form of a thin layer, etc. The successive flowing-out of slices proceeds until it is stopped in a different soil or in sand above the water line where for the time being a steeper slope is possible.

The assumption that also below the water line the flowing-out may proceed in slices is based on the following considerations. Although the rise of the originally dropped porepressures will start from the surface of the slope, it is equally true that in deeper strata the eventual shearing stresses are greater while there the original porepressures had decreased less than at the surface. Meanwhile it is very well possible that the cracks visible above the water line are just tension cracks, giving the impression of a slide occurring in slices, whereas in reality the progress under water is more continuous. Even then there are equally good grounds for the supposition that in fine sands the whole process of a flow slide takes a considerable time.

CRITICAL DENSITY AND ANGLE OF INTERNAL FRICTION OF THE OLDER HOLOCENE SAND.

Since flow slide phenomena in Zeeland are largely governed by the density of the Older Holocene sand layers, the critical density of this sand has been studied in the laboratory and also the relation between density and angle of internal friction. The method of investigation of critical density in the Delft Soil Mechanics Laboratory is described in a paper by ir. E.C.W.A. Geuze.6) The particle size diagram of the sand examined, being a mixture of samples 12 and 15 of boring 6, is given in fig 4.

The critical density tests are performed on dry samples with an initial volume of about 500 cm^3. The object is to study the effect of increasing shearing stresses on the density of the sand. The results are given in fig. 12, where the volume changes of the samples have been plotted against the difference between the vertical and horizontal principal stresses ($p_1 - p_2$), the latter being equal to twice the value of the shearing stresses in planes at 45° with the directions of the principal stresses. During the whole of the test the normal stresses in these planes remained constant. Also in fig. 12 have been noted the initial pore volumes at the beginning of the tests at an all-sided equal pressure of 0,5 kg/cm^2. From these results we see that for the densities investigated at first a more or less growing reduction of volume occurred, at the "turning-point" going over into a volume increase. The turning-point represents a critical point in the density of the sample. In fig. 13 the porosities at these turning-points are plotted against the initial porosities and also against the reductions of volume at the turning-points. Turning-point densities, corresponding with initial porosities between 44% and about 47,5% are apparently reached by relatively small reductions of volume. At lower densities however, up to the limit value of

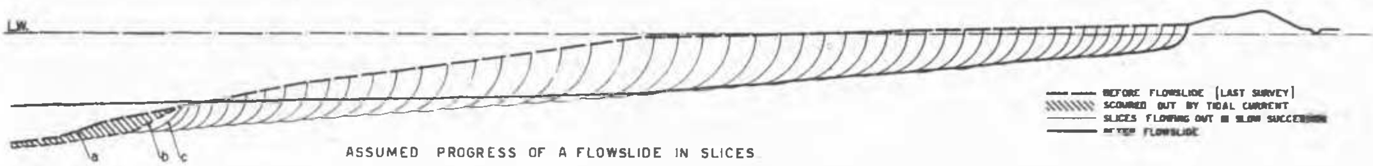

FIG. 11

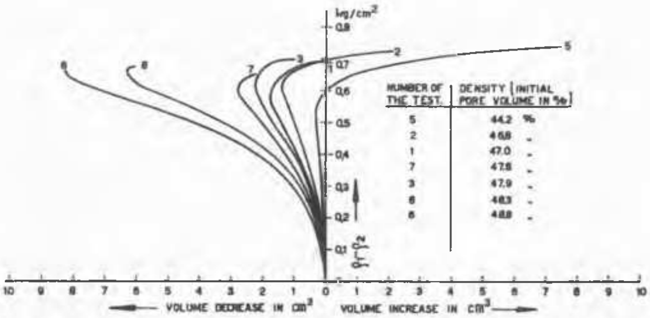

FIG.12

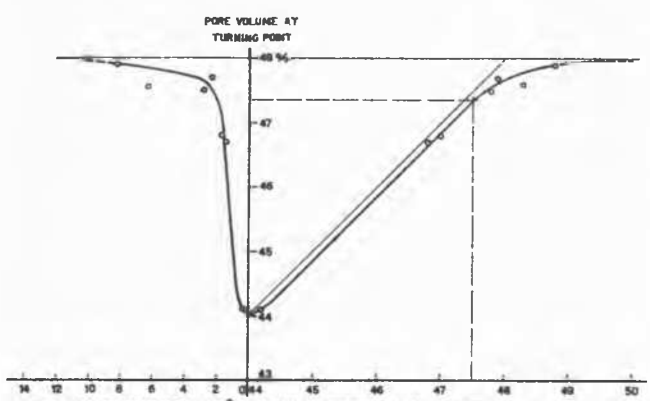

FIG.13

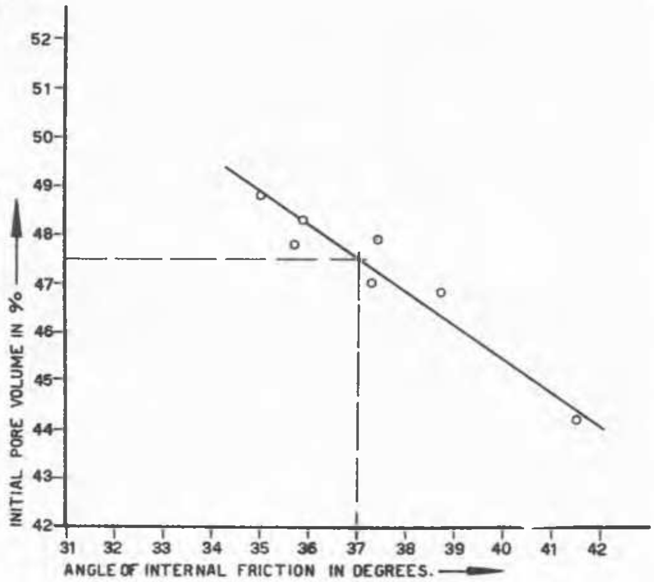

FIG.14

the porosity at turning point (about 48%), the reduction of volume, caused by deformation, increases considerably and at an increasing rate.

In case the sand mass would be saturated with water, the tendency of the system of solid particles toward reduction of volume would, all other conditions being equal, determine the value of the excess pore water pressures. The slight reductions of volume of 0.1 to 0.2% occurring at pore volumes below about 47.5% need not necessarily lead to a considerable drop in the effective pressures and for that matter in the shearing resistances. Between the upper value of the critical density of the sand in question (porosity 44% and the limit value of critical density (porosity about 48%) a porosity of roughly 47.5% indicates a probable value for the critical density below which there exists a danger of flow slides.

Furthermore, in fig. 14 the relation between the initial porosity and the angle of internal friction φ resulting from these tests has been plotted. The latter can be found from the formula

$$\sin\varphi = \frac{\rho_1 - \rho_2}{\rho_1 + \rho_2}$$

For the above mentioned porosity of 47.5% fig. 14 shows an angle of internal friction of about 37°. Inversely we conclude that the Older Holocene sands in the subsoil of Zeeland in as far as they show an angle of internal friction smaller than 37° have a density below the critical density.

In order to check this fig. 5 shows diagrams of penetration or sounding resistance in the subsoil compared with the theoretical lines of resistance for $\varphi = 37°$. The latter have been determined as follows. According to Prof. Ir. A.S. Keverling Buisman 7) the ultimate bearing capacity of non-cohesive sand under a shallow wedge load of small width may be represented by

$$p_{ws} = p_o \cdot e^{\pi \operatorname{tg} \varphi} \cdot \operatorname{tg}^2\left(45° + \frac{\varphi}{2}\right)$$

where p_o is the vertical effective pressure arising out of the overburden. Now the soil will offer at penetration on a relatively greater resistance to a cone than to a wedge and still greater to a cone some distance below the surface than to a cone near the surface, both owing to the formation of greater sliding surfaces. Based on laboratory tests one may take the value of the proportion of the cone-resistance in deeper layers ot the shallow wedge-resistance as 2.5, which is conservative. The expression for the cone-resistance at greater depth becomes then

$$p_{cd} = 2.5\, p_o \cdot e^{\pi \operatorname{tg} \varphi} \cdot \operatorname{tg}^2\left(45° + \frac{\varphi}{2}\right)$$

Assuming suitable unit weights for the various soils, taking the unit weights for the saturated Older Holocene sand, corresponding

SIZE DISTRIBUTION CURVES

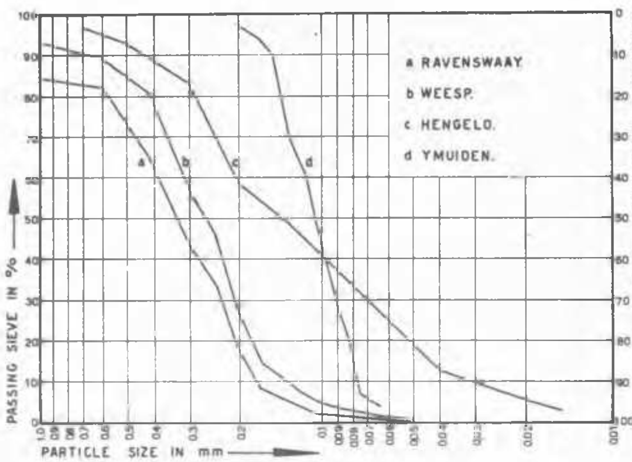

FIG.15

to a porosity of 47.5%, as 1.865 grams per cm^3 (under water 0.865 gr/cm^3) and substituting $\varphi = 37^o$, the indicated lines representing the variation of p_{cd} with the depth are found. From a comparison of the thus obtained lines with the actual resistance diagrams (fig. 5) it is apparent that the latter indicate lower values, except for a few thin layers.

From this it might be concluded that, presupposing that the above mentioned factor 2.5 is right and that the four investigated sites are representative, the density of the Older Holocene sand in Zeeland generally must be lower than the critical density, thus lending support to our supposition in the foregoing chapter.

It may be noted that actual penetration resistances lower than the theoretical ones for $\varphi = 37^o$ only indicate that the angle of internal friction is less than 37^o but cannot furnish the actual value of this angle and the corresponding density, owing to probable flow (decrease of shearing strength) during the penetration of the cone in sand with a density below the critical one. It should be remarked that in the laboratory, pouring sand out under water, no higher porosity than 58.5% could be reached, so that the porosities of the Older Holocene sands in Zeeland giving rise to flow slides lie probably between 47.5 and 48.5%.

MEASURES AGAINST FLOW SLIDES

In past centuries the stretches of the shore under water liable to be attacked were left almost unprotected, but behind the dike bordering the sea "reserve"-dikes were constructed which were able to stem the water in case the sea-dike came to fall. However, in this way vast stretches of land were lost. During the middle of last century two systems of shore protection came to the fore viz. revetment of the banks and guiding of the streams. Revetment consists in the application of a mat of fascine-work, which by virtue of its flexibility adapts itself perfectly to the shape of the bottom, and is weighed down by handstone. Guiding of the streams is effected by building groynes out into the sea in order to keep the path of the stream away from the shore. About the year 1880 however a less expensive mixed system was adopted, the so-called "system of fixed points". This means that some sections of the shore line at certain limited distances from each other are heavily protected, whereas in-between the shore is not protected and account is taken of the possibility of scouring. Subsequently the location of the dike is fixed in connection with the expected flow slides. Notwithstanding all this some of the thus protected shores have been damaged badly by flow slides.

Compacting of the Older Holocene sand-layers or stabilization by treatment with asphalt products or chemicals are impracticable owing to prohibitive costs.

SIMILAR PHENOMENA IN OTHER PARTS OF THE NETHERLANDS

Also elsewhere in the Netherlands similar phenomena have been observed. Fig. 15 shows some particle size diagrams of the sands in question. For instance in 1940 it came to pass that as a result of dredging activities near the sluice at IJmuiden the slopes at the spot flowed out in the same intermittent manner as in Zeeland. The particle size diagram of this sand (fig. 15 curve d) is almost the same as the ones for the Older Holocene sands of Zeeland. Also at the embankments of the Twente Canal, East of the lock at Hengelo, a flow slide occurred in 1937, where over a length of about 35 m a fairly thin slice of soil (fig. 15 curve c) slipped off and flowed out far over the bottom of the Canal. As this slide occurred during the night, the duration is not known.

On the contrary, the flow slides in the approach to the railway bridge over the Merwede Canal near Weesp in 1918 and in the embankments near the locks at Ravenswaay in 1939 took a very short time, a few minutes only, probably because in both these cases, the immediate cause was acting in the whole of the sand mass at the same time. Ir Geuze 6) examined the critical densities of the sands of Weesp and Ravenswaay (fig. 15 curves a and b) and found that in both cases the porosities in the field were more than 1 % higher than the limit value of the critical density. The cause of the flow slides is in both cases thought to be the influence of vibrations. At Weesp these vibrations originated from a train, which subsequently, when the slide occurred, fell down with heavy casualties. This accident was the immediate cause of the start of practical soil mechanics in the Netherlands.

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