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ENGINEERING-GEOLOGICAL INVESTIGATIONS IN THE MOUTH OF THE EASTERN SCHELDT (SW NETHERLANDS)

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ABSTRACT

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The results of the site investigation on behalf of the storm-surge barrier in the Eastern Scheldt basin (SW Netherlands) have been interpreted and correlated stratigraphically. Together with the available geological information, stored in the files of the Geological Survey of The Netherlands, detailed lithostratigraphic and engineering-geological models were developed from which prognoses were made on the extent and distribution pattern of the more or less unconsolidated Holocene and relatively well consolidated Early Pleistocene deposits in the Eastern Scheldt mouth.

INTRODUCTION

In 1975 the Geological Survey of The Netherlands was requested to participate with the Delft Soil Mechanics Laboratory in projects of soil investigation on behalf of the forthcoming semi-closure of the Eastern Scheldt basin. The projects included:
(1) an investigation of the stability of dikes and embankments along the entire Eastern Scheldt basin;
(2) an investigation of the composition and stability of the subsoil at the planned locations of the secondary dams (Philipsdam and Oesterdam, see figure 1);
(3) an investigation of the composition and stability of the subsoil in the mouth of the Eastern Scheldt with respect to the planned construction of the storm-surge barrier.

In this paper a short outline of the site investigation and of the main engineering-geological results of the last mentioned project is presented. In these studies the author cooperated with F. F. F. E. van Rummelen, with F. D. de Lang and with specialists of the Delft Soil Mechanics Laboratory and the Geological Survey of The Netherlands.

The engineering-geological investigations in the mouth of the basin were focused on three main issues:
(1) mapping of the beds with high bearing-capacities;
(2) mapping of occurrences of clay-bearing strata within the beds with high bearing-capacities;
(3) mapping of the distribution of very loosely-packed sands, which are known to be very susceptible to liquefaction

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GEOLOGICAL SETTING

The region of the Eastern Scheldt mouth is, from the tectonic point of view, situated at the southern margin of the North Sea Basin. This basin is bounded on the south by the Brabant Massif. On the northern flank of this east-west oriented massif, the extent and thickness of the deposits were controlled by vertical movements in the massif. Mainly because of this, the number of stratigraphic breaks in this region is relatively large. The formations on the northern flank of the massif all dip basin-inward (towards the north-east). In this direction the deposits rapidly increase in thickness, while the dip decreases. The youngest deposits show a slight dip towards the north-west and are free from tectonic deformations or faults. The deepest strata into which exploratory borings penetrated for the purpose of this geological investigation are of Middle Oligocene age and form part of a succession of marine clays which is characteristically encountered in a large area in the southwestern Netherlands and northwestern Belgium and which belongs to the Rupel Formation. The top of this formation in the investigated area lies between 93 and 135 m below mean sea level (NAP in The Netherlands)(Fig. 2).
Late Oligocene and Early Miocene deposits are absent in this region, very probably due to strong erosion after an Early Miocene tectonic uplift phase. During Middle and Late

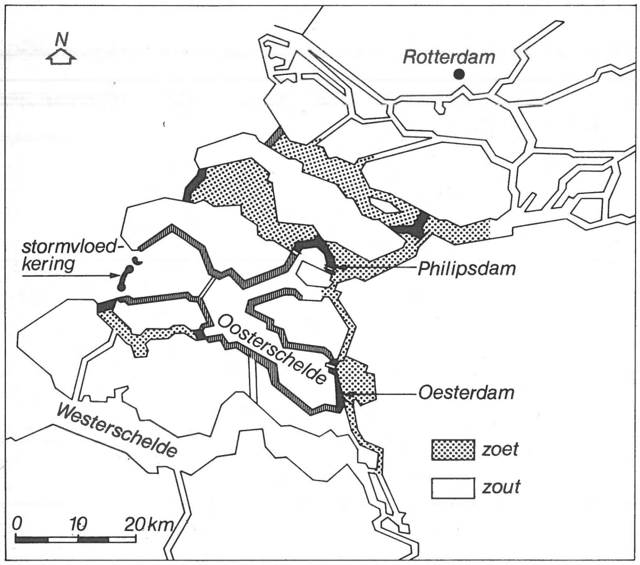

Fig. 1
Map of the southwestern Netherlands.

Miocene times the region was again inundated by the sea and shallow-marine glauconiferous sands were deposited (Breda Formation, corresponding to the Antwerp sands and Deurne sands).

During the Pliocene the sea gradually receded: this is manifest in the near-coastal character of more particularly the Late Pliocene deposits (Oosterhout Formation, corresponding to the Merksem sands and Kallo sands).

At the beginning of the Pleistocene (about $2{,}5 \times 10^6$ years ago) a considerable deterioration of the climate occurred, during which the polar ice caps expanded and the sea level went down substantially. The regression which had started already during the Pliocene continued at a faster rate during the Early Pleistocene, and during the Tiglian the Eastern Scheldt mouth region was also entirely beyond the influence of the sea. The Early Pleistocene marine deposits belong to the Maassluis Formation.

The Early Pleistocene river valleys which may have eroded the underlying formations to considerable depths, are filled with continental deposits belonging to the Tegelen Formation. The age of the youngest deposits of the Tegelen Formation, as encountered in this region, is about 1.7×10^6 years. Between these and the next younger deposits a time gap of more than $1^1/_2$ million years appears to be present here.

During the Eemian (120,000-70,000 years ago), the warm period preceeding the last ice age, the sea again covered large areas of western Zeeland, and in a wide area shallow-marine, littoral and coarse sand deposits were laid down. As appears from the section in figure 2, however, the greater part of the deposits of the Eem Formation were removed by subsequent erosion, though under the southern coast of the island of Schouwen deposits belonging to the Eem Formation are still present. During the last ice age, the Weichselian (70,000-10,000 years ago), The Netherlands were entirely above sea level and periglacial, mainly wind-blown sands were laid down (Twente Formation). Remnants of this formation in the Eastern Scheldt mouth were saved for subsequent erosion only under the southern coast of Schouwen.

At the beginning of the Holocene the first consequences of a new transgression in this region became manifest. The (peri)marine Holocene deposits associated with this new transgression constitute the Westland Formation. The tidal-flat area, which had been built up in the Eastern Scheldt mouth was connected with the sea by tidal channels. These channels may have eroded the surface of the Pleistocene deposits to considerable depths and were filled with sands and, higher in the succession, also with clays (Calais Deposits). In the course of the Holocene chains of coastal barriers merged together off the coast, as a result of which the marine influence in the former tidal-flat area almost entirely ceased. During this period thick accumulations of peat (Holland Peat) were formed. Another transgression period, starting about 500 years B.C., ushered in the final episode of the geological history of the southwestern part of the Netherlands. The marine sediments associated with this last transgression phase belong to the Dunkirk Deposits.

The peat area was completely inundated and was once again transformed into a landscape of mud flats intersected by tidal channels which branched from the major inlets between the chains of coastal barriers. In broad outline the Delta region then acquired its present shape. At the Early Holocene river Scheldt mouth a large inlet developed, and the Eastern Scheldt was formed as an estuary basin. It was not until after 700 A.D. that the more southerly situated Western Scheldt was formed and became the estuary and principal discharge channel of the Scheldt river, functions previously performed by the Eastern Scheldt.

During the last four centuries the Eastern Scheldt basin has become considerably wider and its tidal channels were scoured much deeper. Recent studies by Nio et al (in press) in the construction pit for the piers in the northeastern part of the main work island have shown that at 17 m below NAP a.o. high-magnitude sand waves not older than 1600 A.D. are present, while the upper 10 m appeared to have been deposited between 1920 and 1935 approximately. In the last 10 years scouring has greatly increased as a result of the construction of the Volkerak Dam, the Grevelingen Dam and the work islands in the mouth area of the Eastern Scheldt.

SITE INVESTIGATION

On the basis of the experience gained during the systematic geological mapping of the southwestern part of this country and during the geological investigations on behalf of a large number of previous civil-engineering projects in the Delta region, already some prognoses about the distribution of certain lithologic units could be given in an early stage of the project. However, in order to perform detailed studies on

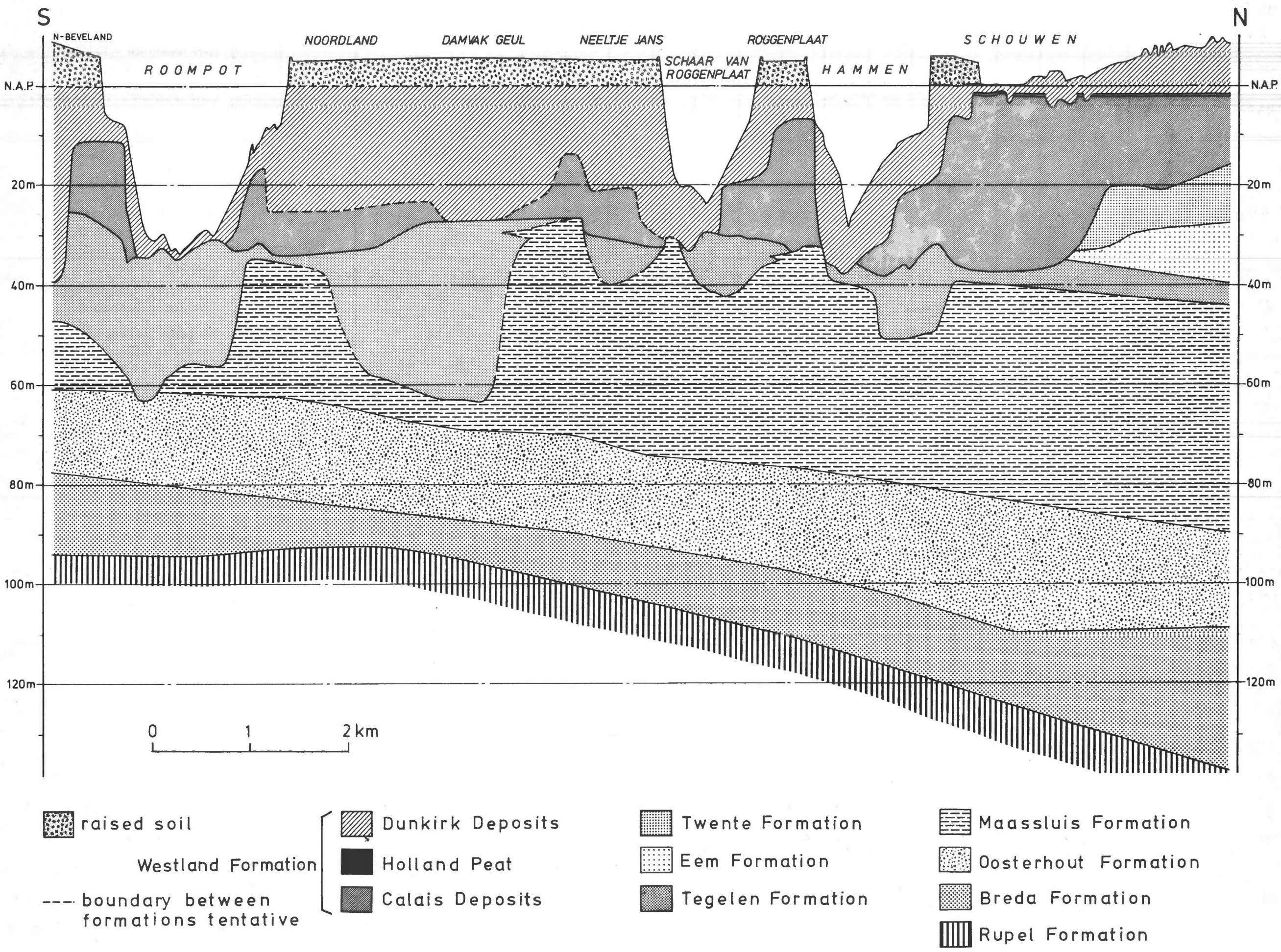

Fig. 2
Lithostratigraphic section along the centre-line of the primary dam in the Eastern Scheldt mouth.

these issues it was necessary to realise a large-scale program of site investigation in the mouth of the basin. This program of site investigation was carried out in several phases and consisted mainly of borings and cone penetration tests.

Borings

The first phase in the exploration of the subsoil on behalf of the initially planned complete closure by an earthen dam, existed of the execution of twelve bailer borings. Next, a considerable number of Ackermann borings, resulting in continuous, only little disturbed samples, were carried out up to 60 m depth.

In order to investigate the drainage conditions in the construction pits east of the work island another 12 air-lift borings were made up to approximately 80 m below NAP.

Besides these types of borings made on water three rotary air-lift borings were performed up to 150 m depth on the work islands and on land. In the last phase of the site investigation which was concentrated on the locations of the piers, predominantly borings of the Begemann type (continuous undisturbed samples, see LUBKING, this issue) were carried out from a diving bell placed on the sea floor and operating from a large pontoon.

After the macroscopic lithological description of the samples, the penetrated sediments were interpreted lithostratigraphically. Whenever boundaries between lithostratigraphic units could not well be established in the borings, biostratigraphical support by means of foraminiferal and molluscan research was given by the laboratories of the Geological Survey.

Cone penetration tests

Besides the borings many hundreds of cone penetration tests were executed, both along the axis of the future storm-surge barrier and in a broad strip at both sides of this alignment. In order to penetrate also the deeper strata a great number of these tests were executed partly as bailer borings. In the final phase of the site investigation the deeper cone penetration

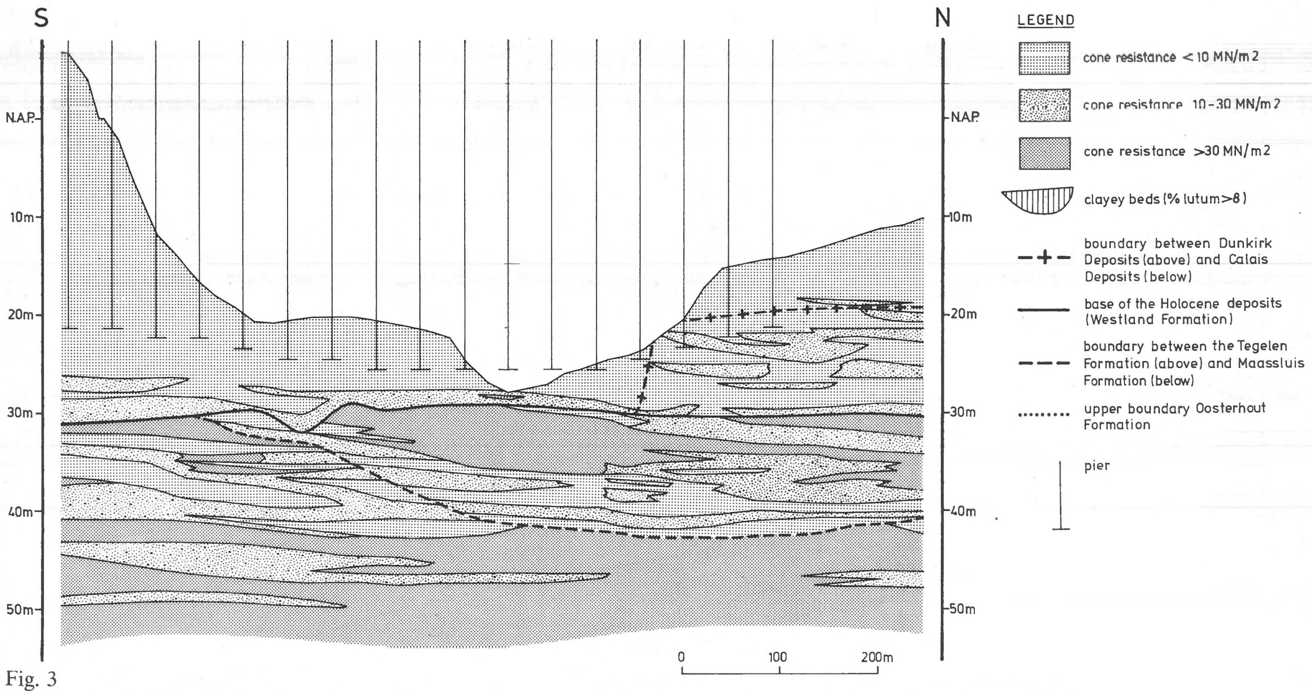

Fig. 3
Section showing the distribution pattern of cone-resistance zones in the subsurface of the Schaar van Roggenplaat.

tests could be realized from the diving bell directly. In the various programs of site investigation not only borings and cone penetration tests occurred, also several other types of soil probes and measurement techniques were tested and executed, such as pressiometer tests and density measurements *in situ*. This last type of measurement a.o. also resulted in a cone penetration test.

With the results of the cone penetration tests the borings were correlated in terms of lithology and lithostratigraphy. For this purpose the cone resistances obtained in the penetration tests were schematized and represented in three categories, namely 0-10 MN/m², 10-30 MN/m² and above 30 MN/m². By correlation of these categories of cone resistances it was possible to establish cone-resistance zones, the spatial configurations of which are determined entirely by geological conditions. These cone-resistance zones were plotted in cone-resistance sections. In addition, lithologic cross sections were compiled, indicating more particularly the extent of the clay-bearing strata.

RESULTS OF SITE INVESTIGATION

General

In the region of the Eastern Scheldt mouth the Early Pleistocene deposits are immediately overlain by the Holocene deposits. The boundary between the Holocene and the Pleistocene deposits under the primary dam alignment is situated between 29 m (Schaar) and 39 m below NAP (Hammen): it has an undulating shape (see figures 3 and 4). On the current axes of the present tidal channels the Early Pleistocene deposits are practically exposed at the sea floor. Apart from the lithologic differences mentioned below the distinction between the Holocene and the Pleistocene deposits lies in a difference in the state of consolidation as follows expressed by the cone resistances of the relevant lithostratigraphic units. This distinction in consolidation is primarily ascribed to the difference in burdening by overlying deposits to which the Holocene and Pleistocene sediments were subjected. For many hundreds of millennias the Early Pleistocene deposits have been overlain by a load of younger deposits, resulting in an optimum grain and particle arrangement both in the sand and clay successions. Calculations on the burdening history of the various lithostratigraphic units have shown that the burdening of the upper strata in the Tegelen Formation has been more than 80 times that of the lower strata in the Calais deposits. Other lithologic differences between the Holocene and Pleistocene deposits in this region exist in the lime, mica and fossil content and in colour. As a result of the site investigation a sediment description of the lithostratigraphic units relevant for the foundation of the piers is given below together with mutual comparisons between those units.

Maassluis Formation

In the discussed region these Earliest Pleistocene deposits consist of two major lithologic units. The upper unit comprises, besides well-consolidated sand beds, rich in shells predominantly, many clayey strata. The distribution of the clayey beds is generally of limited extent, while the thickness

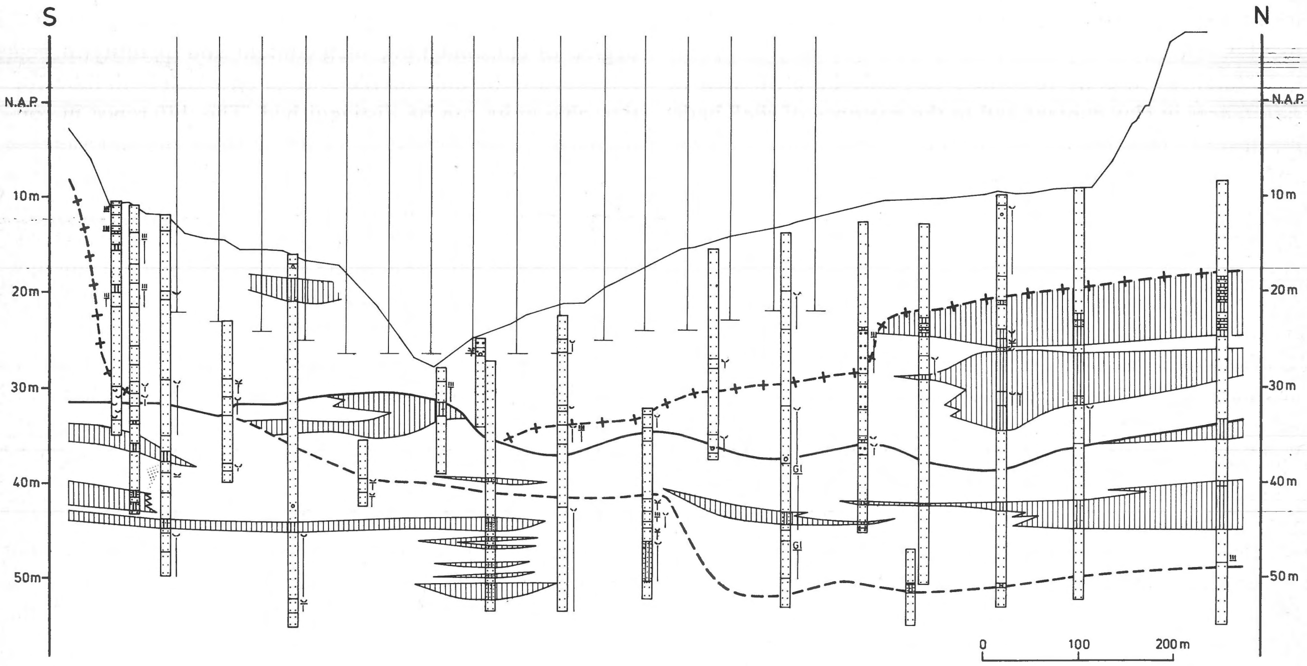

Fig. 4
Section demonstrating the distribution pattern of the clayey beds in the subsurface of the Hammen (for legend: see Fig. 2).

varies from a few decimetres to 7 m. These successions may consist entirely of clay or sandy clay or of thinly alternating clay and sand strata. The grey sands and clays of the upper part of the formation are highly calcareous. The mean grain size (M63) of these sands is between 150 and 300 microns. The percentage of lutum (clay-size particles smaller than 2 microns) of the clayey strata may range up to 45%. The lower part of the formation consists almost entirely of beige-grey sands containing a low amount of shell fragments.

The quantity of shell fragments increases considerably at a few metres above the base of the Maassluis Formation. At 2 m above the base of this formation a clay bed was penetrated by a boring in the Roompot. Otherwise the sands in the lower unit are nearly devoid of lutum, while the M63 size is between 150 and 300 microns, increasing to about 400 microns towards the base of the formation. Cone penetration tests in this formation yielded cone resistances of at least 2 MN/m² for the clayey strata, while values of more than 100 MN/m² were measured for the sands at the bottom of the formation. Most of these tests in this formation were performed with a cone of the non-constricted type.

The boundary between the upper and the lower lithologic unit within the Maassluis Formation is situated between approximately 42 and 45 m below NAP. The total thickness of this formation in the Roompot is about 30 m, which may increase to 45 m in the northernmost channel (Hammen).

Tegelen Formation

This formation consists of sands and clays deposited in river valleys and river plains. Below each of the present three channels in the mouth of the Eastern Scheldt the results of the site investigation demonstrate the presence of fossil fluviatile erosion channels, filled with sediments which belong to the upper part of the Tegelen Formation. The bases of these incisions in the underlying Maassluis Formation or Oosterhout Formation (Roompot) varies between 42 meters (Schaar) and 64 meters below NAP (Roompot). The oldest sediments in the Tegelen Formation are time-equivalent to the youngest deposits in the Maassluis Formation.

The sands generally are non-calcareous, often clayey, whereas the mean grain size (M63) ranges from 150 to 300 microns. These often micaceous sands frequently contain grey lumps of clay and organic remains.

The clay beds in this formation, in particular the 1-3 m thick clay bed at the top of this formation in the Roompot, may contain iron-carbonate concretions of considerable size. The lutum content of the clay beds in the Tegelen Formation may be as high as 45 to 50%.

The sand beds at the base of this formation may contain weathered remains of shells and foraminifera derived from sediments of the Maassluis Formation. The cone resistances in this formation, measured with a non-constricted cone, are between 3 and 6.5 MN/m² for clayey deposits and attain an average value of 40 MN/m² in the sands. This formation reaches its greatest thickness in the Roompot (30 m).

Both the Early Pleistocene Maassluis Formation and Tegelen Formation contain well-consolidated sand and clay beds. Differences between the two formations exist only in lime content and quantity of shells and shell fragments. Where the upper clayey part of the Maassluis Formation contains no macroscopically detectable shell material, this formation is hardly distinguishable from the Tegelen Formation.

Differences in cone resistance can only be attributed to differences in clay content and to the presence of shell beds. No distinct difference in consolidation of the sediments in the two formations has been registrated.

Westland Formation – Calais Deposits

Like the Maassluis Formation, the Calais Deposits can be subdivided into two units: a highly clayey and an entirely sandy succession. The former unit occurs only in the northern part of the Hammen, under the southern coast of the island of Schouwen (see figure 3). It consists of thinly bedded, more or less sandy clays, which alternate with sand beds, with a mean grain size (M 63) of 150-300 microns. The base of this clayey unit in the northern part of the Hammen is situated about 35 m below NAP.

The Calais Deposits in the Eastern Scheldt mouth consist for the most part of highly sandy sediments. These have been deposited mainly in tidal channels. They consist of grey calcareous sands, generally with a high content of shell fragments and peat remains. The mean grain size varies between 150-300, sometimes ranging up to 400 microns.

At the base of this sandy unit frequently reworked peat, clay boulders and iron-carbonate concretions from the Tegelen Formation occur. Beds for the larger part consisting of shells are rather common.

In the clayey part of the Calais Deposits, cone resistances between 0.5 and 10 MN/m^2 are attained, while in the sandy unit values between 15 and 25 MN/m^2 are commonly recorded. The shell beds in the basal part of the Calais Deposits display substantially higher cone resistances (30-40 MN/m^2). In contrast with those from the Tegelen and Maassluis Formations, these values are obtained with a cone of the constricted type.

Westland Formation – Dunkirk Deposits

The deposits associated with this last and, in this region, most agressive phase of the Holocene transgression are assigned to the Dunkirk Deposits. These sediments were laid down in deeply eroded tidal channels forming sandy shoals in the immediate vicinity of the tidal inlet. They consist of beige-grey, calcareous sands, generally with a high content of shells and shell fragments. These sands are often micaceous and glauconiferous, containing a considerable amount of peat remains. The mean grain size (M 63) ranges from 150 to 400 microns. The cone resistances in these deposits are relatively low. They seldom show higher values than 10 MN/m^2. However, this value may be substantially exceeded in sands with a high shell content.

In contrast to the Calais Deposits, the Dunkirk Deposits do not contain thick successions of clay beds in this area. The sandy sediments of the Dunkirk Deposits are, in general, very difficult to distinguish from the Calais Deposits. Colour, degree of consolidation, shell content and quantity of peat remains are the only subtile criteria on which both lithostratigraphic units can be distinguished. The difference in consolidation is determined also in these Holocene deposits by a difference in the amount of overburden and time span during which the younger deposits have rested upon them. The sediments at the base of a tidal channel fill of the Calais Deposits is found to have undergone 35 times the amount and time of burdening of a corresponding bed in the Dunkirk Deposits.

The difference in consolidation, expressed by the difference in density or pore volume of the sand is thought to be the main reason why specifically the sands in the Dunkirk Deposits are susceptible to liquefaction. Liquefaction or quicksand flow is the sudden slide of large masses of loosely packed sands and may take place when the contact-grain pressure is reduced by an increase of the water pressure in the pore water. Liquefaction therefore is one of the most serious threads to the constructions in and around the Eastern Scheldt basin.

The appearance of liquefaction is determined not only by lithology, but also by geomorphological factors such as the depth of the adjacent channel, the width of the foreland and the slope of the embankment, being important factors which likewise may trigger a case of liquefaction. Instead of the execution of a great number of the relatively expensive density measurements *in situ* and laboratory tests to determine the degree of susceptibility of a sediment to liquefaction at a particular place, the distribution and thickness of the younger Holocene sands were mapped by means of the available borings and cone penetration tests.

Mapping of the lithographic units in the subsurface of the mouth area of the Eastern Scheldt basin made it possible to answer very divergent questions and to give prognoses concerning the engineering-geological aspects of the foundation of the storm-surge barrier.

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