DORR, H. C. and DE HAAN, D. W.
Dosbouw Contractors, Burgh-Haamstede, The Netherlands

The Oosterschelde Filter Mattress and Gravel Bag

Le matelas de fondation et bourrelet de gravier de l'Oosterschelde

Main feature of the Oosterschelde Storm Surge Barrier is that the construction will be in open sea channels using prefabricated elements. The foundation of the piers must prevent erosion and water pressure generation in the sandy soil. A layered granular filter has been chosen, which is assembled into a mattress away from the site. This mat is transported and sunk on location. A variety of geotextiles was necessary for the mattress. A description is given of the choice of geotextiles and the composition and transport of the mattress.

The space between pier and mattress will be filled with a mortar. To protect this cavity against sand and silt, a seal is made around the pier base, which also acts as mortar formwork. The seal consists of a geotextile unit ballasted with gravel. The design, research and assembly of this gravel bag is also described.

The mattress and the gravel bag are specific applications of geotextiles, which perhaps will find a continued use in civil engineering.

Charactéristique principale du barrage anti-tempête de l'Oosterschelde est l'empilage en pleine mer par éléments préfabriqués. Comme le sol d'assise des piles est sableux, il y a une condition d'éviter l'érosion et les sous-pression sous l'ouvrage. Les matelas de fondation adoptés se composent de couches granulaires formant filtre. Ailleurs ces couches sont reliées entre elles de façon à constituer un matelas, transporté et immergé à son emplacement. La réalisation de ces matelas necessite une gamme de géotextiles. Une description sera donnée de la composition du matelas.

La cavité entre la pile et le matelas sera injectée de mortier. Autour du pied de la pile un bourrelet est confectionné afin d'empêcher la venue de la vase et du sable Il sert aussi comme coffrage du mortier. Ce bourrelet consiste en toiles de géotextiles bourré de gravier. La conception, la recherche et la fixation de ce sac seront décrites. Les deux solutions adoptées forment l'objet des applications spécifiques de géotextiles, qui peuvent avoir un large emploi dans le domaine du genie civil.

1. INTRODUCTION

The filter mattress and the gravel bag have in common that they will be used at the junction between pier and sandy soil. For the rest they are completely different items, with different purposes.
The filter mattress is described in this paper. The mattress is also subject of other papers of these proceedings (1),(2),(3).
The contribution concerning the gravel bag will be limited mainly to this paper. Therefore design and research are mentioned here in addition to the detailed description (1), (3).

2. THE FILTER MATTRESS

2.1 Brief description of the system

The sill and the foundation bed have been designed in accordance with the filter principle using granular materials, that is to say in layers, the size of material in each layer being coarser than the underlying layer until a stone size is reached which is sufficiently large to resist the current. Each layer is physically impermeable to the layer below, although water is able to pass through freely. The purpose of the foundation bed, as a part of this system, is to hold the fine Oosterschelde sand in place, despite the high water pressure gradient across the pier base. The impermeable filter below the pier is composed of, successively, a layer of sand, grain size 0.3-2 mm, a layer of fine gravel grain size 2-8 mm and a layer of gravel grain size 8-40 mm. On top of this gravel layer layers of stones are dumped .

The filter materials below the pier are not resistant to the current and it is very difficult to place them in the required layer thickness particularly in the Oosterschelde, where the soil is moving constantly and there is considerable natural sand transport. For this reason it was decided to prefabricate the filters in the form of a mattress on shore and then to place them on the sea-bed with a special pontoon.

The mattresses had to be sufficiently thick to be able to distribute the loads involved satisfactorily. However for practical handling reasons the thickness had to be limited and in fact two mattresses are to be placed on top of each other. The upper mattress also protects the lower mattress in the installation stage. There are 66 lower mattresses, each 200 m by 42 m by 360 mm thick, composed of, successively, 3 layers, sand 110 mm, fine gravel 110 mm and gravel 140 mm. The 66 upper mattresses which will lie immediately below the base of the piers are 60 x 31 m by 360 mm thick, however unlike the lower mattresses, they are composed of three layers of gravel. The weight of the filter mattresses is approximately 600 kg/m^2 the total weight being, for a lower mattress, 5×10^6 kg and 1.1×10^6 kg for an upper mattress.

The foundation beds are prefabricated by packing the granular materials into a system of geotextiles. In addition to having to meet the same hydraulic specifications as the foundation bed, the composite mattresses have also to meet high mechanical handling requirements, for which the development of new materials has been necessary. Because of the large quantity, approximately 700,000 m^2, filter mattress assembly has taken about 2 years and because of the quality required, it was decided to use an automated

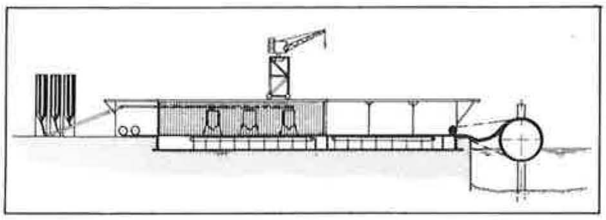


Fig.1 : Longitudinal section-mattress assembly plant.

production process. The filter mattresses are being assembled in a plant, then wound on to a floating cylinder and transported by a pontoon. The sea-bed is dredged and leveled to the correct depth and then the filter mattress is laid.

2.2 Fringe benefits

The fringe benefits, often established after prolonged research for the geotextiles used in the filter mattress, are defined by the hydraulic properties of the connected filter layers, the filter mattress placing operations and the method of production.
The hydraulic properties of the mattress are protection to the underlying sand and the water permeability, which have to meet high requirements in connection with the quality of the mattress. The operations with the filter mattress, such as winding onto the cylinder and sinking are dictated by its mechanical properties (2). The method of production has fixed the size and lay out. It will be obvious that the development of geotextiles to meet all specifications has demanded large-scale research.

2.3 Detailed specification of the filter mattress(Fig.2)

2.3.1 Supporting fabric (Fig.3)

The function of the supporting fabric of the filter mattress is to take the stresses and strains during winding onto the cylinder and the sinking operations. Because of the water depth of 35 m, in which the mattresses have to be sunk, and the high current force an ultimate design load of 800 kN/m is necessary in the longitudinal direction and 80 kN/m in the widthwise direction. For this purpose a polypropylene fabric has been developed, reinforced lengthways with steel wires, diameter 2.7 mm, and having a design load of 800 kN/m. This fabric is supplied on cylinders in lengths of 204 m for lower mattresses and lengths of 64 m for upper mattresses. The width is approximately 4.90 m. In order to achieve the required dimensions 9 widths are stitched together. In order to create enough strength the stitching seam is made with an Aramide stitching thread, which combines a small linear mass with a high strength.

Both outer widths are bent, in part, to shape the sides of the mattress. Polyester cord is used in this part to take the required strain, and not steel wires. During one week approximately 12,000 m^2 of this fabric, weighing approxemately 4,400 g/m^2, is produced with 3 special looms.

To transmit the forces of the mattress to the steel structure of the cylinder, the front and back of the mattress are fitted to heavy steel beams, referred to as the tail and head beam. To connect the mattress to the tail beam wedges of synthetic resin are fitted on to the steel wires in the supporting fabric, a connection device similar to that used with steel cable sockets. The connection for the head beam has to cope with less load and therefore a wrapping clamp is adequate (Fig.4).

2.3.2 Intermediate fabrics

In order to keep the three filter layers apart in the mattress intermediate fabrics are used between each layer. In order to meet the sand impermeability requirement a spun-bonded fabric is inserted on top of the supporting fabric. The intermediate fabrics have to meet the same specifications of water permeability as the filter layers. Between the sand and fine gravel it is sufficient to use a polypropylene spun-bonded fabric, between fine gravel and gravel, however, a gauze fabric is used composed of polyethylene monofilaments. These geotextiles are supplied in lengths of 1000 m with width varying from 1.50 to 5 m. In order to achieve the required dimensions the lengths of geotextiles are placed next to each other with an overlap of 500 mm. In all approximately 2,300,000 m^2 of spun-bonded fabric is necessary.

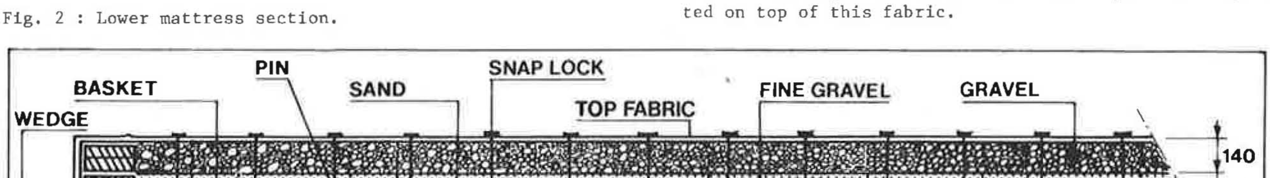
2.3.3 The vertical dividers

Vertical dividers are inserted to prevent the filter material from shifting in a longitudinal direction and to guarantee the thickness of the filter layers during the winding and sinking operations of the mattress. U-shaped baskets are turned inwards to enclose a spun-bonded fabric, the height of a basket being equal to the minimum layer thickness of the filter material. In all approximately 1,500,000 m^2 of gauze fabric and 800,000 m^2 of spun-bonded fabric are necessary.

2.3.4 Top fabric

The top fabric is the outer cover of the filter mattress. So that the filter mattress can follow the curve of the cylinder this fabric has to meet in addition to a water permeability requirement high strain requirements. The fabric,specially developed for this purpose, can take 25% strain in the longitudinal direction with a strength of 100 kN/m and at the same time 15% strain in the width with a strength of 80 kN/m. The fabric is composed of polyamid warp yarns and polyester weft yarns woven in an open-work bond. It is wound onto cylinders, in widths of 4.90 m and lengths equal to the lengths of the filter mattress. The full width of the mattress is obtained by stitching sections of the fabric together. The total amount is approximately 750,000 m^2. On the side of the mattress the top fabric is connected with the supporting fabric by stitching.
To enclose the filter layers at the front and the back side of the mattress wooden end units are fitted to which the various geotextiles are stapled. These wooden units are of the same thickness as the layers of filter material, and are joined to each other with nails and to the supporting fabric with bolts. In order to facilitate under waterinspection of the mattress a pattern is painted on top of this fabric.

Fig. 2 : Lower mattress section.



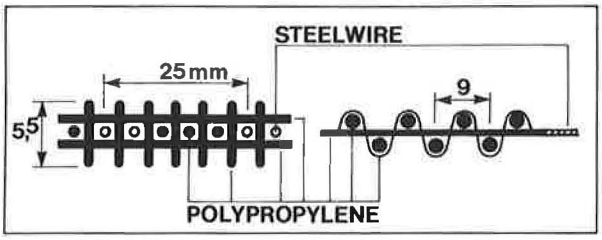


Fig. 3 : Supporting fabric structure.

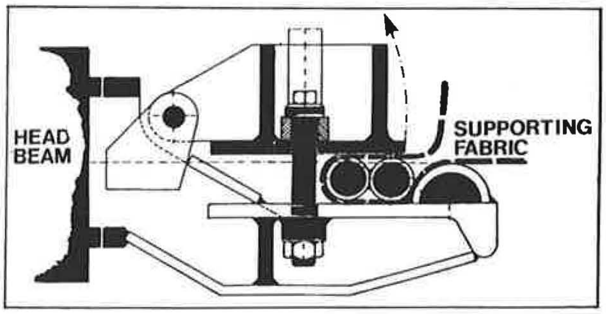


Fig. 4 : Wrapping clamp

2.3.5 Vertical joints

Steel pins are used as vertical joints between the supporting fabric and the top fabric to consolidate the layers together into a compact mattress. These have a diameter of 6 mm, and have on one end a nail head and on the other end a sharp point; a washer is used on the lower side. The connection on the upper side consists of snaplocks, with a minimum gripping force of 5 kN. The pins are also used to prevent the baskets moving. Eight pins are used per m^2, so in total about 6,000,000 pins and associated snaplocks and washers are required.

2.4 Detailed description of the production process(Fig.5)

2.4.1 General

The assembly plant consists mainly of a production hall and a discharging wharf. The production of the mattress in the assembly plant is independent of the mattress-laying process in the Oosterschelde and two transport cylinders are used for this purpose. The production capacity is determined by the progress required at the construction site of the barrier. This means, in fact, that on average one filter mattress must be completed every 40 hours. During the assembling process the mattress is moved underneath stationary machinery. For this purpose the floors of both assembly plant and discharging warf consist of 9 synchronised chain conveyors driven by electric motors. The assembling process takes place at ground level and has been phased in such a way that a two metre strip of mattress can be assembled every ten minutes. The whole mattress is then moved forward a further two metres by 9 coupled chain conveyors at the same height towards the discharging wharf. The conveyors inside the production hall can operate independently of those on the discharging wharf, so that the assembling process can be disconnected from the operations taking place on the discharging wharf. The operation machinery of the plant and discharging wharf is housed in a large concrete basement which also contains some machinery for parts of the assembling process. The time required to assemble a mattress of 200 m is 24 hours; the time to handle the same mattress on the quay is about 10 hours.

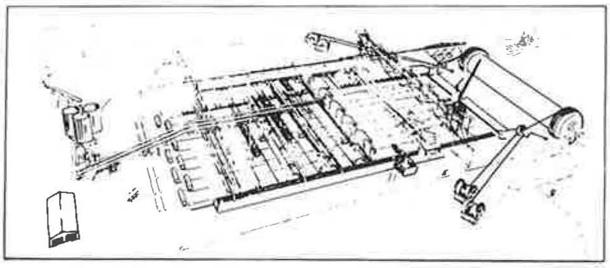
2.4.2 The production hall

The process starts with the pouring of the wedges independently of the production process. This operation is carried out in the wedging shed which is situated apart of the assembly plant. From here rolls of supporting fabric are then taken to the west side entrance of the plant by crane and mounted ready to be decoiled. The 9 widths of the supporting fabric are then stitched together to an overall width of 42 m by 8 sewing machines housed in the basement. To avoid storage within the plant the baskets are manufactured at the same time as the filter mattresses in the basket hall, north of the mattress assembly plant. The basket hall houses three machines which mould the steel netting and cut it to size. Both top edges of the U-shaped baskets are turned back 180° to enclose a geotextile. After having been placed in position, ready for use, the baskets are transported to the assembly plant by 4 basket transporters and placed in the correct position on the mattress. Three such operations operate parallel to each other.
The granular materials are transferred from the storage depots to a hopper by a front loader and transported to the appropriate silos via a movable chute and a conveyor. Three independently operating conveyor systems feed the materials into three moving distributors and four stationary hoppers, the latter being used particularly for the sides of the lower mattresses. When the material has been distributed on a two metre strip of mattress, the moving distributors are refilled, which takes only two minutes, whilst the mattress moves on. The adjustable vibrating chutes below the hoppers ensure an even layer of filter material, unaffected by the inevitable sagging of the supporting structure and conveyors. The sides of the various fabrics which, during the assembling process, have been bent vertically are stitched together with sewing machines before the pins are injected through the mattress. Widths of the top covering are stitched together as they are being unrolled vertically. The top covering is then transferred to a horizontal position and both ends are stapled on to the wooden end units.
The equipment for injecting the pins consists of an upper and an under carriage. The under carriage runs on rails in the basement and hydraulically injects 75 pins every 5 x 2 m area of the filter mattress. A detection and positioning system ensures that the injected pins do not hit the steel wires in the supporting fabric. The synchronised upper carriage, running on a steel structure above the mattress, meets the 75 pins, fixes bowl-shaped snaplocks on to them and cuts off the sharp ends. By this method it is possible to inject, secure and cut 700 pins during the 10 minute period when the mattress is stationary.

2.4.3 Discharging wharf

As soon as the beginning of the filter mattress approaches the fixed quay floor at the end of the second chain conveyor, it is connected to the tail beam by means of the fitted wedges. The tail beam itself is coupled to the filter mattress cylinder by steel cables. In the final stages of winding there is only a small part of the mattress remaining on the quay. To prevent this end of the

Fig. 5 : Mattress assembly plant.



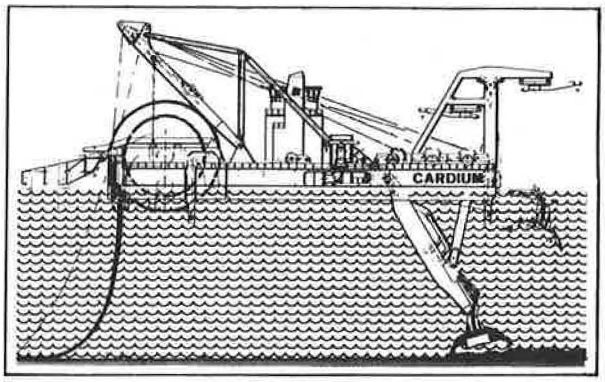


Fig. 6 : Pontoon Cardium

mattress from suddenly sliding off the quay, and to control the whole winding process, a braking system has been devised. This system consists essentially of a heavy steel bridge construction. Two heavy winches have been positioned on the bridge, each capable of delivering a braking force of 1500 kN.

Balancing and loading winches.In order to keep the cylinder in balance during winding two balancing winches have been installed. The winding operation itself is carried out by two loading winches. The winding process proceeds intermittently, each two metre length of mattress, which is completed and fed through every ten minutes, taking only one minute to be wound on to the cylinder. When the mattress is being wound on to the cylinder, the load on each of the two winch cables increases progressively to a maximum of 2250 kN, relative to the balance, mattress radius, mattress weigth and water level.
The whole plant and quay is bridged by a portal crane, which has a lifting capacity of 1200 kN, and is used mainly for operations on the quay, such as the handling of the head beam, which weighs 1100 kN and the tail beam, which weighs 850 kN. After the mattress has been wound the floating cylinder is disconnected from the discharging warf and transported by tugboats to the Cardium.

2.5 The Cardium (Fig.6)

A special vessel has been built for placing the mattresses. This special vessel, the Cardium, with a length of 72 m and a width of 80 m will simultaneously smooth out the sea-bed by dustpan dredging, and place the mattress by unwinding it from the floating cylinder. The cylinder is connected temporarily to the rear end of the vessel, where it is accomodated in a recess. The cylinder has an unloaded diameter of about 15 m and a characteristic width of 46 m between "shields". The cylinder is prevented from untimely unwinding by wires arranged around it.
At the front of the vessel, a recess accomodates a suction ladder with dustpan suction heads and dredge pumps. Eight mooring winches are normally available to position and shift the vessel, the eight mooring lines being attached to piles driven into the sea-bed.
After this operation the foundation bed for the piers is finished. By the time the job is completed at the end of 1983, a new method of foundation techniques involving a great amount of geotextiles will have been developed and intensively tested on the site and will be ready for use elsewhere in the world.

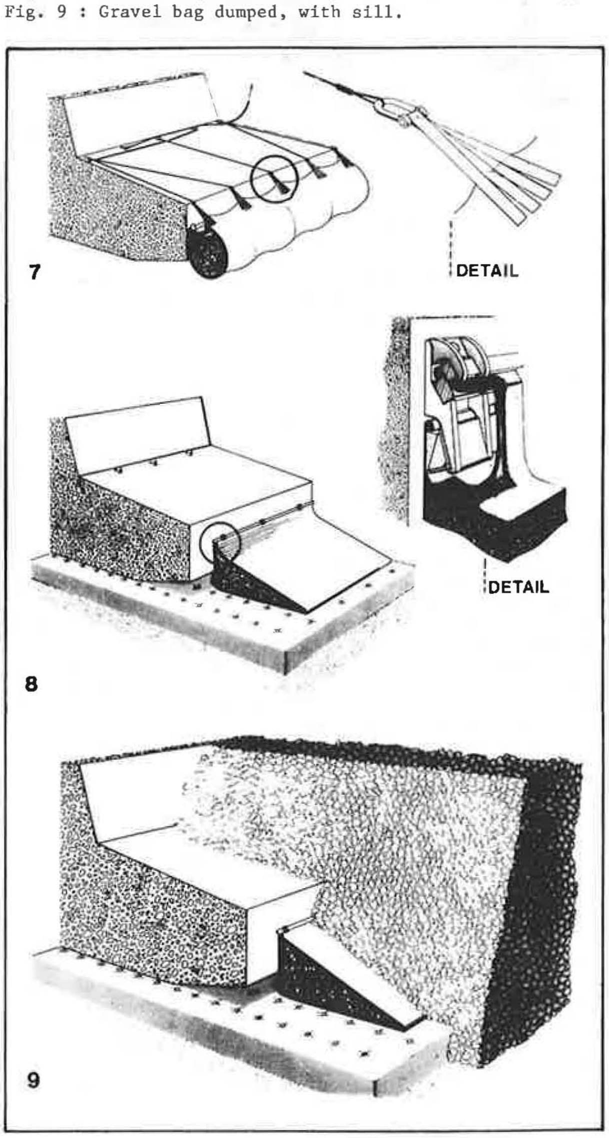
3. THE GRAVEL BAG

3.1 Brief description

After placing the piers on the foundation bed open spaces will remain between the base of the piers and the filter-mattress. This cavity has to be filled with a sand-cement mortar in a later stage of the construction. The gravel bag is necessary to keep that cavity temporarily open.

The phenomenon "gravel bag" (Fig.10B) requires some initial explanation. It is basically a strip of manufactured fabric, 100 x 8 m, that is folded into two along the width and is filled with 160 x 8 m^3/m coarse gravel. This "sausage" of fabric and gravel is positioned round the pier, firmly connected to it and tied up onto it (Fig.7). This gravel bag is a rather vulnerable structural element that is to be attached at the end of the construction of the enormous prestressed concrete piers. After inundation of the construction dock and transport to the site, the pier is placed at its final location. Immediately after placing the spaces remaining under the piers must be protected against penetrating sand, silt and attaching sea-organisms. Therefore the gravel bag is to be unchained from the tied-up situation, so that is falls out onto the

Fig. 7 : Gravel bag tied-up - suspension loop detail.
Fig. 8 : Gravel bag unrolled - pier connection detail.
Fig. 9 : Gravel bag dumped, with sill.



foundation mattress and closes the cavity around the pierbase (Fig.8).
In the following construction stage the sill is dumped and only then the joint between pier and mattress can be completed by injection of sand-cement filling from inside the pier.In this stage the gravel bag acts as mortar formwork (Fig.9).
All 66 piers are to be provided with such a gravel bag.

3.2 Surround seal;functions and conditions

Generally it is necessary to provide a seal around the pierbase. This will have a twofold function: as a seal against penetrating sand and silt and as a mortar formwork.
The first requirement is very essential. When sand or silt deposits in any extent under the piers there is an unreliable element in the foundation. Under the influence of water head and wave loading the pier will exercise large static and cyclic loadings on the foundation. This results in large water pressures and in static and dynamic gradients of many hundreds of percents(400-600%). Sand and silt can thereby be washed away which could result in rotation and translation of the pier and seizure of the gates.
The formwork function prevents mortar leakage and at the same time guarantees the reliability of the underbase filling process and the quality of the filling layer.

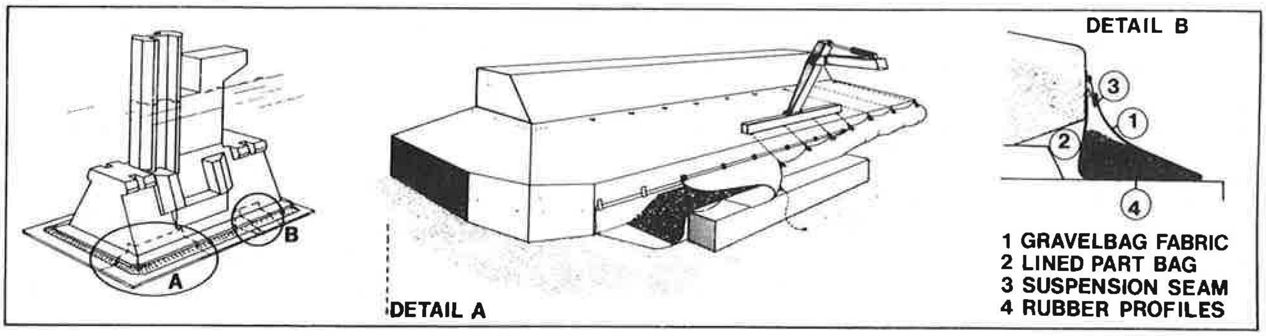
In detail this means also that the connection of the surrounding seal to the pier and mattress must fulfil these requirements, thus a siltproof seal against a rough concrete surface and against a mattress surface which will not be a model of flatness. Finally there is the time requirement that the system has to function immediately after placing the pier. Otherwise it must be sufficiently durable until the underbase mortar filling is executed; set at 5 years, including the necessary margin.

Besides these requirements there are many more boundary conditions, of which the important ones are:
- the height to be sealed can vary between 0.4 and 1.1 m, with local variations from 0.15 -1.35 m.
- the filter mattress may not be damaged by the sealing construction.
- limitations of weight and space in view of transport.
- the system has to withstand currents during transport and after release (2.5 m/sec).
- because of the durability requirement no holes must occur in the sill.

3.3 Detailed description

The main characteristics of the gravel bag are sealing obtained by the fabric; siltproof, and also as porous as possible. The contents of the bag has a weight function and enables the bag to withstand currents. The bag is pushed homogeneously against the bottom and the loose filling prevents the bridging of the fabric as much as possible over abrupt irregularities in the mattress.
The filling itself would not withstand the currents expected, therefore the bag must be closed carefully.
The durability requirement is very limited. The line has been taken that the textile can cease to functionduring the lifetime of the piers which is more than 200 years The grain size of the granular filling should therefore be a part of the filter formation of the sill, in which every layer is inpenetrable to the underlying material. Gravel 8-40 mm has therefore been selected.
The size of the gravel bag is ample, because a large height has to be spanned and at the same time a large connection with the mat is necessary. During transport the gravel bag would hang about 3.0 m below the pier. This however, cannot be allowed, it would be too vulnerable and uncontrollable. Therefore it was decided to tie the bag up against the pier. On the top edge of the pier base pins have been fixed 1 m apart, to which the bag can be fastened. Tying up is achieved using suspension loops sewed to the fabric. Wire ropes connect the loops to the pins.
In the submerged situation the tying up has to be undone. This is effected with the help of long steel ropes, which are lead under the tying up ropes and then upwards. The gravel bag is unfolded around the pier by pulling the ropes.
The connection with the pier consists of a double clamping device for both longitudinal sides of the fabric. Each side is doubled over a 30 mm thick rope with a considerable overlap and fastened with wooden wedges under the clips; 1 m apart (Fig.8).
The rope is tightened by pulling the fabric and pushes the fabric against the pier. A maximum tightness developes against the pier and the fabric is fastened without being exposed to peak loads.
To prevent any imperfections in tightening between the gravel bag and the foundation mattress a rubber profile has been developed which closes the last openings. The profile is tied on to the gravel bag.
In the actual choice of fabric the "permeability" requirement was less important than the siltproof requirement. Therefore the gravel bag is lined at the pierside with an almost waterproof textile.
In practice, based on the forces, a polyamide fabric has been chosen with interwoven strengthened strips 0.5 m wide, 1 m apart, at the same frequency as the suspension loops.
The fabric is woven 5 m wide, in which the five strengthened strips are provided by using three times the number of the warp threads. The direction of the strips is transverse because of the force direction. The unfolded width of the gravel bag is 8 m.
For manufacture, pieces of 8 m length are cut, on which the loops are sewed and the lining connected. Then half of the gravel bag is laid out and assembled on a large floor. The cross-seams and the expansion-seams are sewed on and the ropes connected with the longitudinal sides and the rubber strips fastened. This stage is completed by zig-zag folding of the bag and rolling it up.

Fig. 10A : Pier with gravel bag assembly.
Fig. 10B : Gravel bag section.



For the assembly procedure on the construction dock (Fig.10A), wooden boxes are installed at a fixed distance from the pier of 1.3 m. The gravel bag is unrolled. The clamps and lathes of the pier connections are fastened, the inner brim of the gravel bag clinched to the pier, the fabric pushed smoothly into the gutter between pier and boxes with the remainder of the fabric hanging over the boxes. The gutter is then filled with gravel and levelled. The outer brim of the gravel bag is then clinched and with the help of a crane with balance beam a part of the gravel bag is lifted and pulled in the direction of the pier, after which the ropes can be attached onto the pins of the pier.

3.4 Design aspects

The separate loading situations have been considered for the design in the successive stages. From here the critical loadings are deduced.

The assembly in the dry dock is a first stage with critical loadings. The forces develop from the dead weight of the filling, about 1400 kg/m. The lifting force of about 20 kN, on the gravel bag via the loops is important. This force is halved after connection onto the pins of the pier. The load-distribution is clearly a plane strain situation, especially during the lifting, because only three loops are lifted at the same time pulling up the adjacent part of the gravel bag.

The first important loading in the underwater stage occurs during untying. Because of the delayed fall of the loose granulated filling and the resilience of the elastic fabric it is difficult to analyse this arithmatically. Therefore prototype tests were necessary. In one of these tests an impact load occurred in a loop by a hitch when discharging the suspension wire. The disconnection of that loop gave a chain reaction, in which several loops broke. The fabric appeared to be completely undamaged, only the stitching was severed, so that the hitch was acceptable. The loading force had apparently exceeded the limit of load of 50 to 60 kN. Precautions concerning a premature and unintended discharge are therefore absolutely necessary.

The next critical loadings concern dumping sill material from the water surface. In this process the unrolled gravel bag is hit directly by stones of 8-40 kg and after that a static loading is built up to a σ_V is about 80 kN/m^2 and a σ_H is 20 kN/m^2.
After unrolling, the full capacity of the fabric is utilized. The falling stones set the fabric tight from below through which it is stretched. After this the static load has to be taken up, which overloads the fabric and the pier connection. Therefore an expansion-seam is incorporated into the outside of the gravel bag (Fig.10B). The strength of this has to be sufficient unrolling the bag but smaller than the strength of the pier connection.
Such expansion-seam is not necessary for the fabric at the pierside. The design elasticity garantees a small radius of curvature such that the maximum force is only 25 kN/m.

From these considerations and the tests described below it appears that there will be continuous loads of 10-25 kN/m and loadings of 25 kN on the loops, which have to be taken up locally in the fabric. The necessity of a rather large elasticity has been proved. In addition the expansion-seam will give extra capacity.

Naturally a decrease in strength will occur due to absorption of water in the filement; by ageing of the material as result of UV-radiation (maximum of two years); and the alkaline environment; and by creep as result of durable loading, all had to be taken in account. Also processing details and vulnerability had to be taken in consideration

In connection with these remarks the following primary requirements have been stated:

- linear strength in both principal directions	150 kN/m
- linear strain limit in both directions	150 %
- strength, loop at 45° with the fabric	50 kN
- tensile strength on pier connection at 30°	25 kN/m
- fabric sand tightness	$O_{90} \leqslant 300$
- silt tightness of lined fabric	$O_{90} \leqslant 10$
- strength sewing-seams with regard to fabric	70 %
- strength stitchings with regard to fabric	50 %
- strength expansion-seam	$\geqslant$ 20 kN/m and $\leqslant$ 25 kN/m
- lining strain equal to fabric strain.	150 %

3.5 Research

The design process has been accompanied by prototype tests through out from the very first until completion. All the time the practical possibilities of processing, the realisation of the pier connection and the critical loading situations have been reviewed. The tests were executed in dry conditions, with the assumption that this overloading would amply balance the reductions in strength and other influences on the specifications of the gravel bag as result of water absorption, ageing and creep. This method has been necessary for determination of the development of such a new structural element and its details. Initially tying up gave unexpected problems. The filling consisted of 1 m^3/m sand 0.3-30 mm. The internal friction gave large resistance to lifting the bag and to pulling it to the pier. When the contents were replaced by gravel 8-40 mm, the friction seemed to be so much smaller that simpler methods were possible.
The development of the suspension loop was also an important detail for research. The force of 50 kN at 45°with the fabric posed strong requirements to the connection. Cross-seams or zigzag-seams for the strings and the fabric formed connections which were too inelastic. Only the longitudinal seams proved to be sufficiently elastic, so that the stitches were equally loaded and reliable. In order to ensure that both strings came under load simultaneously small adaptions were made to the form of the loop. Particular examples of the consequences of the present plane strain condition were formed by the expansion-seam in the fabric with the strengthened strings and the lining on the ordinary fabric.
The research on the UV-durability of the fabric and yarns indicated a small reduction of strength (10%). The same applies for the water absorption (15%). The results of creep tests indicated changes of a few percent, particularly the stitching of the loops.

3.6 In conclusion

Because of the vulnerability of the gravel bag system a spare bag has been designed. When diver-inspection of the unrolled gravel bag indicates a possible mal-functioning, the bag can be installed.
The gravel bag has been chosen from various alternative designs, the criteria being the technical aspects mentioned in Section 3.2 and the costs.
The total costs of supply, manufacturing and assembly of the fabric and all other parts amounts to approximately U.S. $250/m.

4. References

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