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A Case Study on the Performance of Embankments on Treated Soft Ground

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ABSTRACT
The proposed construction of a new high-speed rail link between Amsterdam and Brussels involves construction of embankments overlying soft clay and peat deposits with very stringent requirements on the time frame of construction and allowable settlements. A field program of instrumented test embankments, referred to as No-Recess, has compared the performance of five schemes for stabilizing the soft ground behavior. This paper summarizes the No-Recess project and compares the measured performance for an unimproved embankment using finite element analysis, and two tecniques from the project. The results confirm the benefits of geotextile encased sand columns as a practical technique for stiffening underlying soft soils, accelerating consolidation and reducing settlements.

RESUMO
O projeto No Recess envolve uma série de aterros experimentais, onde foram selecionadas cinco técnicas de melhoramento de solo. Este projeto consiste em avaliar diferentes técnicas para estabilização de um aterro ferroviário construído em solo mole para a construção de uma linha de trem de alta velocidade entre Amsterdã e Bruxelas. O projeto “No-Recess” requer novas técnicas de construção de aterros sobre solos moles pela exigência de requerimentos muito rígidos. Foram feitas comparações diretas de instrumentação de campo no intuito de demonstrar a viabilidade dos novos métodos na construção de aterros. Este artigo sintetiza o programa de campo do projeto “No-Recess” e analisam as comparações feitas usando como referência o modelo de elementos finitos bi-dimensional no caso do aterro sem melhoramento de solo e o comportamento em campo de duas técnicas de melhoramento de solo usadas no projeto: (1) drenos convencionais pré-fabricados, e (2) colunas de areias encamisadas com geotéxtil.

1. INTRODUCTION

The new high-speed rail link between Amsterdam and Brussels will require new techniques for construction of embankments overlying soft soils. The principal factors affecting the design of the embankments are related to the high train velocities, short construction time, and very strict requirements on residual settlements. After analyzing these requirements, a research team initiated a program in 1997 to evaluate different techniques for stabilizing railroad embankments constructed on very soft clay and peat foundation soils.

The program, formally entitled “New Options for Rapid and Easy Construction of Embankments on Soft Soils” (No-Recess), was a joint venture of the railroad project manager High-Speed Rail South, the Ministry of Transport, Public Works and Water Management, Road and Hydraulic Engineering Division (RWS/DWW), and the European Community (EuroSoilStab lime-cement columns project).

The No-Recess project comprises a series of test embankments constructed in the Hoeksche Waard polder near Gravendeel in the Netherlands. Five ground improvement techniques were selected during a workshop in 1997 in Delft based on advice from a panel of international experts. Direct comparisons of field performance were intended to demonstrate the viability of the new methods for constructing the railway embankments for the new high-speed line. Since there was no prior experience of these construction methods in the Netherlands, the instrumented embankments were monitored for two years after the end of construction.

This paper presents a summary of the No-Recess project. A two-dimensional finite element model, used as a reference, is developed to represent the in-situ conditions and soil properties at the site for one case of an unimproved embankment and the measured performance of two of the five ground improvement schemes used in the No-Recess project: (1) using pre-fabricated conventional drains, and (2) reinforcement of the soft soil with geotextile encased sand columns.

2. NO RECESS PROJECT

2.1 Objectives of No-Recess Project

The goal of the No-Recess research project was to investigate alternatives for constructing embankments on soft clay foundations, which would provide a cost effective alternative to slab track. The techniques in the No-Recess project are compared with a reference technique of embankment construction using with a traditional pre-fabricated, vertical drains, together with surcharge loading to accelerate consolidation. Since the purpose of the No-Recess project was to address design requirements imposed by the high speed train, the following specification were formulated:

- Short construction time
- Low residual settlement
- Minimum surplus of soil
- Sufficiently stiff behavior of the construction under dynamic loading by high "speed trains"
- Minimum impacts caused by widening of existing rail or road constructions

The purpose of selecting the new techniques was to fulfill the requirements to accomplish the specifications above. Five instrumented embankments were constructed in the Hoeksche Waard as follows:

- HW1: Conventional test embankment with vertical drains
- HW2: Lime stabilized soil columns
- HW3: Stabilized soil walls
- HW4: Geotextile encased sand columns
- HW5: Stabilized soil test embankment on piles

2.2 Site Characteristics

The test site has a plan area of 400x125m, with level ground surface at EL –0.75m + NAP (Niew Amwsterdam Piel, datum). Each embankment was constructed with a high part, 5m above the ground level, and a low part, 1m above the ground level. Figure1 illustrates the lay out of the five embankments area.

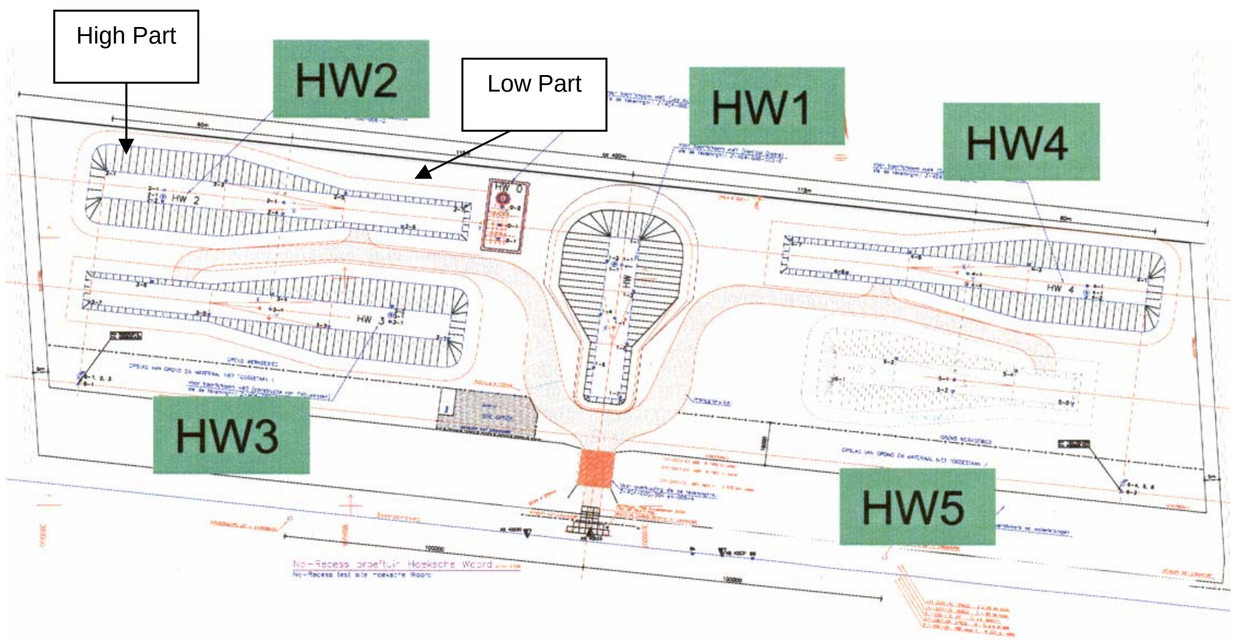

Figure 1. The Hoeksche Waard (HW) test site (Geotechnical Engineering for Transportation Infrastructure, 1999).

The underlying soft foundation soils are typically 9.7m thick and comprise the following main layers:

Clay 1: average thickness of 3.1m of clay, very silt, moderately organic, grey, with sand lamination;
Peat 2: average thickness of 2.0m of peat, slightly clayey, wood fragments, brown, grey (Hollandveen);
Clay 2: average thickness of 3.0m of clay, extremely silty, moderately organic, peat traces, wood fragments, grey;
Peat 2: average thickness of 1.6m of peat, highly organic, brown, with sand lamination (Basisveen).

All of these layers are Holocene deposits. Below the Basisveen peat layer is a thick sand layer comprising medium-fine, slightly silty sand, which is considered to be relatively incompressible and free draining. The watertable is located at el. 2.2m.

3. GROUND IMPROVEMENTS OPTIONS

3.1 Ground Improvements Options

The five embankments were designed to have a high part (5m above initial ground surface) and a low part (1m above initial ground surface) with side slopes of 1:2 (v:h) with a transition zone of 10 m located at the end of the high part. Each embankment was to be constructed within eighteen months (after the working platform was made), followed by a period of six months prior to assume surface construction (rail bed installation). The residual settlements expected after 24 months from the start of the construction must be less than 30mm over a 30-year period.

3.1.1 Conventional Test Embankment (HW1)

The conventional test embankment (with pre-fabricated, vertical drains) was constructed to provide a base reference on performance compared with the other test embankments. The conventional embankment was constructed in stages within a 6-month period. The surcharge of the low embankment was 1.8m of sand whereas for the high embankment was 2.5m of sand, both for a year. In both, low and high embankments, the vertical drains were installed to a depth of 1m above the sand layer and were designed with 1m triangular grids.

3.1.2 Stabilized Soil Columns (HW2)

The stabilized soil columns method used in HW2 is the Scandinavian lime-cement mixing method of stabilizing clay soil mixing 200kg/m^3 of new binder mix comprising 80% of blast furnace cement and 20% anhydrite (instead of the combination of Portland cement and unslaked lime that would be used in Scandinavia). This mixing method of stabilization technique (dry mix technique) uses dry air to transport the binder. The reason for the change in the binder mix is to have better performance with this new mixture in the soft Dutch soils.

The embankment was constructed in 1 month. For both parts, high and low, a surcharge of 1.0m for a period of 260 days was needed to accelerate the consolidation process. The lime columns were 600mm in diameter and were placed in 1.6m square grids for the low embankment whereas for the high embankment they were placed in the range of 1m to 1.2m square grids. For both cases, the columns extend 0.5m into the underlying sand layer. The low part of the embankment uses stabilized blocks (overlapping short columns) of 1.5m, which were produced with a speed of 500m per day.

3.1.3 Stabilized Soil Walls (HW3)

The technique used in the test embankment HW3 comprises the stabilized soil walls installed by the FMI process (Barends et al., 1999), a process of constructing a soil mix wall using a specialized cutting tree device. The machine has a speed around 1m/min with a maximum depth of 9m and width of 500mm. The cutting tree device is inclined up to 80 degrees and is dragged behind the FMI machine. Due to the cutting blades rotated by two chain systems, the soil is not excavated but mixed in place with cement slurry. The embankment was built in two weeks.

In the high embankment, a load transfer platform was used, which is placed at the height of 0.5m with 3 geotextiles (geogrid type SS20, SS30 and 80RE with crushed rock). The stabilized walls are placed at an interval distance of 1m to 2.5m in both parts of the embankments, but in the case of the stabilized block, it is placed at a depth of 1.5m only in the low part. The binder dosage used for both stabilized walls and stabilized block is 150 kg/m^3, where 80% consists of blast furnace cement and 20 % of anhydrite.

3.1.4 Geotextile Coated Sand Columns (HW4)

Geotextile coated sand columns (GCC) system is the technique used in HW4. This process consists of vibrating a casing with two valves at the bottom until it reaches the sand layer. A 40-cm thick layer of sand is made, a geotextile stocking is installing and filled with 1m of betonite/sand mixture to create a geo-hydrological barrier. Then, the rest of each 800mm diameter column is filled with sand to the top of the casing, which is vibrated and pulled upwards, compacting the sand. This system can have a rate of construction of 40 columns per day. The embankment with a load transfer platform of geotextiles in the HW4 test was constructed in 6 weeks.

For both parts of the embankments, the depth of the columns is 9m below ground level and the distance between columns is 2.4m to 3.4m triangular grids for the low part, whereas for the high part, it is in the range of 2.0m to 2.4m. For the low part, a surcharge of 1m of sand for one month and one geogrid Fortrac 80/80-10 were used, whereas for the high embankment, three layers of Fortrac 200/30-30 geogrid were used and no surcharge was necessary.

The geotextile coated sand columns technique involves the in situ joining of large diameter, closely spaced, vertical sand columns within the compressible layers. This technique was used in the No-Recess project (HW4) in order to stabilize the compressive soft soil and minimize the long-term settlements. The geotextile confines the sand and acts as a filter to prevent intermixing with adjacent clay and clogging. It also provides the stiffening effect to ensure integrity of the sand piles. These features allow the columns to act as piles, considerably mitigating settlement and deformations due to dynamic loads. Another advantage of the sand column technique is its relatively rapid construction time.

Many foundation benefits have been found with the use of sand columns in soft soils such as increasing the bearing capacity for overlying structures or embankments, accelerating the consolidation process of the consolidating layer surrounding the granular columns, and improving the load-settlement characteristics of the foundation.

Inclusion of the columns reduces soil drainage path length, and increases the rate of excess pore pressure dissipation. Installation of the sand column by displacement techniques may minimize the soil permeability due to formation of the smear zones along the column boundary, but since the column are closely spaced, the dissipation of the pore pressure can still be achieved quickly (Bredenberg, 1999). One of the major factors to be considered when improvement of the treated foundation is to be predicted is the stiffness of the sand columns relative to that of the soil in which they are installed.

The installation method consists of vibrating a steel casing into the ground to the load bearing layers. The casing has two flaps at the bottom, which are forced closed during driving, displacing the ground. The geotextile is connected to a funnel, which is put in the top of the casing. The tube is filled with sand through the funnel and the casing vibrated out, causing initial compaction of the sand and stressing the geotextile (Nods, 2002).

Sand columns generally have a diameter in the range of 0.8m, and they are normally placed in a triangular pattern with a spacing of 1.7m to 3.4m. In the case of the No-Recess project (HW4), the columns had a diameter of 0.8m and were installed in a triangular grid in the range of 2.4m to 3.4m for the high embankment. A geogrid is laid over the columns in a load transfer platform in order to give extra horizontal stability and help to transfers horizontal railway loads. To avoid large long-term settlement, surcharge is used to accelerate movements (Nods, 2002).

3.1.5 Stabilized Soil Test Embankment on Piles (HW5)

The piled foundation in the technique used in the HW5 trial is made with wooden piles and AuGeo pile system (Barends et al., 1999), and the sand used in the embankment is replaced by stabilized soil from another site, which is made by using mix-in place plant installation. The embankment was built in six weeks, with a production rate of 200 piles a day.

The AuGeo pile system basically consists of a Cofra stitcher that pushes a steel plate into the ground with a casing (180x180x6.3mm) using maximum load of 25tons. After that, a PVC pipe, which is sealed at the bottom, is inserted in the casing and filled with the foamed concrete with unit weight of 1200kg/m^3. The last step of this process, after having sufficient hardening of the concrete, is to lift the casing, cut off the PVC pipe, and cover the top with a concrete tile of 300x300mm.

The depth of the piles for the low and the high embankment is 12m below the ground level but the pile type used for the low embankment was AuGeo pile system only, whereas for the high embankment wooden piles were also used. The distance of piles in the case of the low embankment was 1m square grids, but for the high embankment a 0.8m square grid was used.

For the low part of the embankment, 1m of stabilized soil was used with a binder dosage of 120kg/m3 where 80% was blast furnace and 20% is anydrite, whereas for the high embankment 5m of stabilized soil was used. The load transfer platform consisted of two Fortrac geogrid layers with a thickness of 30cm and with a fill of crushed concrete for both cases.

3.2 Monitoring

Each of the five embankments was monitored to provide detailed information on vertical and horizontal soil displacements, pore pressure, and vertical stresses. Each design is expected to satisfy stringent rail requirements for embankments of high-speed trains (with reduced construction time and long-term deformations). The monitoring was carried out from the start of construction through the end of 1999. The instrumentation for monitoring the embankments was installed after the construction of the foundation and before the construction of the embankments.

Instrumentation is necessary for verifying performance and observing design amendments. The most commonly used instruments are inclinometers, settlement indicators, and piezometers. The inclinometers are placed at the toe of the embankment, the settlement plates are installed along an embankment centerline and the piezometers are installed at three levels in soft soil layer.

4. GEOTECNICAL INVESTIGATION AND METODOLOGY OF ANALYSIS

4.1 In Situ and Laboratory Tests

Many in-situ and laboratory tests were carried out before the construction of the embankments. Fugro Ingenieursbureau B.V. (Masterbroek, 1998) performed the geotechnical soil investigations. In-situ tests carried out in the site consisted piezo-cone penetration tests, mechanical soil borings with undisturbed continuous sampling, field vane tests, cone pressuremeter tests and piezometers.

The laboratory test program was carried out on samples at 1m vertical intervals and consisted of description of the soil, water content, bulk density, Atterberg limits, isotropic consolidated undrained triaxial and oedometer compression tests.

4.2 Parameters

The soil parameters were based in the parameters given in the report of the No-Recess Project (Masterbroek, 1998). Calculations and correlations were done to find other parameters to be able to analyze the unimproved embankment. Tables 1 to 3 and Figure 2 show the parameters used in the analysis.

Table 1: Engineering properties from lab and field testing at No-Recess site

Stratum	Thickness (m)	W_n (%)	W_l (%)	W_p (%)	$S_{u\,FV}$ (kN/m^2)	e_o -
Clay 1	3.1	130	160	81.9	38	3
Peat 1	2.0	235	267	186	45	5
Clay 2	3.0	130	160	81.9	37	3
Peat 2	1.6	235	267	186	36	4

W_n – water content
W_l and W_p – Atterberg limits
S_{uFV} – undrained shear strength (Field Vane)
e_o – initial void ratio

Table 2: Compressibility parameters

Stratum	C_c -	C_r -	CR -	RR -	C_α -	C_v (m^2/year)	K (m/day)
Clay 1	0.7	0.32	0.26	0.081	0.017	2	8,64E-05
Peat 1	1.8	0.47	0.38	0.078	0.034	3	8,64E-04
Clay 2	0.85	0.45	0.25	0.112	0.011	2	8,64E-05
Peat 2	1.9	0.34	0.36	0.068	0.01	3	8,64E-04

C_c – compression index
C_r – recompression index
CR – compression ratio
RR – recompression ratio
C_α - secondary compression index
C_v – vertical coefficient of consolidation
K – coefficient of permeability

Table 3: Engineering design parameters used to model soil behavior

Stratum	ϕ' (°)	K_{oNC} -	c' (kPa)	E (kPa)	υ' -	ψ' -
Clay 1	18	0.69	5	1000	0.35	0
Peat 1	15	0.74	4	500	0.35	0
Clay 2	20	0.66	5	2000	0.35	0
Peat 2	15	0.74	10	1000	0.35	0

ϕ' - effective friction angle
K_{oNC} – coefficient of at-rest earth pressure for normally consolidated soil
c´- effective cohesion
E – Young´s modulus of elasticity
ν' - Poisson´s ratio
ψ' - dilatancy angle

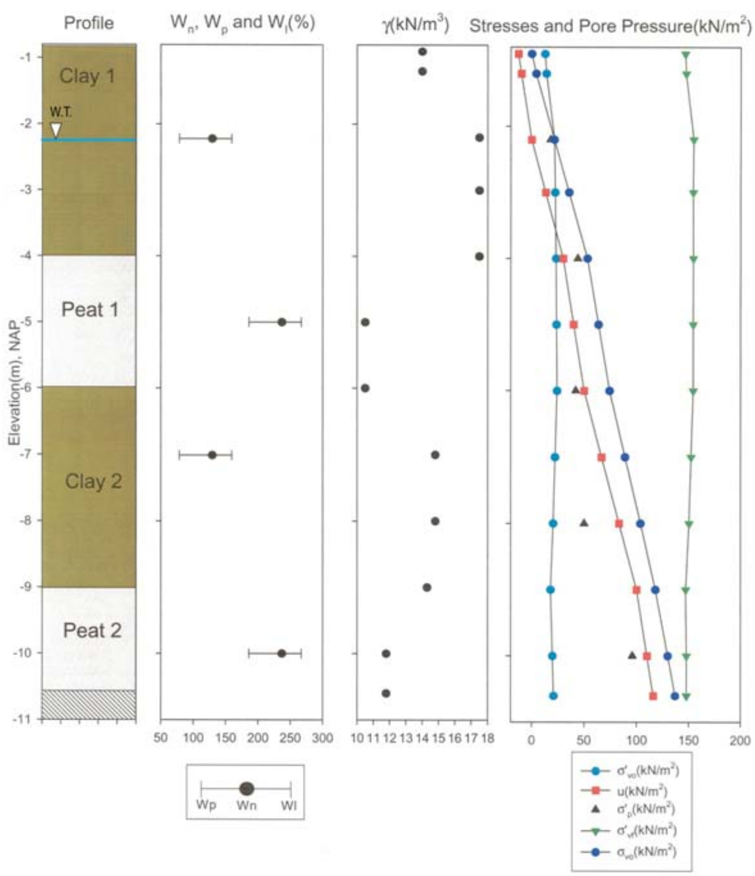

Figure 2. Soil profile and in-situ properties at HW site

4.3 Metodology of Analysis

This part compares results of measured performance for two of the embankments constructed at the No-Recess (HW) site: (1) the conventional design with vertical drains (HW1), and (2) the geotextile coated sand columns (HW4) as well as analyze the results of finite element simulation using Plaxis program of an unimproved embankment with the same site characteristics, soil parameters, and in-situ stresses as the No-Recess project, in order to provide a basis for evaluating the performance with the ground improvement solutions.

Two-dimensional analyses of the embankment can be studied using finite element program. In order to perform two-dimensional calculation, it is necessary to have the tools of a finite element program. The FE program can also account for real time consolidation occurring during phases of embankment construction. During the process of the dissipation of excess pore pressure, the soil obtains the shear strength needed to continue the construction stage process.

The unimproved embankment is 46m wide, and 6.7m high (this accounts for the actual height of the fill placed) with a side slope of 3:1(V:H). The embankment itself is composed of compacted sandy fill. The subsoil comprises 9.7m of soft soil sub-divided into four layers. The underlying artesian sand layer is not included in the model but is treated as a rigid base with prescribed piezometric head, H=+1.25m. The model calculations assumed that phreatic surface coincides with the original ground surface. This model assumes a steady upward flow through the soft clay and peat layers.

5. RESULTS ANALYSIS

5.1 Unimproved Embankment

The unimproved embankment construction was simulated in 5 stages. Figure 3 illustrates the remaining excess pore pressures at the end of construction all over the foundation. A high value of the pore pressure is indicated in the middle of foundation about 87kN/m^2. Figure 4 shows the excess pore pressures at three elevations where the piezometers are installed such as EL.-7.5m, -5.0m, and –2.7m. One can see that the piezometer installed in the elevation -5.0m has the highest value of the excess pore pressure. After the construction time, the excess pore pressure starts to decrease untill a value close to zero.

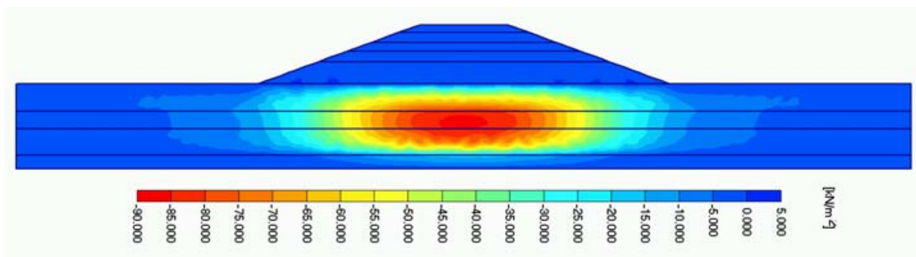

Figure 3. Excess pore pressures at the end of construction

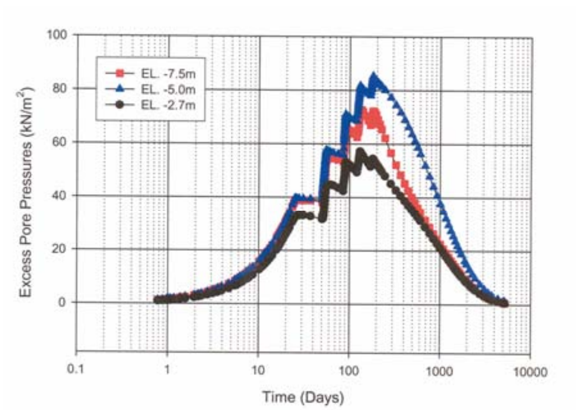

Figure 4. Excess pore pressure at three elevations

Figures 5 and 6 clearly show that the settlements of the original surface and of the embankment increase significantly during the last phase due to the dissipation of all excess pore pressures, which cause consolidation of the soil. It can be concluded that even though consolidation already occurs due to the time interval needed for the construction of the embankment, there is still a great amount of settlement occurring in the last phase (consolidation phase). From the colored scale it is possible to see that the high value encountered is 1.04m after construction and 1.62m after consolidation in the top of the embankment.

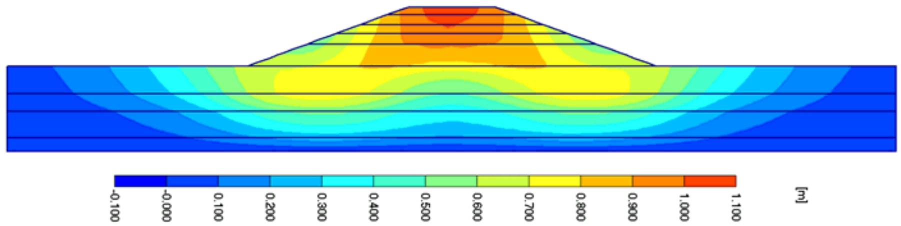

Figure 5: Total displacement after construction

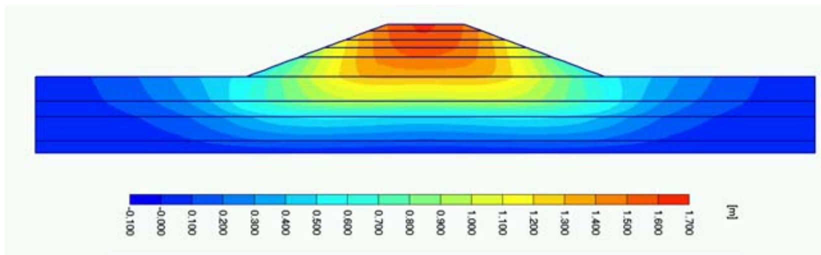

Figure 6: Total displacement after consolidation

Figure 7 illustrates the surcharge sequence used for FE analysis and settlement behavior vs. time at the centerline. 1D-calculations were done and settlement at the centerline encountered was 1.53m. Figure 7 also shows the horizontal displacement at the toe of the embankment predicted during the construction and consolidation phases. The values encountered in the analyses during the construction are 0.60m and 0.62m in the consolidation phase.

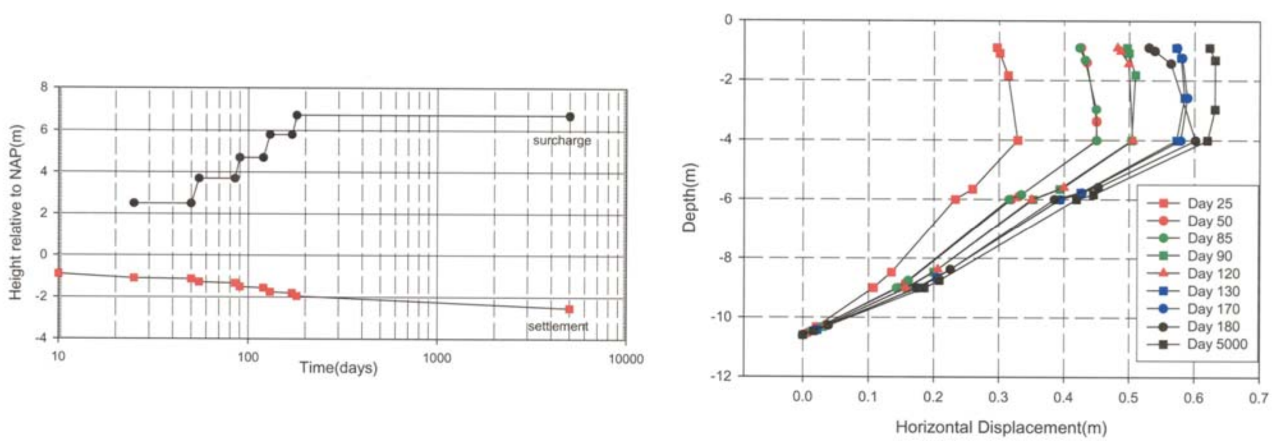

Figure 7: Settlement and Surcharge vs. time and Horizontal Displacement at the toe of the embankment for an unimproved embankment

5.2 Vertical Drains

Figure 8 illustrates the surcharge sequence and the centerline ground surface settlement for the embankment with vertical drains. The total vertical displacement measured for the embankment with vertical drains is 2.15m. This large amount of settlement in the first 4 months is due to the vertical drains, which help to accelerate the dissipation of pore pressure, thus accelerating the settlement rate. The development of the horizontal displacements after construction and consolidation are also shown in figure 8. The measured horizontal displacement during the construction time is about 0.24m and after consolidation is 0.27m. The largest horizontal displacement occurs around the EL.-4m.

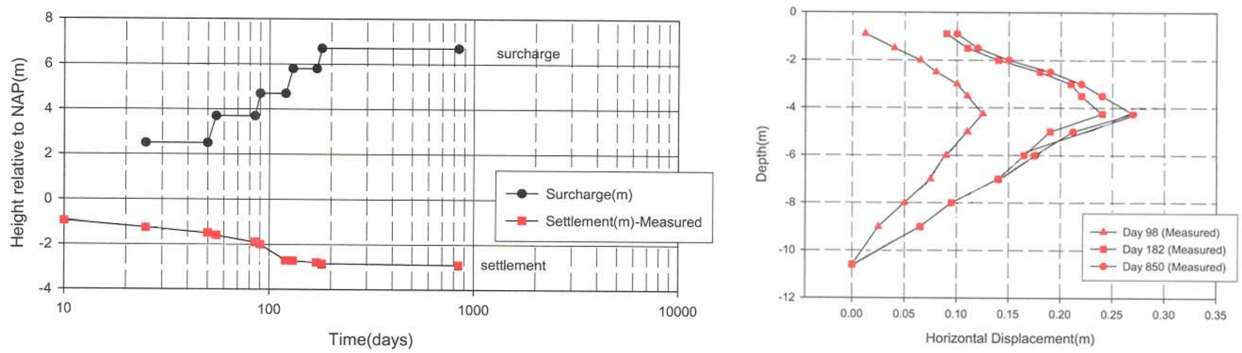

Figure 8: Surcharge vs. time and measured ground settlements and horizontal displacement measured in the field for HW1.

5.3 Geotextile Coated Sand Columns (HW4)

By using geotextile coated sand columns a reduction of the settlement of 1.05m is achieved under the high section of the embankment, relative to the embankment with vertical drains. Figure 9 illustrates the surcharge sequence and the measured settlement in the field. In the case of sand columns, no surcharge was used for the high part of the embankment, only the weight of the embankment. Figure 9 also illustrates the results from the horizontal displacement measured in the field. The highest value of the horizontal displacement during construction is 0.17m and after consolidation is around 0.23m. This reduction can be due to the soil stiffness provided by the geotextile coated sand columns.

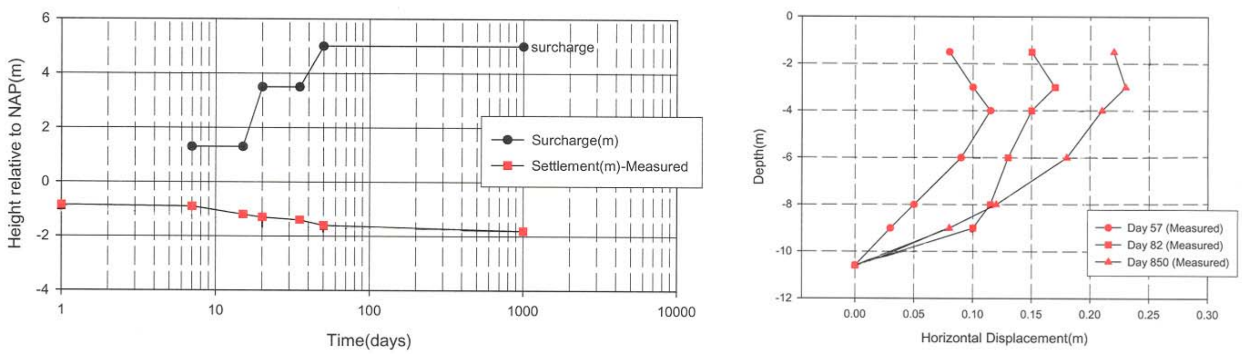

Figure 9: Surcharge sequence and settlement measured in the field and Horizontal displacement for HW4

5.4 Comparison of the three embankments

The results of the settlement, horizontal displacement, and pore pressure dissipation were compared between the three embankments. The pore pressure dissipation in HW4 is not too high due to the rigidity of the sand columns, which prevents the soft layer from compressing, thereby preventing the water from escaping so easily. The large settlement achieved with the conventional embankment (vertical drains) is due to the vertical drains, which accelerate the dissipation of the pore pressure. Therefore, the large amount of settlement is achieved much faster than with the other ground improvement options. In the case of the geotextile coated sand columns, the settlement achieved was much smaller than that with vertical drains. The geotextile casing limits the movement of the sand, making the sand stiffer than the surrounding soil, which allows the transfer of the embankment load to the bearing layer.

Table 2: Comparison of the results of the three embankments

	Unimproved Embankment		Wick Vertical Drains		Sand Columns with Geotextile	
	Construction	Consolidation	Construction	Consolidation	Construction	Consolidation
			Measured	Measured	Measured	Measured
Maximum Settlement (m)	1.04	1.62	1.90	2.0	0.85	0.90
			Measured	Measured	Measured	Measured
Maximum Horizontal Displacement (m)	0.60	0.62	0.24	0.27	0.17	0.23

6. CONCLUSIONS

In the Netherlands the western part of the country consists of soft, very compressible soils -- peat and soft clay. In this area, the organization HSL-South is involved in the construction of a new high-speed railway link between Amsterdam and Brussels. Short construction time and stringent requirements on long-term settlements are important issues in the design of the construction of embankments overlying soft soils. Since conventional railway embankments would not be appropriate regarding these requirements, the No-Recess project was created to test methods for stabilizing soft ground behavior. The five ground improvement trials demonstrate successful applications of recently developed geotechnical techniques.

This paper analyzes an unimproved embankment test and two of the five reinforced embankment trials in order to provide a basis for evaluating the performance of the five ground improvement solutions. Calculations and engineering judgment were employed to develop the proper parameters for the analysis of the Hoeksche Waard site conditions. In conclusion, the results encountered may help to achieve the requirements in the design project. No-Recess ground improvement options are offered to develop better ground improvement techniques in soft soils, where construction and residual settlement are important issues. The geotextile coated sand columns yielded to settlements and horizontal displacements smaller than those obtained with vertical drains; it seems that this technique is the better solution to address the requirements imposed by the project.

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