Proceedings of the South Baltic Conference on
Dredged Materials in Dike Construction
Rostock, 10-12 April 2014
ISBN: 978-3-86009-409-9
www.dredgdikes.eu

THE USE OF ENGINEERED SEDIMENTS FOR THE CONSTRUCTION OF A COMPARTMENT DIKE IN THE CONTROLLED FLOODING AREA OF VLASSENBROEK (BELGIUM)

Joris van Nederkassel[1], Sofie Van Zele[2], Bram Van Renterghem[3], Tom Vermeersch[4] and Hans Quaeyhaegens[5]

[1,2,3] *Envisan NV, member of Jan De Nul Group, Tragel 60 9308 Aalst Belgium;* info@envisan.com
[4] *Jan De Nul Group, Tragel 60 9308 Aalst Belgium; info@jandenul.com*
[5] *Waterwegen & Zeekanaal NV – afdeling Zeeschelde, Lange Kievitstraat 111-113 2018 Antwerpen Belgium; zeeschelde@wenz.be*

Abstract. After the 1953 and 1976 North Sea floods a flood defence plan was conceived to protect the Flemish part of the Scheldt estuary against future storm surges, called the Sigma Plan. It is governed by Waterwegen en Zeekanaal NV (W&Z), a Flemish government agency, and since 2005 aims to combine flood defence with strengthening the river's ecology through the creation of flood control areas. W&Z set up a pilot project in Vlassenbroek (Belgium), involving the construction of a compartment dike of a flood control area using dredged material from the river Scheldt without intermediate storage between the dredging and the dike construction process. As in the case in many rivers, the material to be dredged lacks the necessary geotechnical characteristics for direct construction purposes due to its fine granular nature. Therefore, Jan De Nul Group and its environmental subsidiary Envisan set out a considerable geotechnical testing programme to develop an engineered sediment for use in the construction phase. This involved the geotechnical characterization of the sediment and testing of multiple additive combinations to enhance these poor characteristics. Based on the test results, with respect to the dike design requirements and an economical appraisal, the best performing additive combination was selected. After being mechanically dredged and transported by barges to a location near the flood control area, the sediment was pumped ashore to a solidification plant. Pumping often involves fluidizing the sediment with water; in this case the dredged material was delivered to a barge fitted out with sieves and a set of piston pumps that were able to push the sediment approximately 600m to the solidification plant without adding extra water. This custom built unit constantly monitored the incoming sediment flow and automatically dosed the additives to obtain a material with appropriate geotechnical characteristics for dike construction. To strengthen the dike slopes with respect to surface erosion a mixture of grasses was seeded by hydro-seeding. After six weeks a tight vegetation cover was established on the dike slopes. To ensure that the engineered sediments exhibit the performance as intended in the design phase a Quality assurance / Quality Control (QA/QC) program was installed. This program included construction of test plots on the dike, control of the geotechnical characteristics of the dredged sediments, control of the accuracy of dosing and mixing. Multiple field and laboratory tests were executed during construction to determine strength and permeability of the engineered sediments in the dike body. Post-construction testing involved cone penetration and borehole water permeability and laboratory tests on undisturbed samples taken at multiple locations and depths at the completed dike.

Keywords: Dredged material, valorisation of sediments, solidification, dike construction, building with nature, vegetation cover

1. Introduction

1.1 Mission of Waterwegen & Zeekanaal in relation to re-use of dredged sediments

Waterwegen en Zeekanaal (W&Z) is a government agency, responsible for 1000 kilometres of navigable waterways in the region of Flanders, Belgium and much of the land on their banks. The proximity of the North Sea also presents potential flood risk. After the disastrous 1953 and 1976 North Sea floods a flood defense plan was conceived to protect the Flemish part of the Scheldt estuary against future storm surges, called the Sigma plan. The implementation of the Sigma plan is one of the key tasks of W&Z. Since 2005 flood defense is combined with strengthening the river's ecology through the creation of flood control areas. To construct new embankments around the first series of flood control areas approximately 2.5 million m³ of construction material is needed.

Maintaining the inland navigability of inland waterways is another key task of W&Z. Large amounts of sediments are produced by maintenance dredging. Annual monitoring of the quality of the sediment in the Scheldt estuary shows that at least 80% is chemically suitable for re-use in infrastructure works. However, in practice the poor geotechnical quality is often regarded as a bottleneck. As a result large quantities of dredged material are still disposed in landfill sites, entailing important costs and often causing social resistance. This can be avoided by enhancing the knowledge about techniques that allow a beneficial re-use of sediments. The environmental impact of both dredging activities and large infrastructure works, such as the construction of flood control areas can be reduced significantly when combined. The pilot project described in this article was carried out in the framework of the European PRISMA (Promoting Intergrated Sediment Management) partnership.

1.2 Set up of the Vlassenbroek pilot project

W&Z decided to launch a full scale pilot project comprising the simultaneous execution of maintenance dredging and dike construction including 100% re-use of the dredged sediment. The section of the Scheldt to be dredged was outlined, providing the contractor with non-contaminated sediment with a fine granulometry that lacks the necessary geotechnical characteristics for untreated application in infrastructure works. A secondary flood defense structure was selected to implement the pilot project. The compartment dike within the future flood control area of Vlassenbroek will be serving as a dividing structure between a tidal area with controlled reduced tide and an area that only floods when storm surges occur (see Fig 1).

In order to encourage the innovativeness of the market W&Z set up a design and build project through an open procedure. In addition to the price, the amount of dredged material being re-used and the technical and environmental quality of the bid were assessed in the course of the procurement procedure to select the most economically advantageous tender.

Bidders were asked to develop and implement a method to dredge, transport and re-use dredged material to construct the compartment dike within the future flood control area of Vlassenbroek within a framework of strict boundary conditions. The shape of the compartment dike was prescribed as well as the minimum requirements in relation to the impermeability and micro as well as macro stability. These characteristics take into account the tidal conditions at the precise location of the compartment dike in the Scheldt estuary. To assure a significant re-use of sediment a minimum threshold of 60% of the total volume of the compartment dike, estimated 100.000 m³, was to be constructed with dredged material. After being dredged, the material was to be transported either via the waterway or through pipelines to the construction site for immediate application. Intermediate storage was excluded to minimize the environmental impact of the construction works.

2. Design phase

2.1 Site investigation

2.1.1 Sediment characterisation

Extensive sampling of the sediments over the 2.5 kilometre long section to be dredged on the Scheldt river was done using a piston sampler. The results of the environmental and geotechnical analyses of the samples are summarised in Table 1 and Table 2. The sediment is non-contaminated and can be re-used as construction material under the Flemish legal framework (Vlarema) for re-use of waste materials.

Fig 1. Final stage Vlassenbroek flood control area with compartment dike as a clear boundary between controlled tidal area and controlled flooding area

Table 1. Environmental characteristics of the dredged material in comparison with limits for use as construction material

	Vlarema standard (mg/kg dry matter)	All sediments (mg/kg dry matter)
Heavy metals - total concentration		
As	250	13.0
Cd	10	2.9
Cr	1250	176.3
Cu	375	94.3
Hg	5	0.5
Pb	1250	91.0
Ni	250	18.1
Zn	1250	553.3
Heavy metals - leaching		
As	0.8	0.2
Cd	0.03	0.004
Cr	0.5	0.03
Cu	0.5	0.1
Hg	0.02	0.001
Pb	1.3	0.1
Ni	0.75	0.06
Zn	2.8	0.2
BETXS		
Benzene	0.5	<0.05
Ethylbenzene	5	<0.05
Toluene	15	0.3
Xylene	15	<0.05
Styrene	1.5	<0.05
PAHS		
Benzo(a)anthracene	35	1.19
Benzo(a)pyrene	8.5	1.16
Benzo(ghi)perylene	35	0.64
Benzo(b)fluoranthene	55	1.10
Benzo(k)fluoranthene	55	1.05
Chrysene	400	0.97
Phenanthrene	30	1.27
Fluoranthene	40	2.66
Indeno(1,2,3cd)pyrene	35	0.60
Naphthalene	20	0.04
Hexane	1	<0.05
Heptane	25	<0.05
Mineral oil	1000	243
Octane	90	<0.05
PCBs	0.5	0.09

Table 2. Geotechnical characteristics of the dredged material

Parameter		unit
Dry matter (DM) content	65.8	%
Geotechnical water content	52.3	%
Density	1.65	ton/m³
Organic Matter	3.7	% DM
Particle size distribution		
sand (63µm - 2mm)	61.5	%
silt (2µm - 63µm)	24.4	%
clay (<2µm)	14.1	%
Plasticity index (Ip)	11.5	
Undrained shear strength (cu)	0	kPa

From a geotechnical point of view the sediment has a fine sandy loam texture that lacks the necessary geotechnical characteristics for untreated application in infrastructure works.

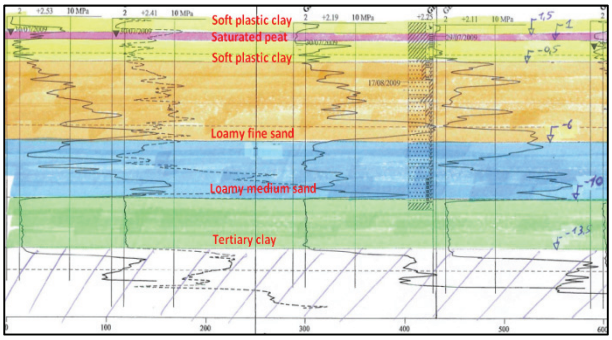

Fig 2. Stratification of the subsoil at the construction area

2.1.2 Geotechnical characterisation of the subsoil

A detailed identification of the subsoil is a vital element in the proper understanding of the geotechnical characteristics of the material at the construction area. Therefore, multiple boreholes were drilled up to 20m deep in the subsoil. At each location minimum five undisturbed samples were taken equally spread over the drilled profile. Tests and analyses that were performed on these samples in the laboratory include: particle size distribution, soil consistency/water content, organic content, settlement and consolidation characteristics and determination of shear strength characteristics. These data were supplemented with field tests such as cone penetration testing (CPT) and pocket vane tests.

The existing subsoil consists of the following layers starting from the ground level: soft plastic clays with a saturated peat layer in between, a loamy fine sand layer, a loamy medium sand layer and finally stiff Tertiary clay (see Fig 2).

The data obtained from the geotechnical characterisation of the sediment and subsoil was implemented in the geotechnical design calculations performed with SLOPE/W software.

2.2 Design requirements

The compartment dike to be built had a length of 800 meters, slopes of 20/4 and a crest width of 7 meters, 4.5 meters above ground level. The dike volume was around 100.000 m³.

The design requirements were similar to that for a conventional dike in tidal conditions. Failure mechanisms such as breaching, bursting and piping had to be addressed with respect to given safety factors. Furthermore, instabilities such as uplifting of impermeable layers and formation of slip planes; and the influence of storm water levels on the stability had to be checked. Permeability of the dike material had to be less than 1.0E-07 m/s. Finally, potential settlements had to take into account in the dike design.

2.3 Adopted solution

The Jan De Nul Group took up the challenge to find an innovative solution for this job. Dredged river sediments of similar quality are usually dewatered in dedicated sediment treatment centers by lagooning or natural dewatering. Lagoons consist of impermeable ponds with a draining system. The lagoons can be used multiple times, but the investment cost is significant. Moreover, the required time is 3 to 9 months. Therefore, lagooning was not withheld as viable solution.

Dredged sediments can also be dewatered using geotubes. Based on the experiences gained by The Jan De Nul Group, some disadvantages to this technique were identified. These include the need of a high volume of transport water, difficulties to assess settlements, and risk of preferential routes for water between the geotube elements.

In civil construction it is a widespread technique to solidify soft soils with additives such as lime. Particularly in Scandinavia it is not uncommon that contaminated sediments are solidified with additives prior to final disposal in a landfill (SMOCS 2012, Swedish Geotechnical Institute 2006, CASST 2004). The use of solidified sediments has following advantages:

- No transport water and associated environmental permitting is necessary
- The dike body can be build up with a high proportion of sediments, minimizing external supply
- Workability of the sediments is quickly improved
- Quick improvement of bearing capacity
- Minimum risk on internal slides as only one type of material is used
- Reduction of settlements as no dewatering takes place and final strength is reached after a couple of weeks.

Based on this appraisal of technologies the Jan De Nul group came up with the innovative solution of *engineered sediments* which is based on the solidification technique.

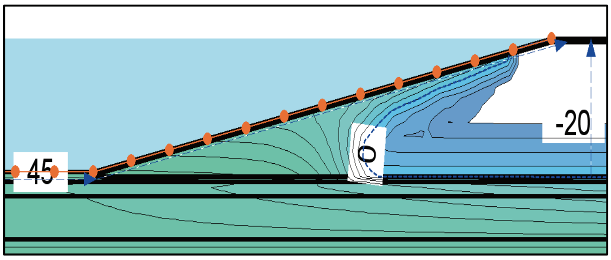

Fig 3. Pore water pressures with 7 days flood in tidal area.

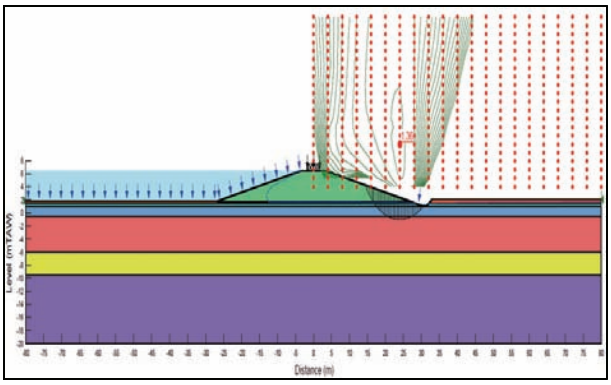

Fig 4. Dike stability under highest water conditions.

2.3.1 Design calculations

Stability calculations were performed with SLOPE/W software and seepage modelling was performed with SEEP/W. Input parameters were gathered from laboratory and field investigations. Laboratory tests on *engineered sediments* showed that the minimum characteristics of the solidified material are as follows:

- Water permeability (kf): 1.0E-07 m/s (ISO 17892-11)
- Undrained shear strength (cu): 35 kPa (BS 1377-7)
- Angle of friction (φ): 25° (BS 1377-8)
- Cohesion (c): 4 kPa (BS 1377-8)

The remaining unknown subsoil parameters were determined using the National Annex table with characteristic values for soil parameters.

As boundary conditions for the transient seepage calculation, a hypothetical worst case scenario with 7 days of continuous high water in the controlled tidal area (equal to crown level of compartment dike) and the controlled flooding area empty, were used. For these BCs the water table is modelled (see Fig 3).

The total calculated flow rate through and under the compartment dike is 1.4942E-07 $m^3/s/m$ dike. The modelled water table was further used in the slope stability calculations. To determine the critical slip surface, the Bishop method was used. Construction phases were calculated as undrained with a global safety factor of 1.1, while the final states were calculated drained with a global safety factor of 1.3.

After the last construction stage (undrained material), a minimum safety factor of 2.08 was found. For the final state, under highest water conditions, a minimum safety factor of 1.36 against slip surface failures at the controlled flooding area side was obtained, which satisfied the requirements (see Fig 4).

Settlements in the subsoil were calculated using Sanglerat's method. Subsoil parameters were obtained from CPT soundings. Density of the dike material was 16.5 kN/m^3 (see Table 2). Settlement of the subsoil was estimated to be 16 cm.

2.3.2 Engineered sediments

To improve the sediments' geotechnical properties it was chosen to mix the sediment with suitable additives. A wide range of additives is available including hydraulic and pouzzolane binders. Due to geotechnical and economical restrictions however, only a minority is suitable. In an extensive laboratory study various types and combinations of additives were mixed with the sediments and tested.

The initial selection procedure focussed on the strength development in function of four key parameters (Boutouil 1999, Boubaker and Boutouil 2009):

- Type of additives
- Application dose
- Water content of the sediment

- Curing time

In a first step, a screening was done to select the additives with promising results. In a second step a more in-depth testing procedure was followed to come down to the most suitable additive(s). The followed testing procedure and interaction with the dike design calculations is shown in Fig 5.

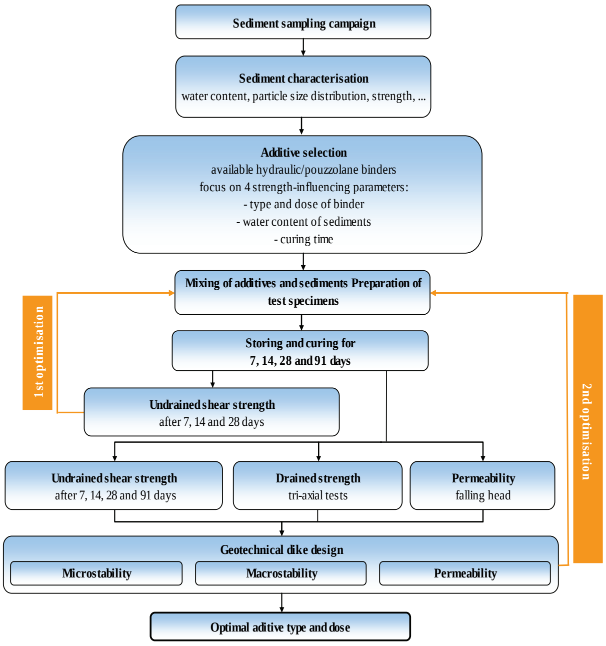

Fig 5. Flow scheme showing followed lab testing procedure and interaction with dike design calculations

Fig 6. Engineered sediments during curing (left), pocket vane tester and the laboratory vane apparatus (right).

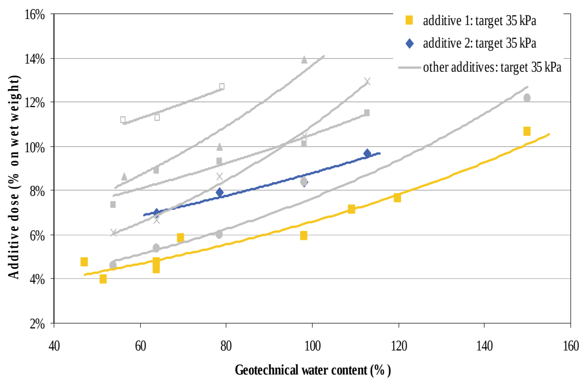

Fig 7. Additive dose in function of water content. Target shear strength was 35 kPa after 28 days.

Additives that were tested include: cements, quick lime, fly ashes, bottom ashes, granulated blast furnace slags and sodium silicate. Besides geotechnical properties also the presence of correct certification and cost effectiveness were taken into account as decision factor in additive selection. In the laboratory tests specimens were made by mixing the sediments and additives to a homogenous mass. These were stored in air-tight plastic recipients. After 7, 14 and 28 days curing the developed undrained shear strength of the specimens was determined using the motorized laboratory vane apparatus (see Fig 6).

From the dike design calculations it turned out that the *engineered sediments* must have an undrained shear strength of minimum 35 kPa. Fig 7 shows for a range of additives the application dose in function of the moisture content to obtain 35 kPa after 28 days. It is clear that the water content and additive dose play an important role. Also the exact composition of the additive mix has an important effect on the developed strength. This is also shown in Fig 7 where the hydraulic binder (cement) in additive blends 1 and 2 is the same, but where the type of pouzzolane (two different types of fly ashes) is changed.

Based on the screening phase results, a blend of Portland cement and fly ashes with high reactive silica content was selected as the best performing additive. In a next step the dose of this additive was optimised. The *engineered sediments* had develop sufficient strength after two weeks to support heavy machinery and from the dike stability calculations it turned out that the permeability had to be minimal 1.0E-07 m/s. Fig 8 shows the evolution of the strength in function of the additive dose and the curing time for sediments with a water content of 52.3 %. It is observed that there's a threshold from which the strength starts to increase exponentially. Follow-up of the strength until 91 days showed that 95-99% of the maximum developed strength is reached after 28 days.

Permeability tests (falling head method) showed that the hydraulic conductivity for these mixtures varied between 6.3E-09 and 3.6E-08 m/s, which was well below the required 1.0E-07 m/s.

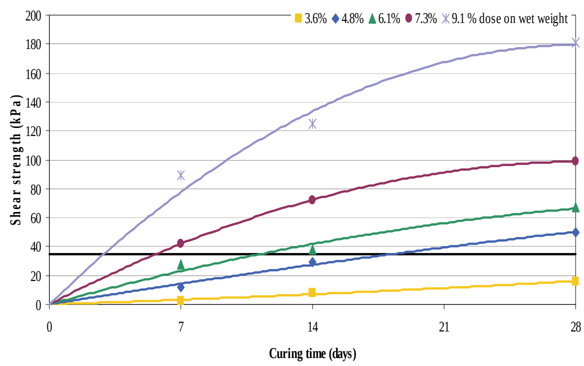

Fig 8. Shear strength in function of dose and curing. Horizontal line indicates minimum required strength.

3. Execution phase

3.1 Dredging and Dike construction

The sediments were mechanically dredged and loaded into barges. Notwithstanding the tidal amplitude of about 5 meter and the dredging location, dredging could take place continuously. The barges were transported with pushing boats to the discharge location. Typical load of one transport barge was between 300 and 550m³. Contrary to hydraulic dredging, mechanical dredging generates near to in situ density sediments as no transport water is required to transfer the material from the river bed to the water surface.

At the unloading area, a specially designed discharge pier was constructed, taking into account the high tidal amplitude and strong currents (up to 4 knots) of the river Scheldt at Vlassenbroek. At the pier, a water based unloading platform was positioned to discharge arriving barges (see Fig 9).

The material was unloaded by means of a long-reach transhipment excavator and placed over a vibrating sieve. The double sieve with mesh diameters 150 mm and 50 mm eliminated debris and stones. The sieved material was captured in a buffer which contains a screw distribution unit. From here, the high-density material is pushed through the pipeline towards the sediment reprocessing plant by the piston pumps.

Depending on the type of material, overall unloading capacity is between 80 and 130m³ per operational hour. Each pump is connected to a 580 m long 250 mm diameter pipeline. The pipeline is conceived to withstand the high pressures of up to 80 bar.

Once pushed through the pipeline, the sediments arrive in the stabilisation unit (see Fig 10). The mixing unit consists of 2 independent plough mixers, each with its calibrated dosing system for additives. The incoming volumetric flow of sediments is constantly measured and the dosing of additives is adjusted to this incoming flow by means of regularly calibrated frequency driven dozing screws. Once thoroughly mixed, the stabilised engineered materials are placed in a 45 m³ buffer before being loaded in dump trucks. The dump trucks transfer the stabilised *engineered sediments* to the dike construction location where they are placed directly into the berm in a 30 cm thick layer. The material cures in place; when it reaches its desired strength and durability a subsequent layer is placed on top.

Fig 9. Unloading platform with pumping installation.

Fig 10. Sediment stabilisation unit.

Fig 11. Placing *engineered sediments* in the dike body.

At the end of the construction works a low-impact excavator levels the *engineered sediments* and a roller compactor shapes the dike material to its designed profile.

3.2 Quality control

A Quality assurance/Quality Control (QA/QC) programme was in place to assure the designed quality throughout the project. The QA/QC program included construction of test plots, control of water content of dredged sediments, quality of the additive blend, and accuracy of dosing and mixing. Geotechnically, the programme includes field data collection and analyses of particle size distribution, strength and permeability.

3.2.1 Process monitoring

A volume of over 100,000m³ needed to be processed. The sediments were dredged in a 2.5 km part of the river Scheldt that became unnavigable in the seventies. Consequently, heterogeneity in the material’s water content, granulometry, organic matter content had to be anticipated for in the process. Therefore, the geotechnical quality of the dredged sediments was checked in every barge. The grain size distribution and dry matter content of these QC samples are shown in Fig 12 and Fig 13. Operational parameters with regard to pumping and mixing could then be fine-tuned according to the nature of the processed sediments.

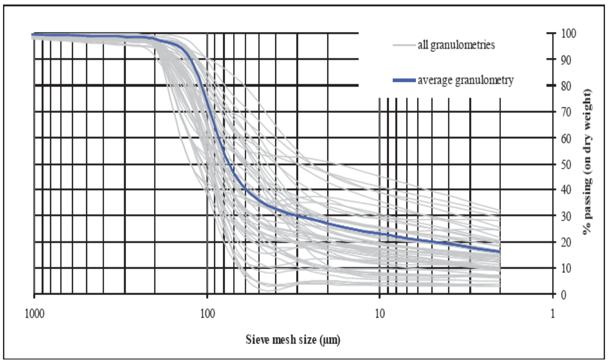

Fig 12. Granulometry of the sediments after dredging

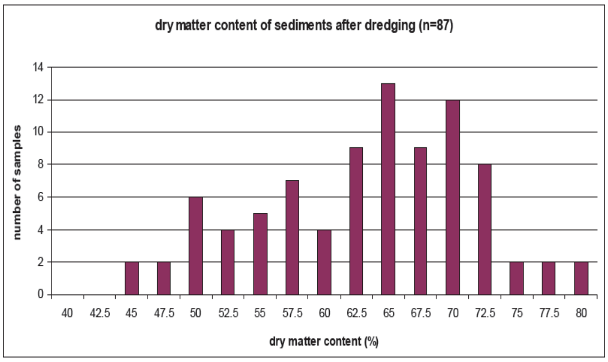

Fig 13. Dry matter content of the sediments after dredging

Fig 14. Measuring field strength with pocket vane tester.

Fig 15. Measuring field permeability with double ring infiltrometer

3.2.2 Dike strength

A quick way to control the strength of the *engineered sediments* in the field is measuring the undrained shear strength by means of the pocket vane tester. The strength was regularly measured during the works on a uniform grid pattern with grid points at every 30m. At each grid point measurements were done at the surface and at every meter in vertical direction. Pocket vane results were corrected for plasticity, anisotropy and rate effects according to the formula of Bjerrum (Van 't Hoff and van der Kolff 2012).

The field vane tests showed that the average undrained shear strength was 76 ± 29 kPa at the surface and 55 ± 20 kPa in the depth. The higher strength development at the surface can be explained by natural drying and compacting of the material by earth moving machinery.

Following the field test, undisturbed samples were taken to determine the cohesion and angle of friction via tri-axial testing in a laboratory environment (BS 1377-8, back pressure 300 kPa, consolidation pressures 50, 75 and 100 kPa). The measured angle of friction varied between 34.0 and 40.0 ° and the cohesion between 8.4 and 34.2 kPa.

The field results showed that the strength characteristics of the *engineered sediments* showed some variation but were well above the minimum required characteristics used in the design calculations (see sub-chapter 0).

3.2.3 Dike impermeability

A quick way to control the vertical surface water permeability of the *engineered sediments* in the field is measuring the hydraulic conductivity by means of the double ring infiltrometer ASTM D3385-03 (see Fig 15).

The permeability ranged from 1.0E-08 to 8.3E-08 m/s. Following the field test, undisturbed samples were taken to validate the field measurements by means of a permeability measurement in the laboratory (NBN ISO 17982-11, 300 kPa cell pressure and 50 kPa loading). This resulted in permeabilities of 1.6E-09 to 3.4E-08 m/s.

The results show that the permeability of the *engineered sediments* measured in the field was well below the maximum allowed permeability used in the design calculations (see sub-chapter 0).

3.3 Vegetation cover

In order to protect the surface of the constructed dike against erosion it was decided to install a vegetation cover on the dike slopes.

In a seeding pre-test experiment it was concluded that a classic sowing technique (surface roughening, seeding and rolling) could not result in a fast sprout of the grass seeds. Dry weather conditions and harsh subsoil characteristics (low permeability, high alkalinity) prevented germination.


Fig 16. Seeding pre-test with hand sowing technique.


Fig 17. Hydro-seeding on dike slopes


Fig 18. Completed compartment dike – autumn 2013

The sowing of around 35,000 m² of dike slopes was realised by hydro-seeding. The seed mixture (50% *red fescue*, 50% sheep fescue), dosed at 300 kg/ha, was mixed with water, mulch and binders. By a binder, based on starch, the seed sticks to the dike slopes. Another polymer serves as a water retaining agent, while the mulch improves the fertility of the surface.

During the two weeks after seeding the dike slopes were watered every 4 days. After two weeks germination of the seed could be noticed.

4. Post-construction phase

Three months after completing the construction of the dike a testing programme was started to check the homogeneity of the dike body. The programme involved cone penetration testing (CPT), laboratory testing (laboratory vane test, tri-axial, oedometer, granulometry) and field permeability tests using the Boutwell permeameter. At the time of writing this article only the results of the cone presentation tests were available.

4.1 Cone penetration Test

A good in-situ technique to control the homogeneity of the dike material is cone penetration testing. This test has the advantage to provide an immediate continuous profile. Soundings were conducted with a 200 kN penetrometer mounted on a crawler. Cone-tip resistance (qc) and cone-tip friction (fs) were recorded every 2 cm at 16 locations across the dike.
CPT profiles over the 16 locations showed good similarity. A typical CPT result is shown in Fig 20. The upper layer of the dike has a high strength. This is because 0.5 m thick gravel road was constructed on top of the dike. Subsequently the cone-tip resistance drops to 800 kPa and stays quasi unaltered for 4 to 5 meters. This indicates a good homogeneity of the *engineered sediments* layer. The increase in strength around 5 m is associated with the subsoil on which the compartment dike was placed.

It is possible to deduce the undrained shear strength from the cone tip resistance (Burgos et al. 2007, Van ’t Hoff and van der Kolff 2012). A frequently used correlation to derive cu from a CPT is

$$cu = qc / Nc$$


Fig 19. Cone penetration testing on compartment dike.

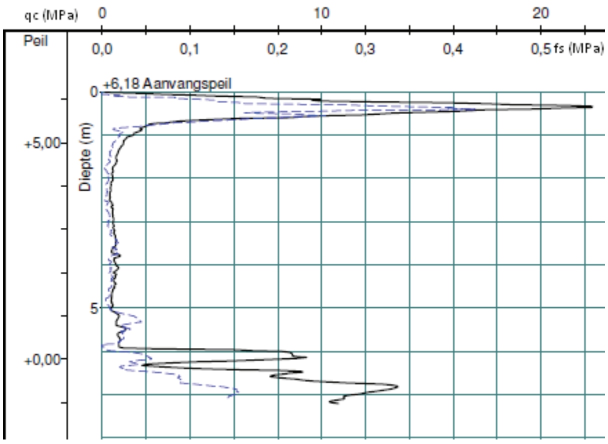

Fig 20. Cone penetration test result.

Where Nc is an empirical factor that usually ranges between 10 and 13. This correlation will be calibrated by vane shear tests on undisturbed soil samples taken during the post-construction phase testing programme.

5. Conclusion

The Flemish government agency Waterwegen & Zeekanaal promoted the beneficial re-use of sediments by supporting the use of sediments from maintenance dredging as construction material for dike works at the Vlassenbroek flooding area. These sediments in their natural dredged form lacked the necessary geotechnical requirements. After thorough investigation of the construction area and the sediments to be used, Jan De Nul Group were able to develop an innovative process to turn unsuitable sediments into viable construction material.

Laboratory testing followed by full scale field trials demonstrated that the requirements in terms of stability and permeability could be achieved. The use of high-density pumps and a well-controlled processing plant eliminate the need for rehandling and intermediate storage of the solidified material.

The applied technique opens the door for a new approach in the application of fine sediments in large scale infrastructure works. By correct selection of additive and application dose, unsuitable sediments are turned into useful construction material within days and with a minimum handling at a cost effect rate.

Nomenclature

cu	= undrained shear strength	(kPa)
qc	= cone-tip resistance	(kPa)
CPT	= cone penetration test	(-)
φ	= angle of friction	(°)
c	= cohesion	(kPa)
fs	= cone-tip friction	(kPa)
kf	= water permeability	(m/s)
σ3	= consolidation pressure	(kPa)

Acknowledgements

The authors would like to give thanks to the staff of Waterwegen en Zeekanaal for their collaboration and to staff and crew from the contractor (Jan De Nul Group) at the project site. This project was carried out in the framework of the European PRISMA (Promoting Integrated Sediment Management) and is co-financed by the European Regional Development Fund, INTERREG IVA 2 Mers Seas Zeeën Programme.

References

Boubaker, R.; Boutouil, M. 2009.Organic matter and cement content effect of geotechnical properties of cement treated sediments. *I2SM conference Lille, France.*

Boutouil, M. 1999. *Traitement des vases de dragage par solidification/stabilisation à base de ciment et additifs*. Ph.D thesis, Caen university, France, 276 p.

Burgos, M.; Samper, F.; Alonso, JJ. 2007. Improvements carried out in very soft dredged mud soil in the Port of Valencia (Spain). *European Conference on Soil Mechanics and Geotechnical Engineering*, 2091-2104.

CASST 2004. Review of scientific literature on the use of stabilisation/solidification for the treatment of contaminated soil, solid waste and sludges. Available online: www.environment-agency.gov.uk

SMOCS 2012. Report on sustainable management of Contaminated Sediments: Review of Potential Applications for s/s. Available online: <http://www.smocs.eu>.

Swedish Geotechnical Institute 2006. Report 72 on Strength of stabilised soils – A laboratory study on clays and organic soils stabilised with different types of binder. Available online: <http://www.swedgeo.se /upload/publikationer>

Van 't Hoff, J.; van der Kolff, AN. 2012. *Hydraulic Fill Manual: For Dredging and Reclamation Works*. 1st ed. CRC press. 642 p.