Abstract

The disposal of fine-grained contaminated sediments inherent to maintenance dredging activities is an increasing problem. For various reasons, new disposal sites are no longer the obvious solution. Therefore, the yet-available storage capacity must be used as efficiently as possible. Besides leading to the development of more advanced environmental dredging techniques, this results in improved dewatering techniques for soft material and in-situ techniques that ameliorate the mechanical soil characteristics.

The Belgian-based DEME Group, together with the Flemish Ministry of Public Works and the Port Authorities of Antwerp, invest in the development of innovative techniques, which opens new options for the management of fine-grained material disposal sites and for the reuse of areas otherwise difficult to access.

Since 1990 large-scale testing on dewatering lagoons has taken place. Today, results show that the needed storage capacity for dredged materials can be reduced by half, owing to the consolidation achieved in dewatering lagoons. Vacuum consolidation with horizontal drains has been developed and applied for dewatering silt stored underwater. Storage capacity, up to 20% of the already-stored volume, can be gained. The installation of gravel piles, in combination with vertical drainage and vacuum consolidation, ensured the stability of the bedding for a railway link through a sludge disposal site. A load of 3.8 tonne/m² for several days induced a mere 3 cm settling.

Soft Soil Improvement, an in-situ sanitation and stabilisation technique designed to improve the mechanical characteristics of very soft soil, stabilises soft soil and immobilises the heavy metals and other soil contaminants. The stabilisation and immobilisation is realised by mixing the soft soil with cement and certain additives. After treatment, no appreciable lixiviation is present and a modulus of compressibility of up to 100 MPa is realisable.

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surface for on-land disposal. This has led the Antwerp Port Authorities and the Flemish Ministry of Public Works to support pilot projects and test programmes concerning the development of new techniques. Since 1990, a large-scale testing and study programme has been operating. The aim is to increase the natural settling and consolidation phenomena as much as possible in specially designed dewatering fields, until a stable clay like material is obtained, which then can be used for beneficial applications, such as landscape projects, and such.

**Preliminary study**
A preliminary study was done to define the main aspects of interest for a pilot programme. An initial theoretical evaluation of different possible techniques was made with the mathematical simulation model CONSOL. This evaluation demonstrated three main dewatering methods useful for consolidation, namely:
- the under drainage techniques;
- the surface drainage techniques; and
- the evaporation enhancement techniques.

**Dewatering fields and in situ consolidation**
A pilot plant for the dewatering of fine-grained dredged material, a so-called dewatering lagoon, was installed in the harbour area of Antwerp, on the left bank of the River Scheldt. The project was realised by a joint venture of Dredging International NV, NV Ondernemingen Jan De Nul and NV Baggerwerken De Cloedt en Zoon on behalf of the Flemish Government of Public Works.

Different combinations of drainage and surface dewatering systems were applied to enhance the natural consolidation process (Table I). The dewatering fields were filled in successive layers with dredged material from the River Scheldt (Table II). Approximately 286,000 m³ equivalent to 157,000 tonne dry solids (TDS) was dredged with a small cutter dredger.

A general view of the silt level variations during the filling period and the consolidation period in a dewatering field is given in the Figure 1.

A continuous follow up of the silt layer thickness in the dewatering fields was executed during the consolidation process. Periodic detailed campaigns of in-situ density measurements were executed during the first four months.

**Results of the consolidation monitoring**
The consolidation of the material in the deposit was monitored daily during the dredging operations and afterwards on a weekly basis. The results illustrate the quicker consolidation in fields L1, L2 and L5, where under drainage techniques were applied. During the first four months the thickness in the drained fields was reduced by 35%, whereas the reduction in the other fields was limited to 25%.
Using the results of the density profiles combined with the evolution of the mud thickness (Table III), the total amount of dry solids in the fields was checked for each survey, resulting on average in 155,000 TDS to be compared to the estimated initial dredged quantity of 157,000 TDS. The variation of the average density in the fields is shown in Table IV.

After four months mechanical techniques were applied to further enhance the dewatering process. First an amphirol was deployed, with poor results. Later ditches were dug with traditional earth-moving equipment to generate horizontal pressure gradients which enhance the drainage. The improvement of the evaporation by vegetation was obtained by sowing a mixture of grass species in fields L2 and L3. This operation was done after three months of consolidation (beginning of autumn). During the first (winter) months the effect was limited but in spring, owing to the natural plant growth on the consolidating mud, the vegetation improved dramatically (Figure 2).

**Further research and conclusions**

For a further evaluation and examination of the different dewatering techniques, last year another pilot dewatering lagoon was installed in the Antwerp harbour area. Considering the results of the former pilot project, under drainage was provided over the whole area of the dewatering field. The lagoon was filled in May 1997 with fine-grained dredged material from the River Scheldt (17,000 TDS). The average density of the stored silt was 1.23 t/m³, with a layer thickness of about 1.8 m.

Within four months of consolidation an average density of 1.35 t/m³ was achieved. Within eight months, thanks to the utilisation of different mechanical techniques and improved surface drainage, a density of 1.50 t/m³ was realised.

The field tests illustrate the effectiveness of a well-planned and adequately realised treatment method for the acceleration of the dewatering and consolidation of fine-grained dredged material on a large scale.

**Figure 1. Layer thickness in a dewatering field.**

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**Table I. Applied drainage techniques in the dewatering fields.**

<table>
<thead>
<tr>
<th>Field nr.</th>
<th>Under drainage</th>
<th>Evaporation enhancement</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>gravitational</td>
<td>ditches, dug with traditional earth-moving equipment</td>
</tr>
<tr>
<td>L2</td>
<td>drains and vacuum</td>
<td>vegetation (after 3 months)</td>
</tr>
<tr>
<td>L3</td>
<td>no</td>
<td>+ vegetation (after 3 months)</td>
</tr>
<tr>
<td>L4</td>
<td>no</td>
<td>+ amphirol and discuswheel (after 4 months)</td>
</tr>
<tr>
<td>L5</td>
<td>gravitational</td>
<td>+ amphirol and discuswheel (after 4 months)</td>
</tr>
</tbody>
</table>

**Table II. Filling characteristics in the fields.**

<table>
<thead>
<tr>
<th>Field nr.</th>
<th>Surface (m²)</th>
<th># of fill operations</th>
<th>Height (m) after the last filling operation and water evacuation</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>42612</td>
<td>7</td>
<td>1.64</td>
</tr>
<tr>
<td>L2</td>
<td>42612</td>
<td>6</td>
<td>1.75</td>
</tr>
<tr>
<td>L3</td>
<td>40216</td>
<td>6</td>
<td>2.09</td>
</tr>
<tr>
<td>L4</td>
<td>64056</td>
<td>6</td>
<td>1.93</td>
</tr>
<tr>
<td>L5</td>
<td>44160</td>
<td>7</td>
<td>1.74</td>
</tr>
</tbody>
</table>
Table III. Evolution of the mud thickness.

<table>
<thead>
<tr>
<th>Field nr.</th>
<th>Initial height (m)</th>
<th>Height (m) after 30 days</th>
<th>Height (m) after 75 days</th>
<th>Height (m) after 90 days</th>
<th>Height (m) after 120 days</th>
<th>Reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>1.64</td>
<td>1.33</td>
<td>1.10</td>
<td>1.07</td>
<td>1.07</td>
<td>35</td>
</tr>
<tr>
<td>L2</td>
<td>1.75</td>
<td>1.33</td>
<td>1.18</td>
<td>1.16</td>
<td>1.15</td>
<td>35</td>
</tr>
<tr>
<td>L3</td>
<td>2.09</td>
<td>1.86</td>
<td>1.61</td>
<td>1.58</td>
<td>1.58</td>
<td>24</td>
</tr>
<tr>
<td>L4</td>
<td>1.93</td>
<td>1.66</td>
<td>1.47</td>
<td>1.47</td>
<td>1.45</td>
<td>25</td>
</tr>
<tr>
<td>L5</td>
<td>1.74</td>
<td>1.30</td>
<td>1.11</td>
<td>1.10</td>
<td>1.09</td>
<td>36</td>
</tr>
</tbody>
</table>

Table IV. Evolution of the mud density.

<table>
<thead>
<tr>
<th>Field</th>
<th>Initial density (t/m³)</th>
<th>Density (t/m³) after 30 days</th>
<th>Density (t/m³) after 75 days</th>
<th>Density (t/m³) after 90 days</th>
<th>Density (t/m³) after 120 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>1.223</td>
<td>1.272</td>
<td>1.314</td>
<td>1.318</td>
<td>1.318</td>
</tr>
<tr>
<td>Drainage</td>
<td>1.223</td>
<td>1.285</td>
<td>1.333</td>
<td>1.345</td>
<td>1.345</td>
</tr>
<tr>
<td>No drainage</td>
<td>1.223</td>
<td>1.255</td>
<td>1.290</td>
<td>1.293</td>
<td>1.295</td>
</tr>
</tbody>
</table>

The volume can be reduced by 35% within four months and by up to 50% in less than nine months. This means that the consolidation process in a dewatering lagoon, inclusive the filling and emptying, can be repeated on a yearly base.

Important details of such a treatment method are the following:
- The installation of a solid under drainage system is essential when creating a dewatering lagoon.
- The under drainage system has to facilitate the dewatering of the lowest silt layer.
- During the dewatering process, special attention needs to be paid to the daily evacuation of rain and rising interstitial water, by means of ditches in the silt surface and canals along the surrounding dike.
- For the same reason, the width of the dewatering lagoons must be kept within 100 m, while the length may be 500 m or more.
- Furthermore, in order to minimise the consolidation period, the initial density of the dredged material must be as high as possible.
- Improved dredging techniques, already make it possible to fill up a dewatering lagoon with silt at a density of up to 1.30 t/m³.

Strategy for the future

The installation of dewatering lagoons is an important, though intermediate step, towards a global solution of the problems of ports where a shortage of reclamation areas exists, especially for fine-grained material. Additionally it is necessary to look for projects where the obtained product (soft clay) can be applied. Different solutions can be suggested, such as the utilisation as fill material for landscaping projects or as a raw material for the construction industry.

The policy of the Flemish Government consists in the installation of about 2 km² of dewatering lagoons. The next few years, the annual production of consolidated dredged material will be very important. Therefore, large-scale utilisation projects will be required.

Vacuum Consolidation with Horizontal Drains

General description

This technique was developed for the extraction of water from silt, stored under water (Figure 3). When the water is extracted the density of the silt increases and the volume decreases. This results in a gain in storage capacity and a better stability of the soft soil.

Since it is impossible to put a surcharge on the silt, pressure has to be created in another way. By inserting a horizontal drain network in the silt layer and connecting the network to a vacuum installation, an underpressure is created inside the drain network. The difference in pressure between a drain and the silt makes the water flow towards the drain. This way a large amount of water is gradually drawn out of the silt, in an area around the drain tube.

When executing this technique, special attention is paid to the following two points. First, the drains have to be tested on clogging and pore size. When a drain starts to clog, further extraction of water is impossible and when the pore size is too big, silt is drawn into the drain tube. Secondly, the drain tubes have to be inserted at least 1.0 m underneath the top of the silt to assure a minimum of leaks (water from above the silt, drawn into the drain tube).

To determine the possible gain in volume and the rise in density, some samples are taken. From these samples, soil mechanical facts are determined and from these results the theoretical gain can be calculated. This makes it possible to determine the most effective number of drains to insert, the period the vacuum has to be maintained and the friction, while inserting the drains.

The advantage of using horizontal drains lays in the fact that no cover is needed on top of the silt. The top layer of 0.5 m to 1 m silt provides a cover and seal from the water above. This makes the technique easier to execute and less expensive than the use of vertical drains.

Technical execution

To insert the drains in the silt a special construction was designed, which can be used in water depths varying from 1 m to 25 m. For the pilot project this...
construction was mounted on the ladder of a converted bucket dredge, while the top of the silt layer was situated 19.5 m under the water level. The number of drains to insert, is a factor which determines the speed and the degree of consolidation that can be reached. Therefore, before executing the project a cost-benefit analyses must be made to determine the most economical combination of drains to insert. In this particular case a grid of 2 m x 2 m was maintained for inserting the drains. A first drain was inserted 1 to 1.5 m below the silt surface and a second one 3 to 3.5 m below the silt surface. This was taken into account when designing the plough construction.

The plough construction
The construction consists of several parts. The plough construction is the part mounted at the end of the ladder. It consists of two hollow blade constructions, which are pushed into the silt by the weight of the ladder. Through each plough two drain tubes are

Figure 2. Layout of the dewatering fields.

Figure 3. Principle of vacuum consolidation.
guided, which exit the plough at a different depth. This way four drains are inserted simultaneously, with a distance of two metres between them. This construction can be rotated around the end of the ladder so at every depth, it is always in the right position. When passing through harder soil layers, the jet nozzles at the cutting edge can be used to limit the cutting and friction forces.

The drain drums
The drains are guided through four separate tubes over the ladder coming from four drums mounted on the ladder at the same height of the main deck, which makes them easy accessible.

Inserting the drains
When inserting the drains the following actions take place:
- The lay-barge is positioned on the starting line. As the installation of the drains must be very accurate (every 2 m) an accurate positioning system has to be used.
- After the positioning the drains are inserted through the plough construction and connected with the shore.
- Then the ladder is lowered and the plough is inserted in the silt.
- By pulling on the back-winch the lay-barge is pulled on one line to the other side. The barge is kept on line by using the side wires.
- At ca. 40 m before the end of the track the drains are cut.
- The barge is pulled further to the end to make sure that all drains are out of the plough and the ladder is hoisted.
- The lay-barge moves back to the start line for the next track.

Collector tubes
On the shore all the drain tubes are connected to a collector tube (Figure 4). For monitoring reasons the upper and the lower drains are collected separately. The two collectors are then connected to the pump installation. On every collector a flow meter is installed to measure the amount of water pumped. The collector tubes are hard PVC tubes, which can resist the under-pressure in the system and which are easily connected with glue.

The vacuum pump installation
The vacuum pump installation (Figure 5) must create a maximal underpressure (80 to 90%) in the drain network and pump away the water that is extracted. The vacuum has to be as high as possible to provide a maximal extraction. The pump capacity has to be sufficient to pump away all the water.

The pump installation is built up as follows. First, a tank, which is put under vacuum by a vacuum pump. In the drum, a submerged pump is installed, to pump away the water that is extracted. An automatic control system controls the water level and the vacuum inside the tank.

Results
As the project has just come to an end a further analysis of the results has to be executed. This means taking samples of silt for further tests to determine water contents and other soil mechanical parameters. A further analysis of the amount of water pumped during these six months will show us the evolution of the flow of water extracted from the silt and a constant flow which gives us an idea of the leak that occurred.

In the pilot project the thickness of the silt layer was about 5.2 m. As the expected efficient radius is about 1 m around the drain, this results in only a 4 m thick layer that is treated. The other 1.2 m is treated much less efficient owing to border effects. On thicker layers, the border effects would become less important.

Gain in storage capacity
The storage used for the pilot project has completely been filled since 1991 and contained about 600,000 m³.
This technique has the possibility to insert a drain-network in a silt storage after the storage has been filled. This means that every existing storage facility for silt can maximise its capacity by using this vacuum consolidation technique.

**CONSTRUCTION OF A RAILWAY THROUGH A SLUDGE DISPOSAL SITE**

To keep its competitive position in the container traffic, the construction of a new container quay along the River Scheldt was a necessary and urgent investment for the Port of Antwerp. The location of the terminal was chosen taking into account the fact that good hinterland connections are essential for the operation of the terminal. Therefore, a new inland navigation terminal also had to be built in the harbour docks near the sea terminal. A good connection to the European highway network was already available, but extra railway infrastructure had to be installed. To make this possible a part of a very difficult to access disposal site for dredged materials near the North Sea terminal had to be stabilised.

The execution of the work was granted to a joint venture of the Belgian contractors SILT NV and Dredging International NV. The stabilisation of a surface of 67,000 m² had to be realised in a time span of six months.

**Description of the site**

The depot has been used since 1975 for the storage of fine-grained sediments coming from the harbour docks on the right bank of the River Scheldt. The depot was installed starting on the "Polder" level +2.50 TAW and is now reaching a level of +10.00 TAW in the part where the job was done. The railway bedding however had to be installed on the level +7.64 TAW. A stable dike needed to be constructed to bridge the difference in height between the bedding and the rest of the disposal site. The dike had to be strong enough to allow the depot to be filled up to the level +11.50 TAW.

The treated silt has been dumped there since 1991. Presumably it has reached a natural consolidation level in the period of five years preceding the test project. Before inserting the drains some samples were taken over the complete thickness of the layer. The density of the silt varied from 1.25 t/m³ at the top, to 1.35 t/m³ at the bottom of the silt layer. When assuming an average density of 1.30 t/m³ at the start and taking into account the gain in storage capacity, an increase in density up to 1.37 t/m³ after consolidation is calculated. This will be controlled on the samples taken after consolidation.

**Features and advantages**

The use of the vacuum consolidation technique to realise a fast dewatering of soft soil has several advantages. The dewatering results in a reduction of the volume and an increase of the density and stability of the soft soil. No surcharge is needed, as the water is extracted from the soil, creating an underpressure in the drain. Neither is a sealing foil needed, as the seal is created by the soil itself. The technique can be used in almost every location, even submerged.

The use of horizontal drains, rather than vertical drains, results in several advantages, especially when used together with the vacuum technique. When the right tools are used the time of inserting the horizontal drains is much less than the time needed to insert vertical drains.
Soil investigation programme
For this type of project knowledge of the subsoil is essential. To this end the Geotechnics Division of the Environment and Infrastructure Department was commissioned and they implemented a programme of borings and cone penetration tests. All the investigations were carried out with light portable equipment as the site was very difficult to access. Most of the investigations were done from a small dike, which was placed between the actual depot in use and the zone that had to be stabilised. This small dike prevented fresh sludge from entering the working zone in the six months proceeding the actual stabilisation.

The geological profile which was built up from this campaign was as follows:
- on top a layer of recent reclamation (harbour sludge), with a thickness of about 8 m;
- then a layer of soft “Polder” clay, whose thickness varied as it had filled all underlying creeks in recent history;
- a more sandy layer, with clay inclusions, called “Stroomzand” (natural sand), with a thickness of about 2 m and absent in certain areas;
- below this, a layer of peat and soft clay with a thickness from zero to some 5 m with an average of 3 m; and
- finally, old quaternary sands containing clay.

The working area was divided into three zones, depending on the topography and the availability of the natural sand layer (Stroomzand) underneath the sludge. The fact that this sand layer was not present in one part of the working area, resulted in the application of two different techniques to stabilise the site.

Description of the works
Zones 1 and 2
Before the real stabilisation started a hydraulic fill with sand in a layer of about 2 m thick took place. The sand came from the dredging activities to clear the new quay and served as a working platform on the site. It brought in place the sand needed for the work with a minimum of costs and thanks to this overload, the consolidation process already started slowly (Figure 6).

The actual stabilisation started with the construction of a stable dike between the future railway and the rest of the disposal site (also in zone 3). This was done with sand on which the dynamic consolidation method “Menard” was applied. The method consists of dropping several times a heavy weight (15,000 kg) from a height of about 15 m. As the sand went down into the

Figure 6. Stabilisation by vacuum consolidation (zones 1 and 2).
sludge, consequently the foundation characteristics of the soil underneath the dike construction were ameliorated. In some, more wet areas, sand drains were added under the dike.

In the meantime the work on the future railway bed took place. Vertical sand drains (\(\Omega 30\) cm, length 12 m) with a spacing of 2.70 m were drilled in from the working platform, reaching the sand layer of “Stroomzand”. The drilling holes were sealed with clay and silt.

Two rows of vacuum pumps were installed along the future railway bedding, lowering the water level in the Stroomzand from +6.50 TAW to +1.00 TAW. Through this forced vertical drainage (50 km of vertical sand drains), a settlement of 1.5 m of the sludge took place (dry matter > 55%). Afterwards a layer of 1.3 m of consolidated sludge was excavated and a top layer of sand (0.5 m thick) was compacted. This brought the railway bed to its finished design level of +7.64 TAW.

**Zone 3**

Here a layer of 2.9 m of sludge was excavated and a 1.0 m thick layer of sand was put on the remaining sludge to serve as a working platform. The whole operation still required a sludge transport of about 125,000 m\(^3\) (zones 1, 2 and 3) to the adjacent disposal site where, by the use of bulldozers, it was stored below +11.5 TAW. From the sand platform, in zone 3, the stabilisation of the railway bedding was done with gravel piles (\(\Omega 80\) cm, length 7.5 to 12 m) with a spacing of 2.50 m. The imposed short time span for execution and the lack of additional material sets, obliged the use of two different techniques for installation of gravel piles, both giving sufficient results (Figure 7).

With the first technique, thanks to its own weight and an additional vertical force, a cylindrical vibrator was brought into the sludge until it reached a sand layer with sufficient bearing capacity. Then the vibrator was lifted for 0.5 m and while the shaft was kept open with compressed air, gravel was added under pressure and forced into the sludge until saturation was achieved. Then the vibrator was lifted again and again, doing the same operation until the surface was reached.

The other technique consisted of vibrating a hollow tube (\(\Omega 80\) cm) into the sludge, using a vibrohammer. The tube had a certain overlength and a valve at the bottom that was closed when reaching down and opened when the tube was pulled up. Once the foundation level was reached, the tube was filled with gravel. While lifting the tube, using the vibrohammer, the gravel stayed in place, creating a gravel pile.

Figure 7. Stabilisation with gravel piles (zone 3).
Testing
After the stabilisation, the site was transferred to the National Railway Company for the installation of the track. The requirements they had for the area were a modulus of compressibility of more than 17 MPa and differential settlements of less than 50 mm on a distance of 10 m. Every 1500 m² of the railway bedding was tested with a plate loading test (750 cm²) with good results.

The standard test method for bearing capacity gives information on the soil only to a depth equal to about two times the diameter of the bearing plate. The standard bearing plates are varying in diameter from 305 to 762 mm, so the bearing capacity could only be estimated to a depth of 1.50 m. As the railway track was to be used quite intensively and heavy loads were to be expected another test was added.

The tender document asked for testing of the bearing capacity on six different locations, spread across the entire area, by constructing a 40 cm thick reinforced concrete slab with a width of 4.5 m and a length of 10 m (this equalled a load of 10 kPa). Each slab had to be loaded with 28 kPa for several days, while the settlements on the edge of the slab had to stay less than 50 mm. The six tests were successfully executed.

The installation of the concrete slab (with a total weight of 46 tonnes) caused, in all cases, a settling of less than 15 mm, after 20 days. The additional load of 28 kPa (an additional weight of 126 tonnes) was installed and caused, in all cases, an additional settling of maximal 15 mm, within the first day. After three days a steady state was achieved and over the entire area the total settling stayed well beyond the prescribed 50 mm.

Nowadays the treated part of the disposal site is bearing the weight of freight container trains heading for the Scheldt container terminal.

Soft Soil Improvement

The properties of soft soil, such as large deformation, low strength, high water content and, recently, contamination by human activity are often responsible for the problems that occur in modern building projects. Soft Soil Improvement is an in-situ technique, invented, developed and patented within the DEME Group, that can help to overcome these problems.

Primarily the technique was designed for soil stabilisation in relation to dredging activities. In a further field of application SSI can also be used for the immobilisation of heavy metals or other contaminants in the soft soil and even to enhance bio-remediation in contaminated soil layers.

The technique

The SSI set (Figure 8) incorporates three main units:
- first, a computerised grout mixing unit, with storage facilities for binding agents, and such;
- then, a high pressure pump unit;
- and finally, a computerised injection unit mounted on a swamp crane (the swamp excavator).

For all the units of the SSI set conventional equipment was used; only the technology and the mixing blades are protected by knowhow and world-wide patents.

The three units of the SSI set and the storage facilities are fully transportable by containers. A surface of about 300 m² (12 m x 24 m) is required for the installation. In three days time, with a minimum of auxiliary equipment, the mobile plant is installed. The SSI set can be erected and operated by a maximum of three workers.

The mixing unit prepares the grout mixture to be injected. Up to four different products can be mixed in predefined quantities through a controlled measuring system. According to the required object, different types of agents can be used, such as cement, bentonite, fly ashes, lime polymers and so on.

The mixing process is executed according to a preconceived recipe, after which the grout mixture is delivered ready for use to the production line. The control of the mixing unit is fully automated and computerised, but it can also be used manually.

After that a high pressure pump sends the prepared mixture with a pressure of up to 400 bar to the injection unit. In order to control the production and the quality of injection, a flow meter has been placed on the production line. The computerised injection unit controls and registers all the injection parameters: injection time, operational depth of the mixing blade, torque for the rotation of the mixing blade, down/up speed, rotation speed and the flow of the injected mixture. All those data are collected on a memory card (PCMCIA standard) and at the end of the week they are transmitted to a standard PC with memory card reader to write the production report. Data for every single executed column is recorded separately.

The injection unit is mounted on a crane, equipped with a large and floating undercarriage (the swamp excavator), which allows the unit to work on the very soft soil particular conditions for which the equipment was designed.

A homogeneous mixture of grout, binding agents and the soft soil, is created in a mechanical way by the mixing blades and in a hydraulic way by the turbulence of the very high pressure injection. The mixing blade itself is prepared in relation to the type of soil to be treated. The blades can have a different length according to the consistency of the soft soil. They are equip-
So executed, the blades create a column of treated soil. A computer registers the precise position of the column by using the data from the K.A.R.T.-D.G.P.S. The Kinematic Accuracy Real Time Differential Global Positioning System is a satellite system which allows the operator to position the drilling rig with a very high accuracy. Each column realised is marked on a laptop screen to distinguish the performed work (Figure 9).

**Fields of application**

By varying the binding agents, their concentrations and the column configuration, different objectives can be achieved. To stabilise soft soils, a mixture, consisting mainly of cement, is injected. The columns can be placed following a predefined configuration according to the expected load on the soft soil. Soils, which can practically resist no load, show an acceptable stability after treatment. The technique has already been tested with this purpose.

**Figure 8. The Soft Soil Improvement set.**

**Figure 9. The K.A.R.T.-D.G.P.S. system.**
Before treatment, the stability of the soil layer to be treated was determined by means of cone penetration tests (Figure 10). This choice was made, taking into account that a plate loading test is practically not executable with such soft soil (Figure 11). The cone penetration tests showed that the sludge layer offered practically no resistance ($q_c < 0.4$ MPa) to the penetration of the cone. After treatment, a cone penetration test was no longer executable, thus the stability was tested with plate loading tests (200 cm$^2$), with a good result (Modulus of compressibility = 99.75 MPa).

For the immobilisation of heavy metals or other contaminants in soft soil, agents such as bentonite are used. The diameter of each column is calculated so that each of them interacts with its neighbours. In this way, the entire volume of soft soil is treated and thus the method prevents any lixiviation of contaminants. The technique has already been tested with the purpose of immobilising heavy metals in river sediments.

Some analyses were performed before and after applying the technique in order to evaluate the lixiviation of heavy metals in the river sediments. Four heavy metals (As, Cd, Hg, Pb) were determined. The results show explicitly the binding of the four metals into the sludge, owing to the reaction of the particular binding agents (Figure 12).

The method described before can also be used to create a vertical shield to isolate contaminated sediments from the environment. The columns are placed in one line and each of them intersects with its neighbours.

For yet another field of application, the unit can easily be used to insert a consortium of bacteria into contaminated soft soils. The technique stays the same, but instead of using a mixture of cement and binding agents, bacteria are implemented to enhance bioactivities for degradation or immobilisation of contaminants.

**Features and advantages**

Soft Soil Improvement is an in-situ technique, so in contrast to classic sand replacement methods, practically no contaminated material need be transported to other locations. This results in a reduction of time and money. Furthermore, the environment is preserved because no disposal site is required for excavated silt.

Owing to the easy transportation and installation of the equipment and the mobility of the swamp crane on the very soft soil, no site is inaccessible for the technique. And owing to the automated control systems, the execution of the technique is not complicated.
techniques for stabilisation were applied. One zone was stabilised by vacuum consolidation with vertical sand drains; an other zone was stabilised with gravel piles.

- Soft soil, contaminated with heavy metals or other pollutants, can be treated by an in-situ, high pressure mixing of the soft soil with cement and certain additives (Soft Soil Improvement). Soil, initially resisting practically no load, shows after treatment a modulus of compressibility of 100 MPa. The lixiviation of heavy metals can be reduced easily to a minimum, far beyond the legal criteria.

All these results demonstrate that the recently developed techniques, or a combination of these, can bring a solution to the actual problems encountered by the Antwerp Port Authorities and the Flemish Government.

Conclusions

- Large-scale pilot projects on dewatering lagoons confirm that, on a yearly basis, this technique results in a 50% volume reduction in the finally needed storage capacity for fine-grained dredged material.
- Vacuum consolidation of silt, stored underwater, creates a large amount of new storage capacity. The technique, tested in the harbour of Antwerp, showed a gain in storage capacity of 20%.
- For the construction of a bedding, through a fine-grained sediments disposal site for the railway link to Antwerp’s new container terminal, two different techniques for stabilisation were applied. One zone was stabilised by vacuum consolidation with vertical sand drains; an other zone was stabilised with gravel piles.

Furthermore, the fact that the whole installation consists of conventional, easy to install equipment, makes the technique, even in very small projects, profitable.

By using primarily the cutting force of the fluid injected at a high pressure the wearing of cutting tools and total installed power is reduced.

In varying the agents and the column configuration every objective can be achieved. This makes the technique far more flexible than the classic methods for stabilising soft soil.

The in-situ sanitation of contaminated soft soil, using the described technique, offers a durable and stable solution.

Figure 12. Immobilisation with Soft Soil Improvement.