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Membrane constructions in civil engineering practice

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ABSTRACT: In this paper the use of synthetic membranes in building infrastructural structures below ground level are discussed.
Beside a description of the membrane construction in a number of important subjects are treated in depth.

INTRODUCTION

As the awareness of environmental aspects has grown among the public and local authorities at large, then the need for constructing environmental friendly below ground (e.g. roads and railways) infrastructure has increased. Hence such aspects as noise and visual pollution could be reduced.roads and railways) infrastructure has increased. Hence such aspects as noise and visual pollution could be reduced.

POSSIBLE SOLUTIONS TO UNDERGROUND TRAFFIC INFRASTRUCTURE

When laying roads below ground in the Netherlands one immediately confronts groundwater. If dewatering is permitted then there are two conventional construction methods available:

- by permanently lowering the groundwater level, with the water being discharged onto open waterways;
- by applying reinforced concrete trough, founded on raft foundation or tension piles. The trough is built in a building pit.

However lowering the groundwater level can cause local subsidence to buildings and possible damage to crops, in which case additional measures are needed such as recharge wells which are normally required to limit the negative effects caused by dewatering.
Permanent and temporary dewatering is becoming increasingly difficult to attain. This is due to the evermore stringent environmental requirements; associated with an approval from local authorities.

If dewatering is not permitted, then we have to resort to more expensive construction methods, such as:

- an open excavation, using vertical walls (e.g. steel sheet piles, cement-bentonite walls or diaphragm walls) reaching to a naturally occurring horizontal impermeable layer such as clay. If such a layer is not existing, then a man-made impermeable layer can be grouted to a determined depth. However, grouting is not considered to be a reliable or cost-effective method;
- building a reinforced concrete trough within a temporary braced pit. This pit is constructed by retaining walls and underwater concrete as a bottom seal. The retaining walls can be of steel sheet piles walls or diaphragm walls.

MEMBRANE CONSTRUCTION

As a more economic alternative to the aforementioned expensive construction methods, Rijkswaterstaat has applied the principle of membrane construction 14 years ago when building highway A27 near Utrecht as a road-in-cutting. Then there were only two such known application in the Netherlands:

- for the drinking water reservoir in the Biesbosch, developed by the Rotterdam Drink Water Authority and;
- an underpass beneath the railway line in Breda built by the Dutch Railways.

Essentially, membrane construction is actually a polder (see figure 1). The polder is separated from the groundwater by means of a watertight membrane. Within the polder, the road is kept dry by maintaining the polder water level using a separate sewerage and drainage system which channels the rainwater into water sumps.

Figure 1 and 2 show two construction methods for positioning the membrane. These methods are

Photo 1: Immersion the membrane

based on the principle whether dewatering is permitted or not. If dewatering is permitted then the membrane can be positioned in a dewatered or dried excavation. If dewatering is not permitted then the membrane must be immersed into position in a dredged trench (photo 1).
Advantages of positioning membrane in dry condition:

- the ability to check the excavation for any sharp obstacles, evenness and firmness of the subsoil;
- the membrane is simple to position;
- it is easy to check the membrane for the presence of any defects before backfilling;
- slopes of the excavation can be steeper than that of a dredged trench. Depending upon the characteristics of soil, the rule of thumb is that

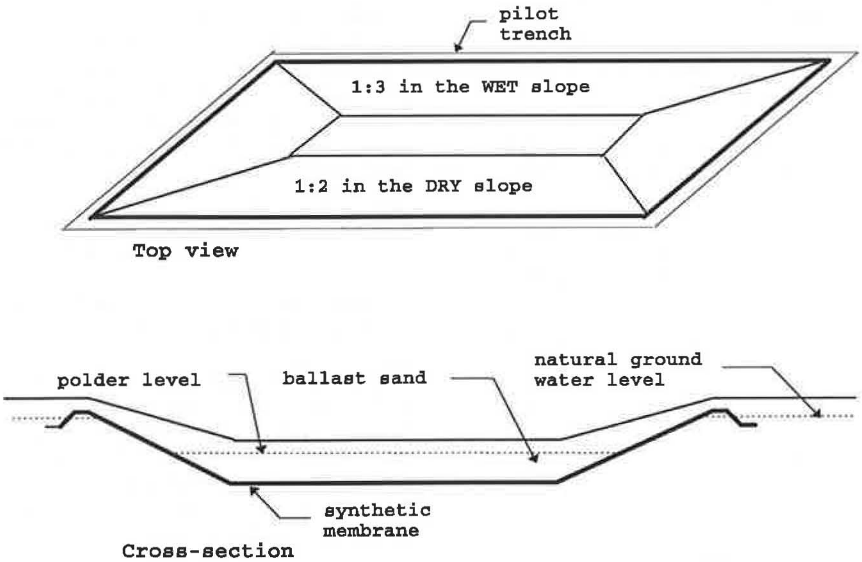

Figure 1: Principle of the polder construction with membrane

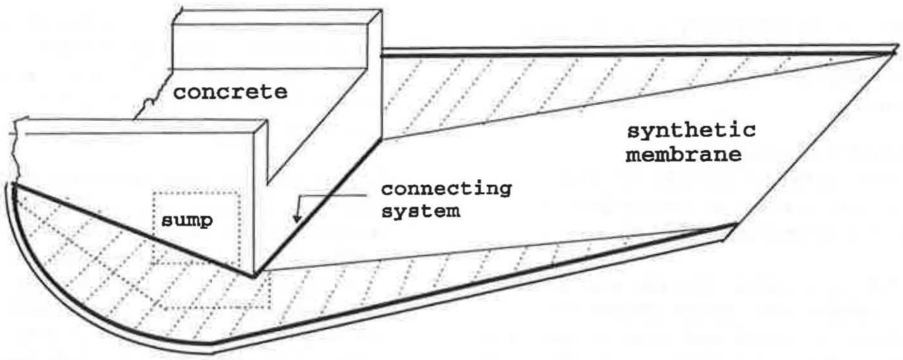

Figure 2: Principle of fastening a membrane to a concrete structure

the slope can be 1:2 in dry conditions while in dredged trench it can not be steeper than 1:3;
- dry positioning is more economic than immersion;
- no possibility of silt being trapped between membrane and the bottom;
- higher rate of compaction of the ballast sand above the membrane can be achieved.

The main drawback is that it requires temporary dewatering of the groundwater.

Apart from the use of membranes on roads in cutting, membranes are also used in the approaches to road tunnels and underpasses.

As can be seen from figure 2 and 3, a connecting system is used to fasten the membrane to the deeplying concrete structure.

The U-polder concept has been developed for road in cuttings in which no space is available for open excavations. In the U-polder construction method, the membrane is turned square at the edges (see figure 4), minimising the use of space required broadwise. Rijkswaterstaat has successfully tested this new concept in the construction of a bicycle tunnel under highway A59 between Goedereede and Ouddorp.

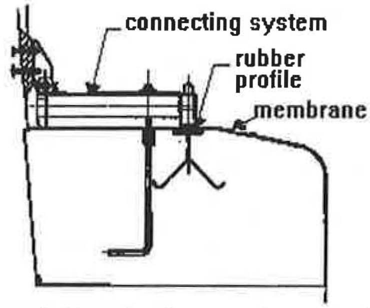

Figure 3: Example of a connecting system for underwater application

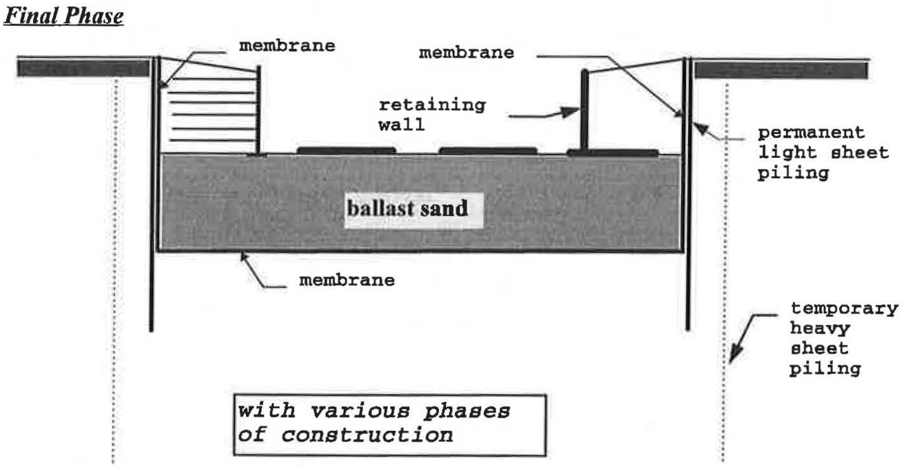

Figure 4: Principle of the U-polder

It should be noted that synthetic membranes are used in larger quantities in the environment and water supply industries than for underground infrastructures.

STABILITY AND RISKS

In addition to being water tight, the other requirement for membrane construction is its stability in terms of soil mechanics.

For that respect conservative values for the specific weight of the ballast sand are assumed for calculating the vertical equilibrium. A value of 16 kN/m^3 is usually taken for the dry specific weight of the ballast sand, and 19 kN/m^3 for the wet specific weight.

In the temporary construction phase, during laying the drainage system, a safety factor of at least 1.05 for vertical equilibrium. In order to avert any possible dimensional deviation of the ballast sand, a minimum soil pressure of 5 kN/m^2 is required underneath the membrane. In the final phase, after asphalt work has been completed, a factor of 1.1 is usually applied.

More advanced calculation can stochastically interpret the various parameters (geometry, material and water levels) with their probability density function (the simplest version being an expectation value with its associated standard deviation). A probabilistic analyses was performed. The results of this analyses gives the annual risk of failure of the construction and also the extent to which the various stochasts can affect the risk of failure.

The probabilistic analyses performed by Rijkswaterstaat indicated that the size of the aforementioned safety coefficients in general lead to acceptable failure risks.
Any further reduction in these coefficients is not advised, however.

The main parameter influencing the risk of failure was found to be the uncertainty in the wet specific weight of the ballast sand. It is therefore important to check whether the specific weight determined from the site agrees with the design principles.

The relatively low safety levels mean that there are only minor granular stresses on the bottom of the membrane, see also figure 5. There is therefore a sliding surface beneath the membrane along the slope and horizontal part. The horizontal component force, resulting from the sliding mass of soil along the slope, is mainly kept in equilibrium by the resistant force generated in the ballast sand above the membrane. This implies that caution must be taken when excavating trenches, for example for drainage and sump, in the horizontal part of the ballast bed. Such excavation can cause both horizontal and vertical instability in which the excavation trench might give in as a result of squeezing.

The low granular stress below the membrane means that it makes little difference whether a smooth or somewhat rougher membrane is used.
If there is a surcharge at ground level, fairly large granular stresses will be generated beneath the membrane along the slope, which favourably effects the total stability.
In order to achieve a better understanding of the various forces acting within the aliding mass it is recommended to carry out computer-aided calculations, such as the finite element programme PLAXIS.

PROCESSING MEMBRANE MATERIALS

The Civil Engineering Division of Rijkswaterstaat has so far gained practical experience in using PolyVinyl Chloride (PVC). The PVC membrane is rolled into strips which are around 1.4 to 2.0 metres in width and several hundred metres in length. To avoid in situ welding as much as

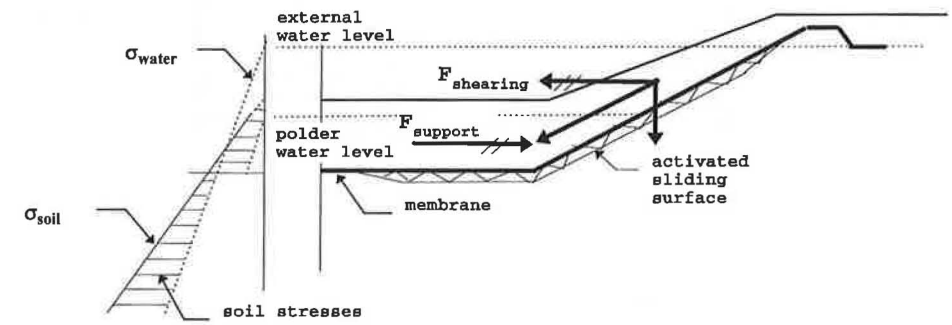

Figure 5: Vertical stresses according to the depth and equilibrium of forces on the slope

Photo 2: Welding the membrane

possible, the strips are welded inside a covered area into manageable sheets of 2,500 to 3,000 m^2 (3,000 to 4,000 kg). The sheets are then welded into a single entity in site. Cross welds should be avoided as much as possible as welding four strips of thick membrane is considered problematic. Particular problems occur in the connection system which fastens the membrane to the concrete structure. The most popular factory welding methods are the high frequency and Heizkeil methods. The Heizkeil method is generally used for in situ welding. The two strips of membrane are heated and mechanically pressed. The advantage of the Heizkeil method is that, in principle, the welds can be made infinitely long without any interruption.

Gluing can also be used. Gluing is suitable for creating special connections, repairs, etcetera. Under water, PVC membrane repairs can be carried out by gluing.

The reasons for choosing PVC in the past is attributed to the great degree of flexibility it offers and the great accuracy in thickness dimensions (thanks to the calendaring- manufacturing-technique). Slight thickness variations result in a better welding quality. The other manufacturing method, blown-film membranes, allows greater thickness tolerances. Further, unlike calander-manufactured membrane, the blown-film-manufactured membrane has the advantage that they can be produced in much greater widths, which means that fewer welds are required. The specific weight of PVC is greater than that of water, which means that the membrane's own weight will cause it to sink to the bottom when immersed. However if another type of membrane with a lower specific weight is used, it can also be immersed by having a slight overburden of the water level above the membrane.

Other options to PVC membranes are flexibilised LDPE and Butyl Rubber.

DURABILITY OF PVC MEMBRANE

The life span of PVC membrane is limited by such factors as sunlight, oxidation, tension corrosion, chemical attack and plasticiser loss.

Plasticiser loss is regarded as one of the major threats to the durability. A PVC without plasticiser is a fairly brittle material and may become porous. This was regarded by Rijkswaterstaat for further investigation into the effect of plasticiser loss in underground applications.

A survey of available literature that was carried out by the Plastics and Rubber Institute of TNO, found that there was little concrete information available from similar application areas, nor was there any answer found to the question of what material remained once the plasticiser had disappeared from the PVC membrane.

This issue was further investigated through two additional studies.
The first one involve the removal of two sections of membrane from the embankment of the road in cutting in the national highway RW 27 near Utrecht. One section above groundwater level and the other below. The age of the membrane then was around 10 years.
From these two samples, the plasticiser loss was measured and compared to those values provided by the vendor. It was found that the plasticiser content had decreased from 35 to 32% over the considered years.

The second study involved removing the plasticiser from a new PVC membrane by using an active carbon agent and by subjecting to higher temperature. The duration of the exposure determines the percentage loss of plasticiser. For this purpose samples with 15, 25, 35 and 45% plasticiser loss of the original plasticiser content has been produced. This treatment was carried out both on free samples as well as samples fastened on four sides. The reason for fastening the sample on four sides was to emulate the site conditions as closely as possible.

In both studies the main properties of the membrane such as tensile strength, elasticity at failure, tearing strength, thickness and water permeability were measured.
It was found that all the samples with various contents of plasticiser have still satisfied the water permeability criteria.

It was also observed that the relatively minor decrease in elasticity and increase in tensile and tear strength which indicate an increase in the E-modulus. This phenomena was associated with loss of plasticiser.

Mathematical analyses, supported by some plasticiser extraction tests at lower temperatures, have shown that at an ambient temperature of 10°C, a plasticiser loss of 30% is attained after 300 years. This is the level at which elasticity at failure start to falls below the minimum specified requirement of 250%. If there is no other ageing processes occurring simultaneously it is then highly likely that the applied membrane will still perform well despite a plasticiser loss of more than 30%. Thus the design life will be amply achieved.

In spite of such positive result from the above study Rijkswaterstaat does not exclude the possibility of applying other membrane types such as flexibilised PE or EPDM rubber for the future.

CONSTRUCTION ASPECTS

Positioning the membrane
The membrane can be positioned in the dry conditions or it can be immersed.

Laying *in the dry conditions* is the simplest way of construction. The construction trench is excavated in the dry using after the trench has been dewatered. After the membrane has been welded together in the factory into large sheets, the membrane will be folded into a bundle and transported to the site. It is folded in such a way that it can be unfolded on site in four directions. Afterwards the membrane is welded to the previous laid sheet. The first layer of backfill must proceed immediately after welding and checking the quality of the weld. This is necessary to avoid mechanical damage and the effects of UV radiation.

Laying the membrane *by immersion* is a more difficult process. During the first project which was carried out by Rijkswaterstaat (Utrecht) small scale submerging tests were carried out in the Hydraulics Laboratory. Floaters were welded onto the membrane, after which the membrane as a whole was submerged by spraying sand between two floaters at a time. This method proved to be very critical. Spraying must be carried out uniformly and once the membrane is on the bottom than it is no longer possible to carry out any positional adjustments. Spraying with sand was later replaced by letting in water between two floaters. This method is regarded as a feasible immersion method. Although is was found to be difficult to direct the water to those place where it should go, in the combination of pumping water and anchoring the membrane, it is possible to submerge the membrane to the position where it meant to lay.

Other submersion methods were then considered for the A27 project, in cooperation with various contractors. Two methods were tested in life-size trials. The first one was submersion using a pontoon offered by Volker Stevin and the other one by unrolling the membrane using a floating tube offered by HAM. As the contract was awarded to the lowest bidder, Volker Stevin, submerging was carried out by using a pontoon. In brief, submersion proceeded as follows: membrane strips equal in length to the width of the construction trench are welded in the factory into sheets which can be transported. Than these sheets are folded in a zigzag manner and rolled up from the ends towards the middle. Later these rolls are transported to the site and unrolled on a pontoon above another and welded together to a single unit.

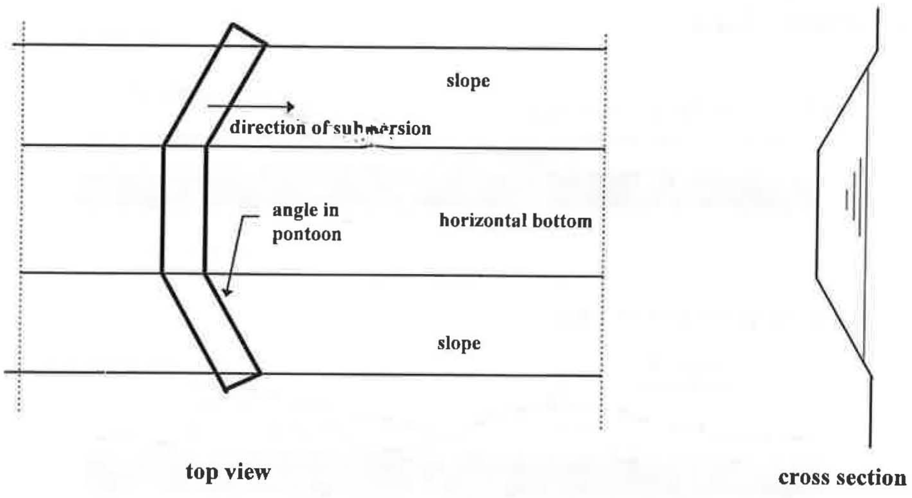

Figure 6: Shape of the submersion pontoon

Than the pontoon is positioned across the dredged trench. If the pontoon were straight, wrinkles would develop in the membrane along the slopes. To avoid that, the outer parts of the pontoon are angled towards the direction of immersion, see figure 6.

By pumping water from behind the pontoon and discharging it on the already submerged membrane, than a slight over pressure is developed which pulls more length of the membrane from the pontoon into the water. Simultaneously the overpressure push the pontoon towards the direction of immersion.

For tunnel approaches and aqueducts the width of the dredged trench narrows as the trench becomes shallower. The outer parts of the pontoon which float above the slopes must therefore vary in length. This can be achieved by detaching parts of the pontoon on both sides. One variation on this is to create a harmonica-like construction in the pontoon by means of hinged triangles. This latter solution was recently used in the construction of an aqueduct near Akkrum.

By the application of overpressure on the membrane by means of raising the water level for a few days, one can guarantee that the membrane settles on the bottom at every point. Through this method any silt trapped under the membrane will be given the chance to consolidate.
Afterwards sand will be sprayed on the submerged membrane. To avoid any sliding of the slopes and thus damaging the membrane, sand spraying is done from the centre of the deepest point of the dredged trench, side and upwards.

For the construction of the Noord tunnel, it was decided to submerge the membrane using floaters as was earlier tested in a small scale laboratory test. When it came to doing the work in practice, it was found how difficult this method is. Water ended up between two floaters in an uncontrolled manner, and the membrane prematurely sunk out of control as a result of insufficient number of floaters and the leakage of a floater. It was no longer possible to recover the membrane undamaged. Subsequently a new membrane had to be manufactured and made ready for immersion.

HOW TO MANAGE TRAPPED SILT

When immersing a membrane, it is not entirely avoidable for silt, which makes up part of the sub soil, to end up floating in water during dredging and later sinks to the bottom of the trench. If the membrane sinks onto the silt layer and later ballasted with sand, in practice the weight of the ballast sand will squeezed (push forward) the silt. However, pockets of silt may still remain under the membrane, thus causing localised protrusions in the membrane, see figure 7.

Therefor a good design principle is to ensure that the inevitable layer of silt remains in position under the membrane during backfilling. This depends upon such features as silt characteristics, thickness of the silt pocket, the slope of the backfill layer and the overburden pressure and time on the silt. The rate consolidation can be increased by slightly raising the water level above the membrane as temporary additional overpressure.

A mathematical model has been developed for determining the behaviour (squeezing) of the

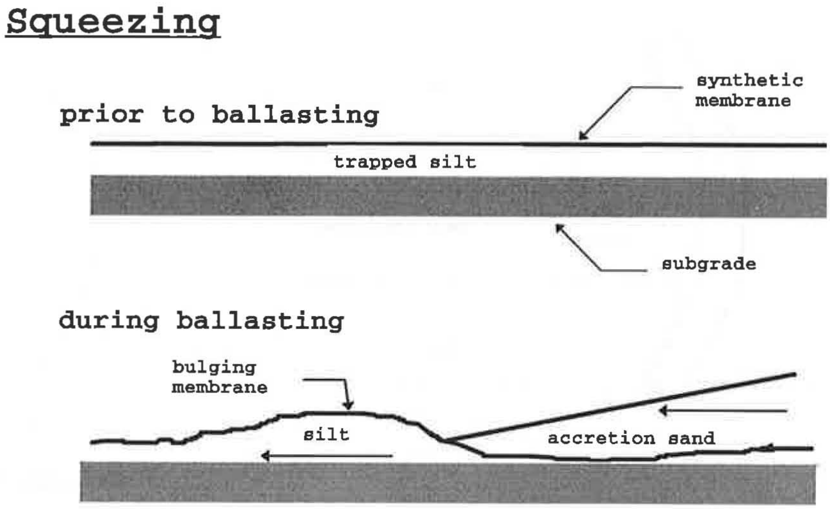

Figure 7: Uncontrolled squeezing out of trapped silt

trapped silt. By using silt characteristics, which are fairly simple to determine, one can calculate whether there is a danger of squeezing or not.

The calculations for the aqueduct Akkrum has shown that 1 cm thick layer of silt may risk being squeezed away by the front of the backfill. However, it is not practicable to remove such thin layers of silt.
Raising the water level for a period of 14 days accelerates the consolidation of the silt so that it would be not objectionable to have a 10 cm layer for the silt trapped under the membrane.

ELECTRICAL LEAK DETECTION METHOD
In 1992 the Civil Engineering Division of Rijkswaterstaat developed an under water detection system to find leaks in membrane constructions.

Following an analysis of the available detection methods, a choice fell on an electrically operated technic. Published papers from the United States indicated that some experiments had already been carried out in this field. TNO Groundwater and Geo-Energy had a device for geo-electric measurements which could be used fairly simply as a leak-detection system. After carrying some experiments with this system, TNO has done a number of a numerical simulations with the help of a computer program for groundwater flows. Flows of groundwater and electricity can be described with a similar equation, with the physical units as the only difference. The calculations were deemed necessary to gain some understanding of how the system worked and to avoid expensive experiments on construction projects. Simulation showed that the system can also be used in a live scale experiment provided that the electrodes are put sufficiently apart. On the basis of such acquired knowledge it was decided to apply the leak-detection system in the "U-polder" trial project.

This system comprised of a PVC frame on which gauging cable and electrodes were attached. Outside the building pit another electrode is fixed. A voltage difference was applied between those two electrodes. If there was a tear in the membrane, current will then flow between the two electrodes and an electrical field will be created in the building pit. By shifting the measuring frame from one location to another and measuring at each location, it was possible to create a picture of the voltage distribution over the entire surface of the building pit. The leak can be identified by looking at the voltage distribution.

One drawback of this detection system is that it can only work adequately for constructions which are electrically insulated. No other electrically conductive elements as sheet piles or concrete walls may be present within the building pit.