The Dutch experience with geomembranes for road constructions evaluated

J.J. van Meerten
GeoDelft, Delft, the Netherlands

J.P. Vercouteren
Arcadis, Amersfoort, the Netherlands

G.L. Tan
Formerly: Department of Public Works, Utrecht, The Netherlands

J.W.M. Lambert
Geodelft, Delft, the Netherlands

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ABSTRACT: In The Netherlands geomembranes have been used to build a number of civil engineering projects, consisting of large and deep tanking constructions for roads and railroads. The geomembrane must ensure the permanent waterproofing of these constructions. Differing from hydrological and environmental projects with the aim to prevent outflow of fluids, in this case the membrane protects the construction against the inflow of groundwater and waterlogging. The use of this building method is almost certainly typically dutch due to the soft soils and groundwater circumstances with high levels in the deltaic regions of The Netherlands. The success of geomembrane constructions is a result of the relatively simple and cheap building techniques. As will be explained the success depends on a good knowledge of materials, design aspects and quality assurance to prevent or detect and repair leaks during the building process.

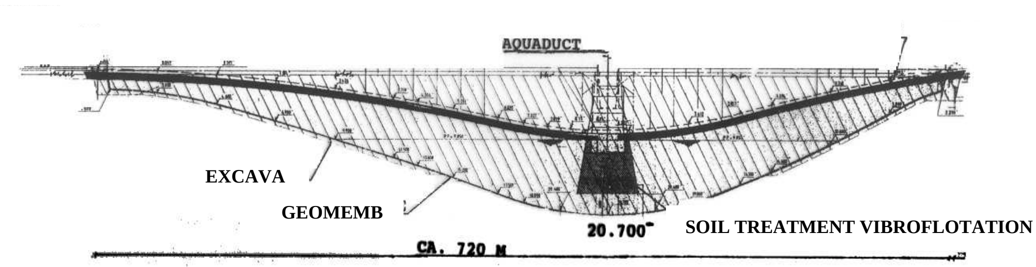

Figure 1. Lay-out for a design of an aquaduct in a geomembrane construction

1 INTRODUCTION AND DEFINITION

The geomembrane construction, as is dealt with in this paper, is a civil engineering solution to build below the existing natural groundwater level. The geomembrane is a thin, watertight construction element that is placed underneath a ballasting sand layer. In the construction design the geomembrane has a permanent function. The geomembrane forms an artificial aquitard underneath the structure and will prevent upward flow of groundwater.
Applications of these constructions are for instance: tunnel ramps, road or canal crossings, lowering of roads in cuttings for reasons of planning or noise reduction near cities.

2 EXPERIENCE

From the 1970's until present a number of 25 road constructions have been realised in The Netherlands with geomembranes in soft soils (sand, clay). Based on the dutch experience also in Denmark (ramp of the Øresund tunnel) and Ireland (design for a tanking of a motorway in a glacial till formation) succesful applications were found. Mostly the choice for a geomembrane construction comes forward if a natural aquitard (clay layer) can only be found at very large depths and the needed space for the work is not a problem. Until now 1,0 to 1,3 mm PVC is the material that was used in most projects to manufacture the membrane. It is recommended to protect the membrane against accidental spills of chemicals by constructive measures in the road design (sealed ditches or sewers or extra drainage of water coming from the road).
Some recent examples of large projects in Holland are:
Akkrum Aquaduct (river crossing): A = 100000 m^2 PVC 1,3 mm;
built by sinking membrane; 1994
Grouw Aquaduct (river crossing): A = 30000 m^2 PVC 1,0 mm;
built by sinking membrane; 1992
De Noord Tunnel (tunnel ramps): A = 20000 m^2 PVC 1,0 mm;
built by sinking membrane; 1992
Amelisweerd motorway (tanking): A = 68000 m^2 PVC 0,8 mm;
built by sinking membrane; 1984

3 BUILDING METHODS

Difference must be made between two types of conditions at building the geomembrane construction. (1) *Dry conditions*: According to traditional methods a large excavation is made in a dry building pit using groundwater pumping equipment and maybe a temporary sheetpile wall. Good quality control of the placement and welding of the membrane is possible in this way.
(2) *Wet conditions*: To reduce the negative effects on the surroundings due to lowering of groundwater levels with the above mentioned method it is possible to excavate a flooded pit with dredging equipment, if this can be transported to the site. In the period of dredging and later on during sinking of the membrane the waterlevel must be higher than the groundwater head. It is important that stones and other obstacles are removed from the bottom of the pit by divers, guided by lines in staked rows. If a lot of stones are present a spreading layer of about 0,5 m of fine sand can be made. It is important to control and reduce the amount of dredging sludge in the pit because this may lead to instability of slopes or bursting of the membrane during filling with ballasting material on top of the membrane. The prefabricated packages of membrane are spread from a role on a specially constructed pontoon (see fig. 2), from where it is hauled off to give it the proper shape.

Figure 2 Sinking the membrane from a pontoon

The sinking procedure of the geomembrane depends on the weight of the membrane material. If the membrane floats (LDPE) it must be lowered by managing an overpressure on one side of it. Membranes that are heavier than water (PVC) can be floated to the proper place with air filled tubes, that are emptied when the membrane is rightly positioned.

The filling with ballasting sand must take place from the bottom upward either with trucks in a dry pit or a spraying device from a pontoon making thin layers (max. 2 m) without causing sliding on the slopes. The material must be protected against puncturing by equipment or personnel.

4 ADVANTAGES AND DISADVANTAGES

Certainly the biggest advantage is found in the relatively low costs of a geomembrane construction. The dutch department for public works that invested a lot in the research on these constructions, claims that the price is about 40 to 50 % of the costs for the realisation of traditional solutions, e.g. consisting of a concrete structure and tension piles to resist the uplift forces from the groundwater. In some cases it is cheaper than building sheet pile or slurry walls when the clay layer lies at a great depth and it is certainly easier and more reliable than realizing a vast injection or grouted layer.

In The Netherlands also the preservation of high quality fresh groundwater is an important issue. With special sinking techniques the geomembrane can be put in place under wet conditions. In that way even lowering of the groundwater level by pumping wells in the building stage with all negative aspects like settlements, drying out of agricultural land or nature reserves and the loss of good quality groundwater can be eliminated. Nevertheless, building in dry conditions is probably always cheaper.

A negative aspect is that, due to the depth of the construction and for geometrical reasons in the standard case with easy slopes of the excavation, a large area is needed. However, new building techniques have been developed to combine the ground retaining property of sheet pile walls with the waterproofing quality of geomembranes to prevent water flow in vertical direction. This so called U-polder solution has been tried succesfully at a test site and later on was found to be a suitable design for a railroad passage through the town of Best. An example of such a design is shown in figure 3.

To banish leaks severe quality control measures on the handling of the geomembrane, the welding activities and a good care during the earth works is absolutely an important necessity.

And when the construction is ready preventive measures (registration, management and control system) have to be implied to minimize the risk of damaging the geomembrane during the lifetime of the construction.

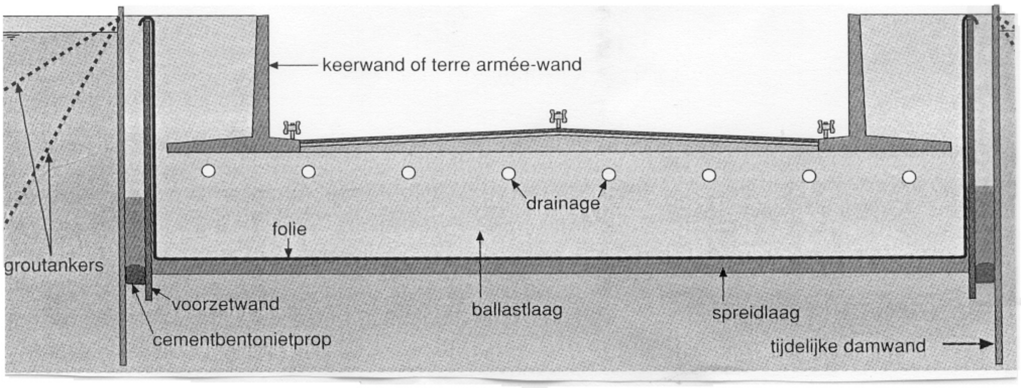

Figure 3. U-polder design

5 DESIGN

The depth below surface where the geomembrane has to be positioned must be fairly large as to ensure there is enough thickness and weight of the ballasting layer on top to resist the uplift forces. Because of this the geological investigation must also reach the right depth to get enough information to choose the correct dredging equipment, to decide about the best building method (wet or dry conditions), to examine possibilities to recycle excavated soil and to learn whether stones or obstacles occur that might be harmful for the membrane. The investigation must give proper parameter values for geomechanical calculations of possible deformations of the surrounding soil (settlements and slope stability).
First of all the space proofing of the road or railroad construction is the starting point. But also the necessary depth of sewers and drains and sewer collection cellars must be taken into account. The depth of the geomembrane is selected through an equilibrium calculation considering the thickness of the ballasting soil inside the construction, not only for the deep part but also for the slopes. The possible risk of sliding of the membrane due to low effective stresses underneath the membrane should be prevented by taking proper safety factors on volumetric weight of ballasting soil in the calculations, good predictions of groundwaterlevels and a margin of approximately 5 kPa on the effective ground stresses below the membrane in all stages.

As the state of art nowadays dictates, the quality control measures already start in the design phase with a serious risk analysis. This consists of an analysis of possible failure mechanisms during the building process and lifetime of the construction.
The above mentioned deformation calculations (settlements and stability failure of the excavated earth slopes, and if needed below waterlevel) must also consider the risk of squeezing of silt that may occur as dredging spill under the membrane. Deformations in earth works could lead to rupture of the membrane. In the preliminary design in Holland the slopes are chosen as follows: 1:2 for a green surface, 2:3 for a paved surface, 1:2 for the excavated membrane slope in dry conditions, 1:3 for the excavated membrane slope in wet conditions. It is highly recommended to make finite element calculations for the relevant building stages in the final design phase. Also the possible thrust of the soil at the deepest point due to the weight of the soil on the slopes must be concerned. There is no sense in enlarging the friction between membrane and soil by taking a

membrane with a roughened surface because the effective ground stresses underneath the membrane are small. For the friction coefficients in finite element calculations the values according to table 1 can be taken.

Table 1. Friction coefficients

membrane material	$\tan\delta/\tan\phi$
roughened PVC	0,88
smooth PVC	0,81
HDPE	0,56

δ = angle of internal friction between membrane and soil; ϕ = angle of internal friction in the soil (sand $\phi = 30^o$)

The ending of the geomembrane sheet will normally be realised in one of the following two ways: (1) with a clamping construction near steel or concrete walls, or (2) with a ballasting soil load on top of the membrane in a ditch at the upper end of the slopes. In the first case the clamp must be absolutely watertight. In the last case the level must be above maximum freatic groundwater head. The covering soil layer must be at least 1 to 1,5 m thick. An example of a clamp construction is shown in figure 4. This is a detail of a clamp where the geomembrane is held and secured by the weight of the overburdon ballasting soil. From practice it was concluded that the risk of failure in this way is less than with a solution based on boulting of the clamp, with serious risk of punching the membrane by the boulting forces, certainly when this has to be realised in wet conditions below water level.

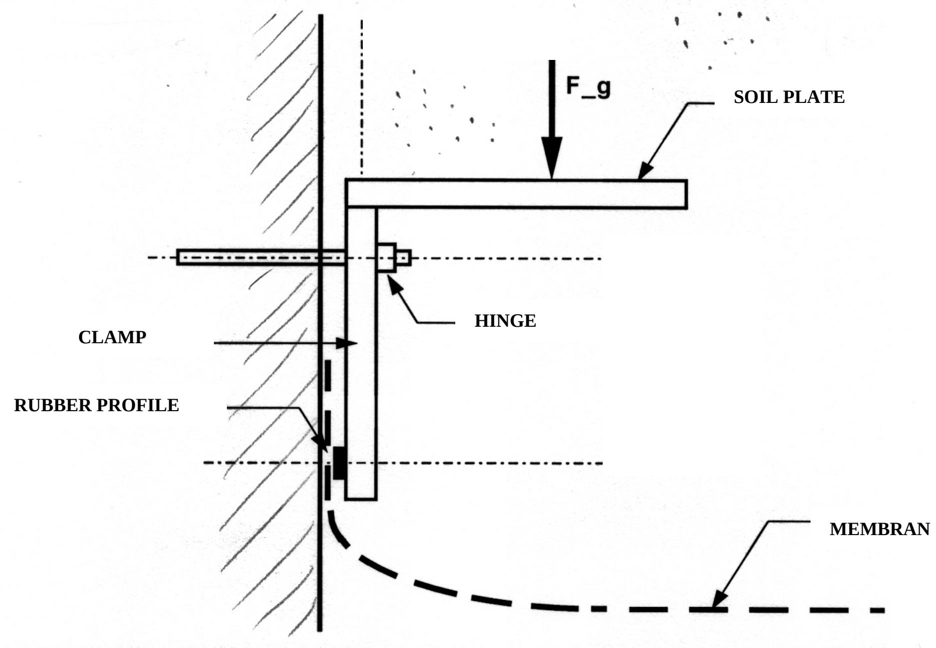

Figure 4. Clamp construction governed by weight of overburdon

The decision on the thickness of the membrane is a matter of practical ideas. Although it is possible to calculate the material stresses in all building stages, the strength of the material is not often a design criterium. Often the choice depends on manageability, susceptibility to damage, certification by the supplier, the suitability for welding, the expected durability. Thicknesses of 0,5 to 2 mm are usual. Lately in dutch practice a thickness of 1,3 mm is customary.

Other important design aspects concern the definition of the dimensions of the drainage and sewerage system because the construction is closed off from it's surrounding in hydrological sense.

6 MATERIALS

The material types most suitable for use as geomembrane in civil engineering constructions are PVC or PVC-P and LDPE and lately also LLDPE and VLDPE. HDPE is too stiff for managing on site. New flexibilised PE-types and also laminated composite membrane types are still in the developing stage and for the time being without certification not yet suitable in practice. Combinations of geomembranes with geotextiles are possible but were until present only necessary for some design details near joints at concrete tunnel structures, especially at clamping constructions.
An important difference between PVC and PE-types is the width of the production roles, respectively 2 m and up to 10 m. The number of welded seams can therefore be minimized using PE-type membrane. With the works carried out until present PVC-membranes were prefabricated with high standard factory seams and brought to the building site in folded or roled packages. In most cases PVC was prefered because of the flexibility, implicating easier handling and larger volumetric weight, which comes in handy if the membrane must be sunk into place.
Although PVC contains up to 30 to 40 % of flexibilising solvents the conclusion from recent investigation is that the loss of solvents from PVC-P to groundwater is very limited. The environmental impact of the application of PVC-P and the loss of strength due to aging are therefore negligible factors. The expected lifetime of geomembranes in normal conditions below ground surface and groundwater level may be set to over 100 years. However there is a shift to use of LDPE-types rather than PVC, because PVC also contains heavy metals and chloride components are used in the production process.
To facilitate the choice between the different materials a collection of property values was put up as good and complete as possible (see table 2 at the end of this paper). Notice must be taken that PVC and PE have a different stress-strain relation, PE having a plasticity or apparent plastic point and PVC reacting more brittle.
The dutch department for public works only accepts certified material (suitable for application in drinking water basins) and has its quality controled on specimens of the membrane that is delivered on the job (variation in thickness, smoothness, permeation for water, strength in a punching test, tensile strength and ultimate strain, tearing resistance). For certification of materials a range of tests has been standardized (e.g. DIN, ASTM).

7 WELDING

In the design phase a welding plan must be set up. Crossing seams must be prevented and seams on sloping areas must be planned from top to bottom and not run along the slope. The several welding methods and seam configurations have been discussed by Koerner. Welding for prefabrication of membrane packages in the factory is often done by ultrasonic or electric welding. The control with ultrasonic testing gives a high standard membrane.
On site the contractors mostly prefer the "Heizkeil" or hot wedge method with double track weldings for PVC. If the welded seam is correctly made the channel between the two tracks is completely sealed. Inspection of the quality can be easily performed with a pressure test. During the welding process the quality depends on the temperature of the wedge (first mentioned as most

important factor), the thickness of the material, the pressure load, the speed of the process and the role of external factors in this. These conditions have to be registered. For the circumstances in Holland the optimum conditions can be found in the directives of KRI-TNO. Test samples of welded seams must be produced every day to be tested on leakage and strength. In controling measures on location the quality of seams must be tested through peeling and pulling tests, checking whether the seams are weeker than the geomembrane material itself. At works realised in dry conditions control on the job can be done by checking with the electrical sparking method on an electrical wire inside the seam. However, the wire in the seam could lead to a weeker seam on the long term. Use of glue or solvents is rarely encountered and if done only for small repairs.
It is important for welding that good conditions prevail, so the weather must be dry, temperature between 5 and 35 ^{o}C and winds are less than 4 Beaufort. In Holland this means that the available working season is very short.

8 INSPECTION AND LEAK DETECTION

The occurrence of leaks can lead to high water levels inside the construction exceeding design criteria. To the authors four cases are known were damage to the membrane resulted in larger flow of drain water inside the construction than according to design. In one case repair near a slide of the surface slope was succesfully performed, in another case by injection. In two other older cases the problems are probably located near the clamp construction but repairing has not yet succeeded. In the worst case damage even may lead to piping, soil erosion and loss of stability, but that fenomena was not encountered.
As stated above repairs can be prevented by a good control during the building period. One has to be aware of the fact that finding a leak in a geomembrane in a construction that has already been backfilled, is almost impossible until present. The accuracy of the geofysical research methods is simply not good enough. But before backfilling leak detection on the readily placed geomembrane is not only possible under dry conditions in the way that was discussed earlier, but can also be performed with great success in wet conditions deep under the water level. The two suitable methods are hydrogeological and geoelectrical investigations. With hydrological measurements (waterlevel in the sealed pit, evaluation of the flow, standpipes) one can control at first if there is a connection with the groundwater outside of the membrane. The dutch governmental research institute TNO [see Van Dalfsen] developed a stepwise geoelectrical control method. The method is based on the work of Parra on surveying liners in basins. After a 50 V potential difference is realised over the membrane, cables with electrodes are hauled along the bottom and slopes, first in the axis direction, secondly in perpendicular direction.
The distance between electrodes must be small (2,5 m) to measure potential differences of 10 to 100 mV. Through combining different pairs of measuring electrodes voltage anomalies are searched. Computerised data analysis is necessary. When anomalies have been detected in the gross a framework with electrodes is lowered to the bottom and the position of the leak is located. After eliminating the larger leaks the quest must go on for the smaller ones. That a good guiding system in such a measuring program is important, must be obvious.

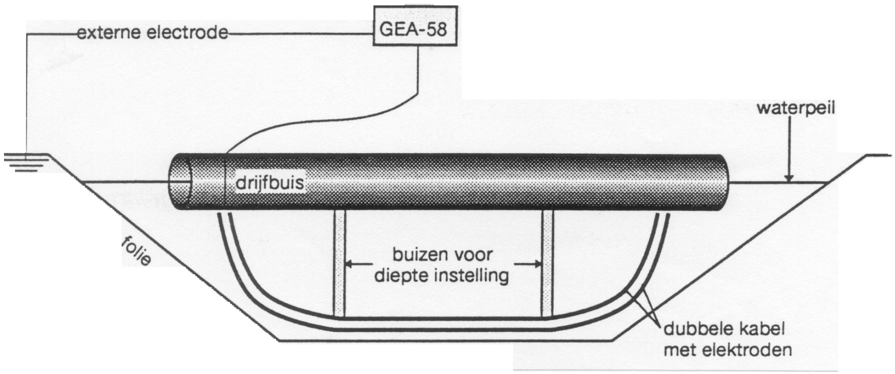

Figure 5. Floating measuring device

When using the geoelectrical method it is necessary to banish false leaks, e.g. along sheet pile walls, by covering these conducting structures with membrane sheets or curtains.
Application of permanent leak detection wire systems like in heavy polluted depots are not yet in use due to the high price.
Leak detection methods based on other geophysical principles have been found to be too indirect, too inaccurate or too experimental for practical use.

9 LONG TERM MANAGEMENT AND CONTROL

To guarantee a long life of the construction it is necessary to register the construction, of which the main structure is hidden below surface level. This should be in the national database with subsurface infrastructure like pipelines and cables. Registration can prevent damage when other activities are being performed on the location, such as foundation piles, excavations, lamp posts and traffic signs.
An important item concerns the transfer of design data and "as built" data from the designing office and/or contractor to the local responsible road authorities so that proper management and control programs can be developed to keep the construction safe on the long term.

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Table 2. Collection of data on some types of geomembranes for road and railroad constructions

Property	LDPE	HDPE	LLDPE	VLDPE	PVC
specific weight [kg/m^3]	915 - 930	945 - 960	915 - 930	900 - 915	1200-1300
melting point [^{o}C]	110 – 120	125 - 135	± 120	± 125	87
cristallinity [%]	40 – 55	60 - 800			
permeation of water vapor [m/s]	10^{-12} – 10^{-11}	10^{-12} - 10^{-11}			10^{-11} - 10^{-10}
permeation of water [m/s]	3,5.10^{-15}	10^{-15}			10^{-13}
uni-axial tensile strength [N/mm^2]	80 – 250	350 - 600	80 - 250		15 - 30
uni-axial ultimate strain [%]	20 – 80	10 - 45	20 - 80	> 100	
uni-axial elasticity [N/mm^2]	200 – 1200	600 - 6000	10 - 1200	> 30	10 - 300
un-ax.long term tens.strength [N/mm^2]	18 – 25	20 - 30	25 - 40	28,5	
un-ax.long term ult.strain [%]	175 – 250	125 - 240	850 - 1100	800	
bi-axial strain capacity	reasonable	small	large	large	adequate
tearing strength [N/mm^2]	100	132	25	79	100
tear blow strength [N/mm^2]	> 40	5 - 20			2 - 5
friction coefficient [-]	0,5 - 0,575	0,2 - 0,25			
thermal resistance					
chemical resistance	moderate	good	reasonable	reasonable	limited
susceptibility for becoming brittle under stress	moderate		good		
biological resistance	good	good	good	good	good
weldability	good	critical	good	good	good
manageability	reasonable flexible	stiff, tough	flexible, stable shape	very flexible, elongating	flexible

Remark: if no value is presented in the table no data are known to the authors or were found in literature on that item