Conceptual method for estimation of dike breach sensitivity, including geotechnical and geophysical testing.

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ABSTRACT

In order to estimate breach sensitivity of Flemish river dikes a conceptual method was developed. For each failure mechanism representative parameters are weighed and the outcome is a failure index for the considered failure mechanism. On basis of these failure indexes critical dike sections can be detected, which can be investigated in detail, including extensive geotechnical in situ and laboratory testing. Geophysical methods apt to give a first raw insight in possible weaker dike sections were investigated on their merits and results. For 2 typical dike sections geophysical methods were performed and compared with the results of standard geotechnical testing (CPT, borings).

It appeared that not all geophysical methods were useful, and even among those that proved to be valuable it is necessary to use a combination of different techniques for a good interpretation.

RÉSUMÉ

Afin d'estimer la sensitivité à la rupture des digues en Flandres une méthode conceptuelle a été développée. Pour chaque mode de rupture des paramètres représentatives sont déterminés et le résultat est un indice de rupture pour le mode de rupture pris en considération. A base de ces indices de rupture des zones critiques peuvent être l'objet d'une investigation détaillée, comprenant des essais géotechniques in situ et de laboratoire. Des méthodes géophysiques ont été examinées sur leur mérite pour une reconnaissance de premier ordre. Pour deux tronçons de digues différentes méthodes géophysiques ont été appliquées, et les résultats furent comparées à ceux d'une recherche géotechnique standard (CPT, forages).

Il apparût que pas toutes les méthodes géophysiques furent appropriées, et même entre celles qui l'étaient il s'avère nécessaire d'utiliser une combinaison de différentes méthodes, afin d'assurer une bonne interprétation.

1 INTRODUCTION

To offer the population optimal protection against flooding, authorities perform cost benefit studies to evaluate needed infrastructure measures. Analysis of costs (building and maintenance) and benefits (prevented damage and victims) are to be made. For this purpose diagnosis of sensitivity to breaching of dikes is essential in risk evaluation of our water management.

This analysis should taken into account overflow, wave overtopping and geotechnical failure.

For dike diagnosis a staged approach is adopted, starting with basic and ending with in-depth diagnosis.

In-depth diagnosis not only requires an enormous amount of data which is currently not available in Flanders, the process of data collection through extensive field surveys is expensive and time consuming. In order to reduce the total diagnostic work load, a conceptual method based on failure indexes was developed for rapid diagnosis starting from readily available data, eg. topographic data, (simulated) flow velocities, revetment types, … aiming for rapid identification of critical sectors without missing out possible weaknesses (Peeters et al., 2008). Subsequently, in-depth diagnosis through historical research, visual inspection and geotechnical and geophysical exploration, can be restricted in space and time.

Geophysical methods can be used as a practical tool for a rapid detection of geotechnical weaker zones in the critical sections. These geotechnical weaker zones then are investigated through standard geotechnical investigation (in situ and laboratory testing).

2 THE CONCEPTUAL METHOD

Flemish authorities ordered a study to evaluate sensitivity to breaching of river dikes in Flanders. Aim of the study is to perform a thorough analysis of dike failure mechanisms which can lead to rupture. This study should result in a methodology, adapted to the diagnosis of Flemish river dikes, and be incorporated in a global damage and risk management.

The methodology aims for a pragmatic approach in describing the failure behavior of dikes. The following failure mechanisms were considered:

- erosion of outer and inner slope
- slope stability of outer and inner slope
- piping
- micro(in)stability.

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The overall assessment of the failure behavior of a dike is described in terms of two figures:

- the minimum failure index associated with one of the failure mechanisms
- the sum of all failure indexes.

$$F_{globaal} = F_{\min} = \min(F_1, F_2, F_3, F_4, F_5, F_6)$$

or $$F_{globaal} = \sum_{i=1..6} F_i$$

Figure 1 shows the scheme for dike failure assessment.

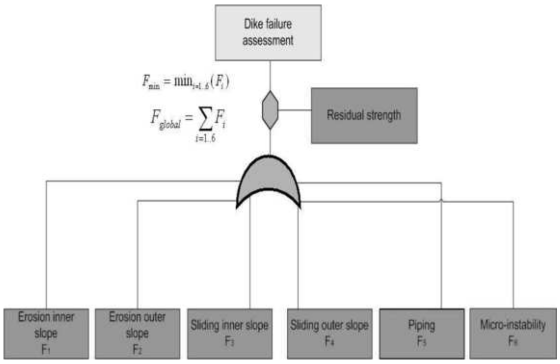

Figure 1: Overall assessment of failure behavior of dikes

The decision to adopt 2 figures for dike failure assessment was inspired by the benefit of combining both approaches

- adopting the minimum score is the most obvious choice, as dike rupture will occur when the most critical failure mechanism is triggered.
- adopting the cumulative score for all considered failure mechanisms offers a global evaluation of the stability status of the dike.

As development of a failure mechanism does not necessarily result in dike failure, the residual strength of the dike is taken into consideration when assessing failure indexes.

The residual strength of a dike is assessed when the failure index F_{min} equals zero. Depending on the considered failure mechanism, Peeters et al. (2008) suggests either absence of residual strength (eg. general slope failure and piping), or either to evaluate the residual strength using values based on available formulas and literature (Steenbergen et al, 2003). If the presence of residual strength is evaluated positively, the failure index F_{min} is augmented to 0.5, ie. the considered failure mechanism is likely to occur, but some residual strength exists.

Interpretation of global failure index is as follows:

- score 2: there is little risk for a dike rupture
- score 1: there is moderate risk for dike rupture
- score 0.5: there is evident risk for dike rupture, but a certain residual strength remains.
- score 0: there is a great risk for dike rupture, residual strength is insufficient

This rather pragmatic conceptual method of failure indexes is based on simple parameters and gives an idea of where dike breaching is likely to occur. This information is useful for dike engineers to prioritise management and restoration works and for decision makers to have a general overview of their estate.

In addition, Flemish water management today no longer chooses to prevent floods at all costs, but instead seeks to limit the damage. This can be achieved by using the idea 'risk = probability x vulnerability'. When producing flood maps, failure by overflow and wave overtopping should be accounted for, as well as breach formation. Neglecting the latter will result in an overestimation of the safety level. Therefore a risk analysis is suggested that accounts for the uncertainty regarding geotechnical failure mechanisms and associated (geotechnical) parameters and hence, ends up with a failure probability at certain locations (Peeters et al., 2008). Again lacking data and time, a risk analysis is performed primarily at those locations where low failure indexes were obtained and/or where high damage costs can be expected and secondly, those areas affected by the possible breaching at other locations.

This statistical approach is more complex but will be the tool for decision makers to plan long term projects based on a correct cost benefit analysis (taking into account failure caused not only by overflow, but also by possible breaching).

Both methods are complementary. At present, a validation exercise is carried out by comparing the results with observations in situ at locations where high as well as low failure indexes are assessed.

3 SLOPE STABILITY OF INNER AND OUTER SLOPES

Slope stability of inner and outer slopes is of major importance in assessing sensitivity to rupture of dikes.

Determination of failure indexes is based on directive slope stability calculations for different heights of dike crest, inner and outer slopes, material of dikes and subsoil. One of the simplifying assumptions in these calculation was that the subsoil of the dike had the same material characteristics as the dike core itself.

Material characteristics used in calculation are summarized in table 1.

	γ_{unsat} (kN/m³)	γ_{sat} (kN/m³)	E (MPa)	c (kPa)	φ (°)
clay	18	18	3	5	25
Loam (silt)	18	18	5	3	27.5
sand	17	20	25	0.1	30
Toplayer	20	20	15	5	30
Soft subsoil	16	16	1	5	17.5

Table 1: Mechanical properties of different fill and foundation materials.

Factors of safety obtained by directive slope stability calculations are converted to safety classes as follows:

- FOS ≤ 1.15: unsatisfactory safety level, value 0
- 1.15 < FOS ≤ 1.30: satisfactory safety level not fully reached, detailed study necessary, value 1
- 1.30 < FOS ≤ 1.50: satisfactory safety level, safe situation, value 2
- FOS > 1.50: satisfactory safety level, very safe situation, value 3

The presence of soft subsoil layers is not taken into account in the safety classes of table 2, as thickness of soft subsoil is in most cases unknown.

Therefore, if from expert judgment and experience (or extrapolation of data) the presence of such soft layers may be expected, safety classes of table 2 are adapted as follows:

- no change if height of dike ≤ 2m
- reduction with 1 unity if height of dike > 2m en ≤4m
- reduction with 2 unities if height of dike > 4m.

As the presence of soft subsoil have a significant impact it was decided to investigate how geophysical investigation might give a valuable input.

Table 2 summarizes safety classes for different dike configuration and soil materials

height = < 3 m					
			Slope		
	16/4	12/4	10/4	8/4	6/4
clay	3	3	3	3	3
loam/silt	3	3	3	3	2
sand	3	3	2	1	0
height > 3 m en < 5 m					
			Slope		
	16/4	12/4	10/4	8/4	6/4
clay	3	3	2	1	0
loam/silt	3	2	2	1	0
sand	3	2	1	0	0
height > 5 m en =< 7 m					
			Slope		
	16/4	12/4	10/4	8/4	6/4
clay	3	2	1	0	0
loam/silt	3	2	1	0	0
sand	3	1	0	0	0
height > 7 m					
			Slope		
	16/4	12/4	10/4	8/4	6/4
clay	2	1	0	0	0
loam/silt	2	1	0	0	0
sand	2	1	0	0	0

Table 2: Safety classes slope stability

4 GEOPHYSICAL INVESTIGATION

4.1. *Purpose of the geophysical investigation project*

The purpose of the geophysical investigation project was dual:

- Propose a set of geophysical methods that could give a substantial input in the study of dike breach sensitivity.
- Validate and calibrate results of selected geophysical methods against geotechnical test results.

The contractor who was offered the job had to propose and perform a geophysical exploration program that was apt to give a maximum input for assessment of dike breach sensitivity: homogeneity or heterogeneity of dike section, material of dike and subsoil, phreatic line, presence of local anomalies…

Two dike sections were selected for geophysical exploration. The contractor had to

- perform a geophysical exploration, including processing and interpretation of the results, with emphasis on the relevance for dike breach sensitivity
- collect any information (historical research, geology, visual inspection…) that might be helpful in the interpretation.

After having submitted a detailed report on the above mentioned items, the contractor received an extensive dataset of geotechnical investigation results. The contractor had subsequently to validate and calibrate his test results against these data.

4.2. *Applied geophysical methods.*

- Classical geo-electrical tomography

The principle of the method is based on the measurements of the current intensity, the potential difference and the calculation of the apparent electrical resistance of the soil between the electrodes. Along the length of a straight line, a geo-electrical pole-dipole array is positioned, with the potential electrodes placed at equal distance (1 m or 1.5 m).

With the supply of electric current the horizontal and vertical variation of the electrical resistance in the subsurface is measured.

Linear sections (length of ca 100m) and cross sections (length of ca 40m) were surveyed.

Depth range was about 15m.

- Seismic tomography (P-waves)

P-wave seismic tomography is based on the emission of acoustic compression waves in the soil; travel time of reflected and refracted waves by contrasts in acoustical impedance is measured by means of geophones placed at equal distances (2m) at the surface. This allows for determination of mean seismic velocity of the soil.

Linear sections (length of ca 100m) and cross sections (length of ca 40m) were surveyed.

Depth range was about 15m.

- Seismic tomography (S-waves)

S-waves seismic tomography is essentially similar to the P-wave technique. Here travel time of reflected shear waves is measured, resulting in the determination of the apparent seismic velocity of the soil. Elasticity and Poisson moduli can hence be calculated.

Linear sections (length of ca 50m) and cross sections (length of 25m) were surveyed.

Depth range was about 15m.

- Ground penetrating radar (GPR)

GPR uses high frequency electromagnetic pulses transmitted into the soil by suitable antennas. When the wave hits a buried object or a boundary with different dielectric constants the receiving antenna records variations in the reflected return signal.

The depth range is dependent on the electrical conductivity of the soil and can reach more than 10m in sands, but be limited to a few decimeter in clays.

Linear sections of 700m length were surveyed; the measuring interval was 10 cm.

- Side scan sonar

Side scan sonar operates by emitting a narrow beam of high frequency acoustic energy in a plane orthogonal to the direction of ship travel and then recording the acoustic returns from the riverbed. The acoustic transceivers are mounted in a streamlined housing (tow fish) that is towed behind the survey vessel.

The beam reflects on the river bottom and is received by the sonar; dependent on the nature of material the signal is reflected and an image of the riverbed is constituted. This technique can be used to obtain a detailed image of under water slopes of the riverbed.

Other methods like electromagnetic measurements, ground tracer, thermal scanning… were also considered but not selected for the detailed study.

4.3. *Interpretation of test results and relevance for dike breaching sensitivity.*

From the results of the geophysical exploration project it shows that geo-electrical and seismic tomography are very useful tools in assessing dike breach sensitivity.

Geo-electrical methods give information about soil type (clayey or sandy material), and also on degree of compaction of sands.

A drawback of this technique is however that below the phreatic line (about +1.5 in the considered dike section) resistivity is invariably low due to saturation of the soil. Water has good conductivity and therefore measured resistivity is low, independent of sandy or clayey type of soil. However, this is not always the case and also depends on the salinity of the water.

The geo-electrical tomography profile shown on the upper part of figure 2, gives a clear indication of lower degree of compaction of sandy material of dikes. (section 75 -100m)

This is confirmed by CPT diagrams on figure 2 (lower cone resistances in upper sand layer in CPT16).

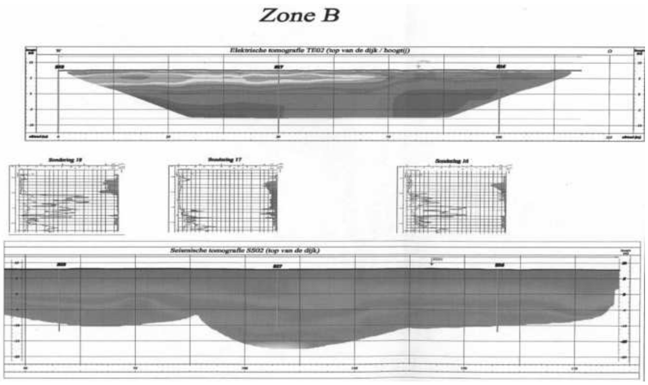

Figure2: Results of geo-electrical sand seismic tomography combined with CPT diagrams.

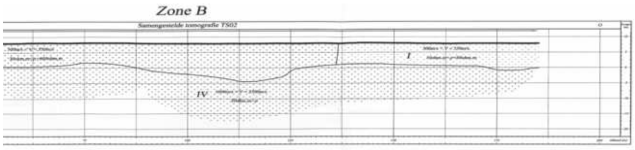

Figure 3: Indicative soil layering

The seismic tomography profile on the lower part of figure 2, gives complementary information on the thickness of the soft clayey subsoil in this dike section. Profile SS02 shows that the layer with lower seismic velocities (300-350 m/s), extends to greater depth in the middle part of the profile. This is in full agreement with CPT results, in particular CPT17 where the very soft clay layer (cone resistances < 1MPa) was shown to reach up to level -6.00.

Based on results of geo-electrical and seismic tomography an indicative soil layering could be proposed, as shown on figure 3.For some applications the drawback of geo-electrical measurements in fully saturated zones can be an asset. The cross section on figure 4 shows between about +2.50 and +5.00 (this is above the phreatic line situated at about +1.50) a zone of lower resistivity.

This lower resistivity might possibly be a result of the presence of a pervious saturated sand layer in the dike, prone to seepage. (figure 4)

Visual inspection on the site showed indeed the occurrence of puddles in the vicinity of this section. (picture on figure 5).

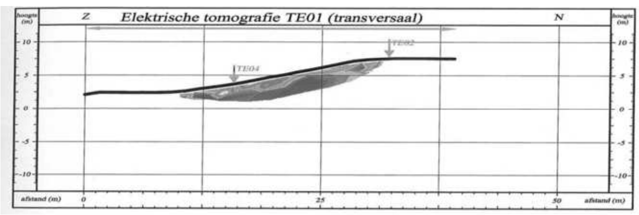

Figure 4: Cross section geo-electrical tomography

Figure 5: Occurrence of puddle at toe inner slope

Interpretation of side scan sonar measurements give also valuable input, but from a quite different point of view.

Figure 6 shows a typical interpretation plot:

- Facies 1 (blue).

Zone with little sedimentation possibly slight scouring.

- Facies 2 (yellow)

Zone with sedimentation (fine sediments)

- Facies 3 (orange)

Zone with active scouring, uneven river bottom

- Facies 4 (red)

Riprap dike revetment

The broader red zone, combined with orange zone of active scouring show that in this particular section specific attention should be paid to erosion of outer dike slopes. (figure 6)

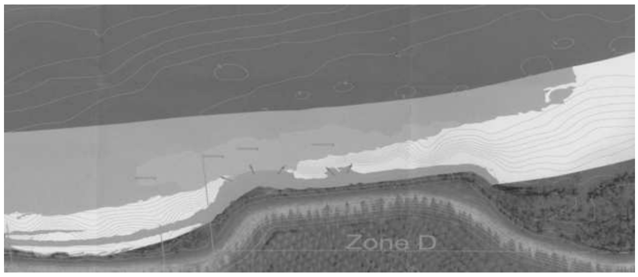

Figure 6: Interpretation of side scan sonar measurements

5 CONCLUSION

Through the conceptual method for dike diagnosis sections that have a higher potential risk for failure can be detected in a direct, simple way. For these sections an in-depth diagnosis is needed, consisting a.o. of a detailed study of geotechnical failure mechanism.

For this aim geophysical method proved to be a useful tool to detect possible weaker zones. It showed however that for a good interpretation it is appropriate to combine different methods. And even then geotechnical investigation proved to be essential to calibrate geophysical test results. Both methodologies are complementary: geophysical methods allow for a more efficient planning of geotechnical investigation; geotechnical test results are needed for an accurate interpretation of geophysical tests. At the present stage geophysical methods cannot provide a quantitative input for the study of geotechnical failure mechanisms. Parameters, such as resistivity or seismic velocity cannot be directly linked to geotechnical parameters. However further study might result in a better calibration between both approaches, and geophysical methods might result in an indicative geotechnical soil profiling.

REFERENCES

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