Wide Green Dike (WGD) concept for grass revetment under coastal conditions

Concept de Large Digue Verte pour le revêtement en gazon dans des conditions côtières

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Abstract. The Dike along the Dollard estuary in the northeast of the Netherlands has a grass cover. This revetment is not sufficiently strong for the local hydraulic conditions. Traditional dike strengthening leads to the replacement of grass with a hard revetment. An alternative under investigation is the "Wide Green Dike" (WGD) concept: a grass-covered dike with a gentle slope of around 1:7, naturally merging into the salt marsh located in front. The WGD concept is easily adaptable to future challenges, such as sea level rise. Furthermore, sediment of the estuary is currently being ripened to clay near the dike, potentially saving numerous truck movements needed for strengthening. The WGD is therefore the example of a circular, innovative and sustainable concept. However, the WGD needs to comply with the national flood safety standards to make it a feasible alternative, while the current assessment methods and instruments are not yet suited for this particular type of dike. During normative conditions, the grass cover is allowed to fail and the underlaying clay experiences erosion. A clay erosion model is used to design the thickness of the clay layer and proof that the WGD has sufficient residual strength to meet the norms of flood risk.

Résumé. Les talus de la digue le long de l'estuaire du Dollard au Nord-Est des Pays-Bas sont engazonnés. Ce revêtement n'est pas suffisamment solide pour les conditions hydrauliques locales. Le renforcement traditionnel des digues conduit au remplacement de l'herbe par un revêtement dur. Une alternative à l'étude est le concept de "Large Digue Verte" (LDV) : une digue en gazon avec une pente douce (1:7), se fondant naturellement dans le marais d'eau salé situé en face. Le concept LDV est facilement adaptable aux défis futurs, tels que l'élévation du niveau de la mer. De plus, les sédiments de l'estuaire déposés près de la digue sont actuellement en cours de maturation en argile, ce qui permettra d'éviter toute la logistique et le transport relatif à l'apport des terres nécessaires au renforcement. Le LDV est donc l'exemple

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d'un concept circulaire, innovant et durable. Cependant, le LDV doit se conformer aux normes nationales de sécurité contre les inondations pour en faire une alternative faisable, alors que les méthodes et instruments d'évaluation actuels ne sont pas encore adaptés à ce type particulier de digue. Dans des conditions normatives, la couverture herbeuse peut se rompre et l'argile sous-jacente subirait, le cas échéant, une érosion. Un modèle d'érosion d'argile est utilisé pour concevoir l'épaisseur de la couche d'argile et prouver que le LDV a une résistance résiduelle suffisante pour répondre aux normes de risques d'inondation.

1 Introduction

In a delta such as The Netherlands, the work on flood protection is an ongoing effort. Fortunately, it has been decades since a large flooding has occurred. However, population growth and increase of economic value of the assets, combined with global issues such as climate change, increases the risks of flooding. The primary flood defences of The Netherlands consist of around 3700 kilometres of dikes. In 2017, the national safety standards have been updated according to the newest insights and calculation methods. Embedded in the Flood Protection Programme (Hoogwaterbeschermingsprogramma) there lies the enormous task of reinforcing the primary flood defences up to the legal safety standards. It is expected that around 1300 kilometres of dikes needs to be reinforced, together with 500 water retaining structures [1]. An operation that will take up to 30 years, making sure that all primary flood defences are safe in the year 2050. This makes the Flood Protection Programme in the Netherlands the largest dike reinforcement operation since the completion of the famous Delta Works.

Innovation and knowledge development are crucial to fulfil the goals of the Flood Protection Programme. Innovation can contribute to a faster realisation of reinforcement projects at lower costs. Furthermore, innovative projects can lead to less social impact caused by dike reinforcement projects, such as loss of ecological value, disturbance of the landscape and (temporal) nuisance for those living near the dike.

One of the dikes that is on the list of the Flood Protection Programme is the sea dike along the Wadden Sea, in the northeast of the Netherlands, between Kerkhovenpolder and the border with Germany. The dike is under the control of regional Water Authority Hunze and Aa's. The dike currently has a grass cover, which is not strong enough for the local hydraulic conditions in extreme storm situations. Traditional dike strengthening would imply that the grass is replaced with a hard revetment. An alternative currently under investigation is the "Wide Green Dike" (WGD) concept: a grass-covered dike with a gentle slope of around 1:7, naturally merging into the salt marsh located in front. The Wide Green Dike should be large enough to allow for erosion to take place and still live up to the legal safety standards. The current official assessment methods and instruments are not yet suited to design a dike concept like this. This article shows how different erosion models are put into practice, to dimension a grass covered dike that can meet the legal safety standards. Before that, the article zooms in a bit more on the motivation behind the Wide Green Dike concept. Despite the models, it is not possible to prove the feasibility of this concept, without doing appropriate field tests. This article ends with the research that will be conducted in the near future, to help substantiating how this concept is a feasible alternative compared to traditional strengthening methods.

2 Why the Wide Green Dike?

2.1 Synergy

The sea dike is situated adjacent to the Eems-Dollard estuary. This part of the Wadden Sea is known for its great ecological value, but also for its extreme turbidity. Sediment is carried into this area by the river Eems. Because of land reclamation and deepened waterways, there is a disbalance between sediment supply and the ability for sediment to settle. This is causing trouble for fish and other aquatic fauna living in the estuary. Various researches had been carried out over the years to solve this issue and improve the water quality in the estuary.

The idea of the circularity had been the main driver for the design approach regarding the Wide Green Dike. The regional Water Authority Hunze en Aa's came up with the idea of extracting the Wadden Sea sludge for production of the clay suitable for the dike strengthening projects in the area. It is intended not to use any hard revetment in the design of the outer slope, what is, certainly in the Netherlands an unusual practice. To proceed with this innovation a new approach to the design needs to be deployed as well as the characteristics of the material in the clay riping area need to be profoundly understood.

The circular approach is accompanied not only by technical challenges. The governance for the realisation of an experimental dike like this had to be custom tailored as well. For the strengthening of a regular dike as a primary defence the national Flood Protection Programme (Hoogwaterbeschermingsprogramma) provides the formal decision for the availability of the budget based on transparent substantiation of the application by regional Water Authority. In this case the regional Water Authority Hunze en Aa's needed to proceed an alternative way of application for the pilot project Wide Green Dike.

2.2 Aspects of circularity

The concept of the Wide Green Dike anticipates at the presence of the fine sludge in the area. It is intended to use the fine sediment in the clay riping area and use it for the construction of a strengthened dike. This approach stresses the circular idea in the use and handling of the building materials for the strengthening of flood defences. One of the sources of clay (the so called "Klutenplas") is designed as such, that excavation of the salt marsh enhances the ecological value of this part of the Wadden Sea, by providing breeding grounds for Pied Avocets. As the ripening area is in the close vicinity of the dikes that need strengthening, transportation movements and ecological impact will be reduced.

Fig. 1. Location of demonstration project WGD, with clay depots in front and "Klutenplas" on the salt marches [2].

3 Technical approach

3.1 Current practice

One of the biggest challenges of a sea dike without a hard revetment is the resistance against wave impact. Grass revetments are often not resistant to waves that exceed heights of 1 meter, according to the Dutch safety standards [3]. The combination of a thick clay layer and a gentle slope increases the resistance against wave impact [4-6]. Within the currently used 'standard' calculation methods for dikes with a grass revetment, the erodibility of the clay is not taken into account. Those calculations are made to assess the impact of waves and run-up on the grass revetment, where the clay layer with a thickness up to 0,5 m is taken into account. The method is only applicable for grass revetments with waves up to 1 – 1,5 m. If waves exceed this range, the usual step is to implement a stone or asphalt cover at the outer slope of the dike. The Dutch safety regulations allow the opportunity to implement other calculation methods, however the user has to prove the applicability of the method.

3.2 Dutch Safety Standards

In the Netherlands, the safety standards for dikes are based on the probability of flooding. This probability is equal to the chance that the load is greater than resistance. The primary flood defences are evaluated every twelve years by the regional Water Authorities. The calculated probability of flooding is used for these evaluations.

The Netherlands is divided into dike sections. Every dike section has its own legal probability of failure, with which the dike section has to comply. The "Wide Green Dike" is part of dike section 6-7. For this section the legal probability of failure is 1/3.000 per year.

All failure mechanisms, such as dike stability, piping and erosion of slopes, have their own percentage of permissible failure probability. The percentage for erosion of the waterside slope is 5%. Therefore, the permissible probability of failure for the erosion of the waterside slope is 1/60.000 per year. This value is used to derive the hydraulic conditions in order to determine the thickness of the clay layer and the width and height of the crest of the dike.

3.3 Erosion due to wave impact

As mentioned above, the erosion due to wave attack is a big challenge in the case of the Wide Green Dike. The erosion of the grass revetment is caused by overpressure below the grass revetment caused by waves, as is shown in Fig. 2. The incoming waves cause pressure on the slope of the dike which penetrates into the soil and eventually results in an overpressure after the wave attack [7]. This causes damage to the revetment and can even torn the top layer apart.

Failure of the grass revetment does not necessarily mean that the dike fails. Without a grass revetment the dike will still withstand wave attacks for some time. The materials below the top layer, the grass revetment, will be attacked by the waves and slowly erode. When the dike is not wide enough and the storm is continuing (and therefore the erosion process too), the dike crest will disappear and the dike will fail eventually. With a thick layer of clay below the grass layer, the dike can withstand long lasting erosion caused by extreme storm situations.

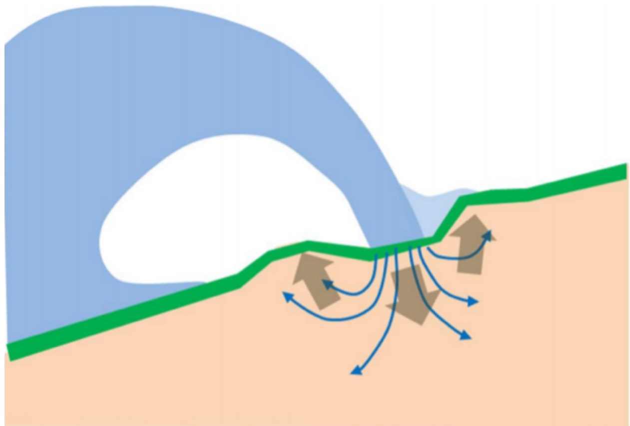


Fig. 2. Schematisation of wave impact with groundwater flow (blue arrows) and soil movement (brown arrows) [7].

The calculation of erosion of the waterside slope (a failure mechanism abbreviated in Dutch to "GEBU") is based on the combination of resistance-duration of the grass revetment and the wave heights during one storm [8]. Resistance-duration is the duration until the grass revetment is eroded due to wave impact caused by a given wave height. The resistance-duration values differ for grass with closed sods and open sods, and are based on experiments.

The normative storm conditions that are used, consists of water levels and the corresponding wave heights over time. The assessment of the dike is executed with a storm duration of 45 hours in total. The maximum water level is corresponding to the given return period [9]. For the outer slope assessment, the normative storm conditions derived according to the Dutch guidelines with the software Hydra-NL. The water level is a combination of the tide and a schematized storm surge, as the example shows in Fig. 3.

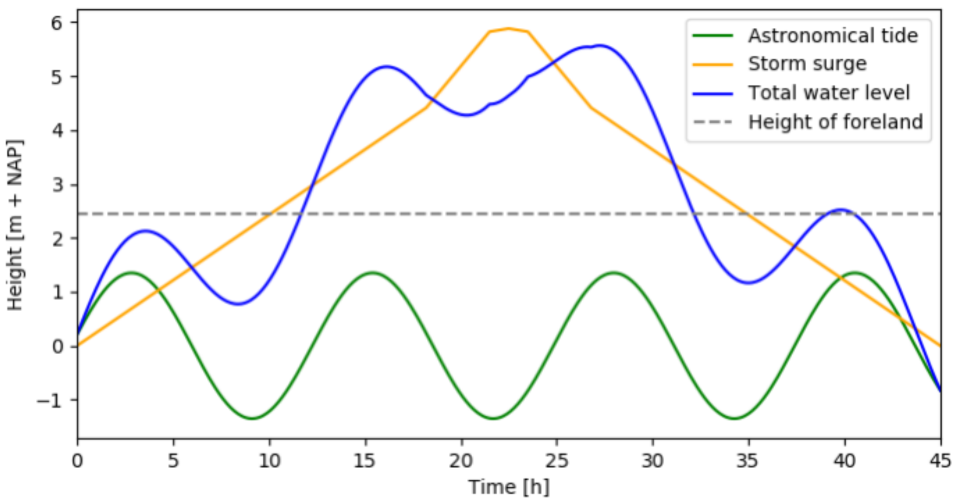


Fig. 3. Water level during a storm (example of a storm with a return period of 100 years without climate change) which is the result of the tide and storm surge [5].

For every time step, the corresponding wave height is determined and compared to the resistance-duration to calculate the failure fraction as is shown below [8]. When the sum of all calculated failure fractions per time step is more than 1, it means that the revetment failed. The failure fraction (F_{frac}) can be calculated for every times step (t_s) by using the resistance-duration (t_s) as is shown in equation 1.

$$F_{frac} = \frac{\Delta t}{t_s} \tag{1}$$

In the current Dutch guidelines, the resistance-duration of the grass revetment with a maximum of 0,5 m clay can be calculated. This means that, according to the Dutch guidelines, a clay layer of more than 0,5 m does not affect the calculated resistance-duration. Another limitation of the Dutch safety assessment is that the resistance-duration is only valid for slopes between 1:2,5 and 1:4. Additional research shows that the grass revetment on a slope of 1:7 can handle storms that occurs once every 90 years at the location of the Wide Green Dike, but the design return period is 200,000 years [5].

As mentioned before, failure of the grass revetment does not necessarily mean that the dike will fail. The clay layer below has additional strength which cannot be assessed according to the normal assessment of the dike. In order to tackle this problem, an additional semi-probabilistic method is used to determine the erosion of the clay.

3.4 Semi-probabilistic assessment

This paragraph describes the model which has been used to determine the depth of the erosion profile. This model is based on existing models developed by Deltares [3, 10]. The depth of the erosion profile relates to the thickness of the clay layer. This is the minimum thickness of the future clay layer in the design of the pilot dike. Furthermore, after a storm at least one meter width of dike crest should be left, in order to withstand a second storm. Therefore, in addition to the erosion profile, the width and height of the crest are calculated as well.

In the following subparagraphs, first of all the erosion model will be explained. The second subparagraph describes how the hydraulic conditions are derived, which are used in the model. The last subparagraph shows the results of the calculations.

3.4.1 Erosion Model

Fig. 4 shows a dike with an erosion profile. The parameters used in the calculations are shown in this figure. An erosion profile is shown with its volume per meter dike (V_e), the depth of the erosion profile (d_e) and the slope of the dike (α). The so-called terrace in the erosion model has approximately a slope of 1:7 to 1:10. However in our study, the slope of the dike is already 1:7. The slope of the terrace becomes therefore more gentle. Furthermore, the cliff always has a slope of approximately 1:1.

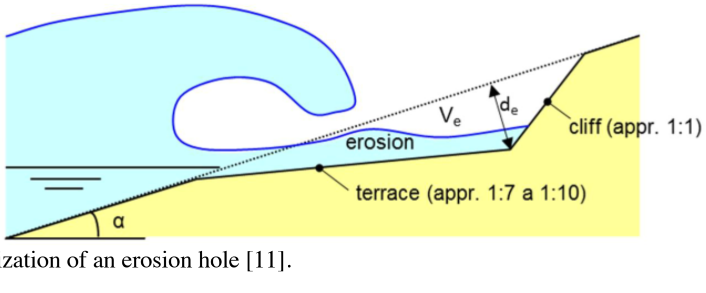
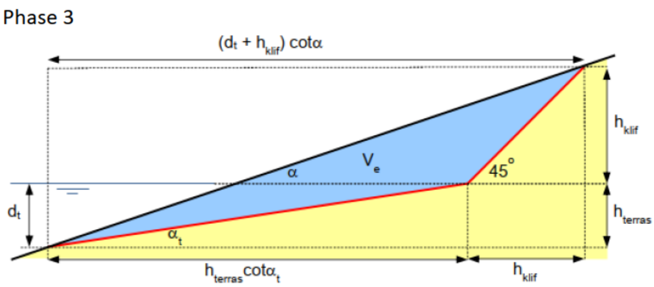


Fig. 4. Schematization of an erosion hole [11].

During the formation of the erosion profile, five different phases can be distinguished. In the first phase the slope of the terrace is steeper than 1:8 and in the second phase the slope is 1:8. In our model study, the erosion volume for outer dike slopes between 1:6 and 1:8 were calculated. Therefore, we started with the third phase.

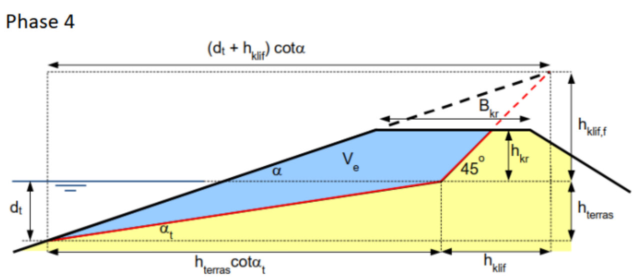
In the third phase (Fig. 5) the slope of the terrace becomes more gentle than 1:8. The still waterline is at the same height as the transition from the terrace to the cliff. The end of the cliff ends in the slope of the dike. As the storm lasts, the erosion profile becomes larger and the end of the cliff ends in het crest of the dike.



Geometrical conditions:

- $\cot\alpha_t \geq 8$
- $h_{terrace} = d_t$
- $h_{kr} \geq \frac{\cot\alpha_t - \cot\alpha}{\cot\alpha - 1} * d_t$

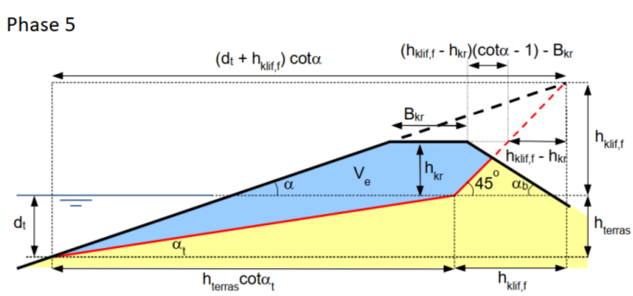
Fig. 5. Phase 3 of the erosion model with the geometrical conditions [10].



Geometrical conditions:

- $\cot\alpha_t \geq 8$
- $h_{terrace} = d_t$
- $h_{kr} < \frac{\cot\alpha_t - \cot\alpha}{\cot\alpha - 1} * d_t$
- $B_{kr} \geq \left(\frac{\cot\alpha_t - \cot\alpha}{\cot\alpha - 1} * d_t - h_{kr}\right)(\cot\alpha - 1)$

Fig. 6. Phase 4 of the erosion model with the geometrical conditions [10].



Geometrical conditions:

- $\cot\alpha_t \geq 8$
- $h_{terrace} = d_t$
- $h_{kr} > \frac{\cot\alpha_t - \cot\alpha}{\cot\alpha - 1} * d_t$
- $B_{kr} \leq \left(\frac{\cot\alpha_t - \cot\alpha}{\cot\alpha - 1} * d_t - h_{kr}\right)(\cot\alpha - 1)$

Fig. 7. Phase 5 of the erosion model with the geometrical conditions [10].

The fourth phase (Fig. 6) characterizes itself, because of the ending of the cliff in the crest of the dike, instead of in the slope of the dike. And finally in the fifth phase (Fig. 7) the ending of the cliff is in the inner slope of the dike.

First off all, the erosion volume is calculated for every timestep using the equation of Mourik [11]:

$$\frac{\partial V_e}{\partial t} = \left(c_e * \left(1{,}32 - 0{,}079 * \frac{V_e}{H_s^2}\right) * (16{,}4 * (\tan\alpha)^2 * \left(\min\left(3{,}6; \frac{0{,}0061}{s_{op}^{1{,}5}}\right)\right) * (1{,}7 * (H_s - 0{,}4)^2) \right) \tag{2}$$

Whereas:
V_e = Erosion volume [m3/m]
c_e = Erosion coefficient [-]
H_s = Significant wave height per time step [m]
α = Dike slope [rad]
s_{op} = Wave steepness [-]
t = Time since initiation erosion hole [hours]

$$d_t = min\left\{0{,}4 * \frac{V_e^{0{,}25}}{\sqrt{H_s}} + 0{,}7\,; 2 * H_s\right\} \text{ if } H_s > 0{,}5\ a\ 1\ m \tag{3}$$

Using the erosion volume there can be determined in which phase the erosion process is in. Therefore, every phase has its own geometrical conditions. If all geometrical conditions of a phase are met, the situation is in that particular phase. The calculation of the slope of the terrace and the perpendicular erosion depth is dependent on the phase.

In phase three the slope of the terrace is calculated as follows [10]:

$$\cot\alpha_t = \frac{1}{2}(\cot\alpha + 1) \pm \sqrt{\frac{2V_e}{d_t^2}(\cot\alpha - 1) + \frac{1}{4}(\cot\alpha - 1)^2} \tag{4}$$

In phase four the slope is of terrace is calculated as follows [10]:

$$\cot\alpha_t = 1 - \frac{\frac{2V_e}{d_t^2} + \left(1 + \frac{h_{kr}}{d_t}\right)^2 * (\cot\alpha - 1)}{1 - 2 * \left(1 + \frac{h_{kr}}{d_t}\right)} \tag{5}$$

Whereas:
α = Outer dike slope [rad]
α_t = Terrace slope [-]

The erosion depth, perpendicular to the outer slope, can be calculated as follows [10]:

$$E_\perp = \frac{h_{terras}}{\sin\alpha_t}\sin(\alpha - \alpha_t) \tag{6}$$

3.4.2 Application conditions of the model

In order to use the model as described before, a few application conditions should be met. The application conditions are:

- Wave height: 0,9 m ≤ H_s ≤ 1,5 m

- Wave steepness: $0{,}01 \leq s_{op} \leq 0{,}05$
- Outer slope of the dike: 1:3 to 1:5

The first and the last condition are not met, therefore a surcharge has been added to the erosion volume. The erosion coefficient is a parameter for the uncertainty of the clay characteristics. However, this surcharge does not say that this uncertainty gets larger.

3.4.3 Hydraulic conditions during a storm

The hydraulic conditions for the Wadden Sea are set up using the manual to design the level of transition from hard revetment to grass [9]. The load of the water on the dike slope is determined by the prevailing water levels and wave conditions. Therefore, it is important to know the duration of a storm surge, the maximum water level and the wave heights and lengths. As shown before in Fig. 3 the water level is a combination of the astronomical tide and the schematized storm surge. The foreland consists of salt marshes with lengths up to 1 km of width. This effects the incoming waves and reduces their size. The salt marshes have a height of around 2 m above mean sea level. This means that during water levels up to 2,5 m above mean sea level, waves larger then 0,6 m cannot be generated. This is the wave height the grass should be able to withstand. Since we are only interested in the conditions leading to erosion, the head and tail of the storm can be left out of the entire duration of the storm. This reduces the storm duration in which erosion is expected to take place to 18 hours.

The storm is divided into time steps of one hour. For every timestep the water level is derived from Fig. 3. The corresponding wave heights and periods to the water levels are derived from the program Hydra-NL [12].

Waves perpendicular to the outer slope of the dike have more influence on the clay layer than waves which reach the outer slope in an angle. Therefore, the wave heights are diminished with a factor of influence because of the angle of wave attack. The factor of influence is calculated as follows [13]:

$$f_\beta = \max(0{,}35; (\cos\beta)^{0{,}67}), with -90° \leq \beta \leq 90° \tag{7}$$

Whereas:
f_β = factor of influence for angle of wave attack [-]
β = Angle of wave attack relative to dike normal [°]

The mean angle of wave attack is 34° end the factor of influence in this case is 0,88. Furthermore, the time series are derived for two different climate scenarios and for three plan periods. The climate scenarios are the ‘moderate (G)’ climate scenario and the ‘warm including circulation change patterns (W+)’. The plan periods are 2035 (12 years), 2048 (25 year) and 2073 (50 year). For all six combinations the time series are derived from Hydra-NL and the erosion volumes are calculated.

3.4.4 Results

After the initiation of erosion, the erosion profile follows the phases as described earlier. As the storm lasts, more clay is repelled from the outer slope, and the erosion profile increases in size. The design of the dike should be adapted to at least one meter residual width. With the erosion profile from phase four, the required width and height of the dike crest can be determined.

Our main focus is on the plan period of 2073 and the climate scenario W+. However, the other five time series are also used for the calculations, because there are a lot of uncertainties in the equations. By using six different calculations it is shown what the degree of uncertainty is.

The crest height used in the model is NAP +9,0 m, the initial crest width was 8 m. The total erosion volume per climate scenario and plan period is shown in Table 1. As explained in the previous section, using the geometrical conditions, the erosion volume can be converted into an erosion profile from one of the five phases. Subsequently, the width of the crest of the dike can be adapted, so that the erosion profile has the form of phase four.

Table 1. Erosion volume for every plan period and climate scenario.

Plan period	Climate scenario G	Climate scenario W+
2035	19,58 m^3/m	20,20 m^3/m
2048*	20,33 m^3/m	22,59 m^3/m
2073	21,29 m^3/m	22,92 m^3/m

The thickness of the clay layer is calculated perpendicular to the slope of the dike, see Table 2. The thickness of the clay layer differs up to 0,2 m between the two climate scenario's.

Table 2. Thickness of clay layer perpendicular to the dike slope.

Plan period	Climate scenario G	Climate scenario W+
2035	1,70 m	1,74 m
2048	1,74 m	1,94 m
2073	1,80 m	1,97 m

A part of the crest is eroded due to the wave impact. The designed crest width is determined dependent on the eroded part. For the final crest width one meter of extra width is added to the calculated crest width. The crest width for the scenario of W+ and the plan period of 2073 is 6,1 m width (included the one meter extra width).

Table 3. Eroded crest width.

Plan period	Climate scenario G	Climate scenario W+
2035	0,48 m	1,30 m
2048	0,89 m	3,39 m
2073	1,94 m	5,06 m

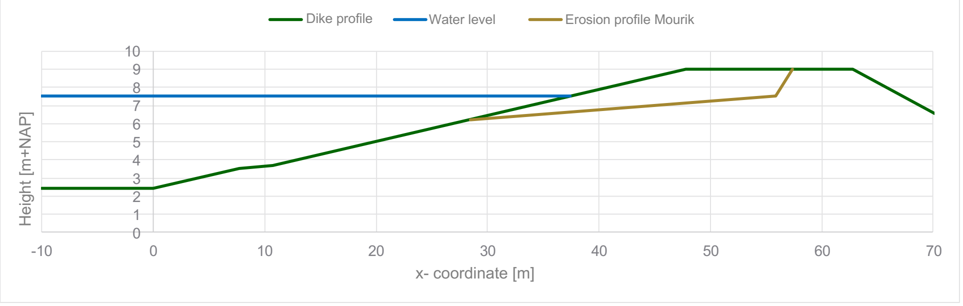


Fig. 8. Erosion profile.

4 Research and field tests

In the elaboration of the design of the dike non-conventional methods are being used. In order to optimize the design, knowledge gaps have to be further investigated. These knowledge gaps and the approach to investigate them are described below.

4.1 The clay and the erosion coefficient

To strengthen the dike, the locally ripened clay will be used. In order to determine whether the clay can be used, it has to meet the Dutch standards of clay for dikes conform TR clay for dikes [14]. Since the critical mechanism of failure is the erosion of the clay, the so-called erosion class is the main attribute of the clay to determine. This can be indicated by determining the plasticity of the clay. During the filling of the clay ripening depots this was already tested and the highest erosion class I was found. However, the salt and organic content is much higher than prescribed and especially the organic content has a large influence on the erodibility of the clay. Over time clay with a high organic content will swell during wet periods and during dry periods it will show cracks in the top layer. These cracks are the weak spots in the top layer. The internal strength of the top layer is lower and large chunks of clay will erode along the cracks. This is why the ripened clay is not applicable conform the standards.

However, the regional Water Authority has the ambition to meet is own durability goals and therefore still wants to use the non-conventional clay. The approach in the project is actually quite simple; if the clay is more erodible, the clay layer should be thicker in order to obtain a safe dike. To illustrate this: in the West of the Netherlands the coast exists of dunes, made of sand. This is way more erodible than a regular dike, but with widths around 1 km the safety standards are met. Thus, due to the high salt and organic content of the ripened clay, the design of the dike should now include an extra component, the uncertainty of the erodibility of the clay.

Because there is no experience with the use of these materials, the regional Water Authority intends to run a number of tests. The goal is to gain knowledge of the attributes of the ripened clay, but the attributes of the clay is changing over time (as it is still in the depots to ripen). The ideal situation the regional Water Authority is aiming for, is to use the locally ripened clay for more projects. Therefore, running tests on the now available clay and determining its characteristics is not sufficient. The main goal is to know what the influence of the clay attributes is on the erodibility. However, none of the usually measured attributes is connected to the calculation method. The erosion coefficient in het Mourik formula is an empirical found relation which can only be determined by testing by wave tests.

In order to become familiar with the characteristics and get accustomed with application of the clay, a small dike is being constructed on the salt marches. The dike will be constructed with the clay from the three sources and a reference clay. During the construction of this dike, several methods and repeated steps are executed to reach sufficient compaction. During these tests the plasticity of the clay will be assessed. The construction will give inside in how pliant the clay is. This will help to get familiar with the clay, but will also result in a handling regime for the construction of the actual dike.

After the construction the dike will be tested for 1,5 year, until the construction of the actual dike. During the 1,5 year the riping of the clay and the structuredness in the dike can be researched. This will give insights for the management of the dike after construction.

In order to gain knowledge of the erosion of the different clays, the regional Water Authority is preparing a wave flume test. By testing a dike of the different clays and different structuredness of the clay, the erosion parameter can be determined. Currently tests are only preformed on regular dike clay and boulder clay. The boulder clay, which is less structured than regular dike clay, is more erosion resistant. The expectations for the ripened clays is that the erosion coefficient is worse compared with the dike clay due to the structuredness. However, it is impossible to predict the behaviour and therefore the aim of the tests is to reduce the uncertainty.

In the design the clay layer will be a couple of meters thick. The structuredness, however will be large at the surface of the clay layer and will decay over the thickness. It's expected that this effect will lead to the erosion of large chunks of clay. The clay below the surface is less prone to influence of the climate conditions and will be less structed. It is expected that the erosion resistance below the surface is higher. During the test this hypothesis will be tested by preforming tests on structured clay and compacted placed clay

4.2 The empirical formula of Mourik and its limitations

The technical approach describes the conditions of the Mourik formula which should be met in order to stay within the range of the preformed test leading to the formula. The biggest deviation between the case and the application conditions is the wave height. With waves between the 2,0 and 3,0 m, the limitation of the formula with its range up to 1,5 m is surpassed. Since the wave height is dominant in determining the load, this has large influence on the minimum thickness of clay layer. As already mentioned, a correction for the wave height has been included to ensure the safety.

The angle of the slope will benefit the erosion resistance of the dike. However, this effect isn't fully included in the formula either. By conducting new tests in a wave flume, the effects of the higher waves and the slope angle can be determined. This will reduce the uncertainty in the results and may lead to a more accurate and customized design. This is why not only the ripened clay will be tested. Preforming the test on normally used clay will add knowledge and may expand the limitations on the formula.

Another aim of the test is to enlarge the duration of the erosion. The formula is mostly based on results with the initiation of a hole. To include the growth of the erosion hole, the program ComFlow had been used.

With the opportunity to perform a new series of test, the ComFlow models can be calibrated with the new data. This will lead to a more accurate description of the erosion which will be applicable for several other situations.

5 Conclusion

The concept of a Wide Green Dike along the Eems-Dollard estuary has many advantages. A traditional dike strengthening would imply that the grass cover is replaced by a hard revetment. The WGD allows for a grass covered dike, widened with locally ripened sediment into clay. In the same time, this contributes to reducing the turbidity in the estuary.

The current standard calculation methods are not applicable to design a grass covered dike along the sea. Several erosion models are used, to calculate the erosion profile that might take place during extreme storm conditions. By widening the dike, erosion is allowed, while the dike still meets it legal probability of failure.

The characteristics and applicability of the ripened clay still has some uncertainties. Field tests will be used to learn more about the erosion resistance to optimize the dike design. In the end, the concept of a Wide Green Dike has the become a feasible alternative, that can compete with other forms of dike strengthening.

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