New approach for uplift induced slope failure

Nouvelle methode d'approche de la pente de rupture induite par soulevement

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ABSTRACT: Uplift induced slope failure occurs due to high water pressures in the sand layer below the top layers in a polder. The toplayer is lifted due to water pressure and slope instability of the dike may occur. The mechanism is significant and representative in the Dutch polders. In this paper a new uplift model has been presented and numerical, geocentrifuge and field validation is discussed. Comparisons of the new model with four existing models are shown for ten Dutch representative polder dikes. Furthermore, safety aspects are discussed and conclussions are drawn. The new model has been included in the Dutch national guideline for dike design.

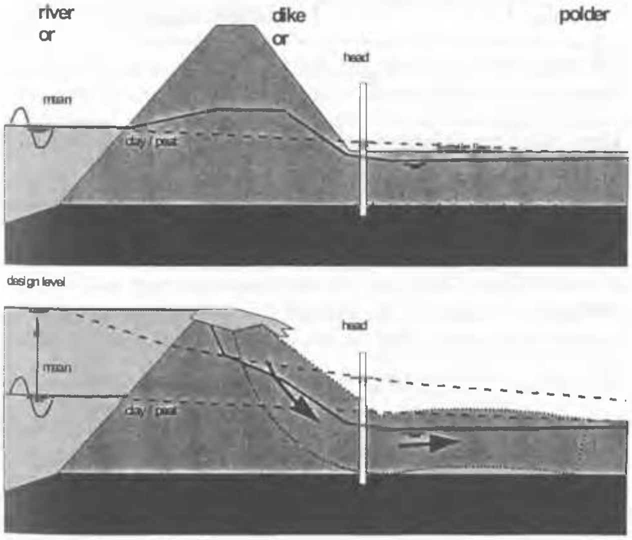
RÉSUMÉ: La pente de rupture par soulèvement se crée par de hautes pressions d'eau ayant lieu dans la couche sableuse localisée sous les couches de surfaces dans un polder. La couche se trouvant à la surface se soulève à cause de la pression d'eau et la pente d'instabilité de la digue peut se produire. Ce mécanisme est important et représentatif des polders Néerlandais. Dans cet article, un nouveau modèle de soulèvement a été présenté et des validations aussi bien numériques, en géocentrifigeuse et qu'en pratique ont été discutées. Des comparaisons entre le nouveau modèle et les quatre autres existants sont présentées pour dix digues représentatives Néerlandaises. En outre, les aspects liés à la sécurité sont discutés à la suite desquels des conslusions ont été tirées. Le nouveau modèle a été inclu dans le guide national Néerlandais sur la conception des digues.

1 UPLIFT PHENOMENON

In West-Netherlands the Holocene toplayer is commonly situated on top of a relatively rigid and permeable Pleistocene sand layer. Through this sand layer high water levels in adjacent rivers and estuaries may generate locally high pore pressures directly under or beside a dike.

Consequently, effective contact stress at the layer interface decreases, eventually to zero, giving rise to uplift and sliding (Fig. 1). In the mid eighties this phenomenon was not well understood, and it caused a sudden collapse of a dike at Streefkerk (Fig. 2).

Since then careful observation of various dikes, geocentrifuge tests and FEM-calculations have proven that uplift is a serious failure mechanism as visualized by Bauduin & Moes (1987).



Figuur 1. Schematic process of uplift induced slope failure.

Figure 2. Uplift induced dike failure at Streefkerk, the Netherlands

2 KRIMPENERWAARD, A DUTCH POLDER

The last decade the uplift failure mechanism is included in the Dutch national guideline for dike design and evaluation (TAW, 1985). In the polder the Krimpenerwaard (Fig. 3) uplift is representative and significant for river dike stability assessment over a length of 10 kilometer. The dike is, in fact, unsafe. Technical improvements and specific calamity regulations are due. Unfortunately, many houses exist along the dike and even on top of the dike (Fig. 4). A well-defined and properly validated design rule for the uplift failure mechanism is therefore urgently required in order to avoid unnecessary building removal and superfluous protection measures

Figure 3. Polder Krimpenerwaard between two rivers

Figure 4. Living houses along and on the dike

3 EXISTING METHODS FOR UPLIFT PREDICTION

A numerical approach to assess the uplift phenomenon came available in 1988, the computer program MLift, developed at GeoDelft. Subsequently, many adjustments have been adopted. The original approach assumed a triple sliding zone: an active circular, a straight, and a passive circular sliding segment. The resulting horizontal force I_a (Fig. 5) interacting at the separation of the active segment and the straight segment (the beam) is counterbalanced by the friction force F_s resulting from the beam's net weight affected by the lift caused by pore pressures, and the retaining horizontal force I_p generated by the passive segment. The determination of the force I_a was based on a full circle analysis while at its passive part subjected to friction $\varphi=0$ and cohesion c taken such that the Spencer stability factor is 1 (Spencer, 1967). The force is taken from the inter-slice separation right under the actual circle center. By considering various circles the lowest force is adopted. For I_p a similar approach is adopted.

The method shows some inconsistencies. It does not coincide with Bishop's method (Bishop, 1955) when the beam vanishes. Furthermore, when an additional bank is placed on top of the dike's lee side, its weight causes unrealistic increase of I_a. The benefit of a bank is modeled improperly.

A logic alternative is the assessment of the entire sliding body by Spencer's method. However, the passive side should then be modeled by a straight wedge, as a circular plane renders the approach unstable. This method does either not coincide with Bishop's method. Moreover, calculations require much time.

For situations with a vertical safety factor *n*, which is the vertical weigth divided bij the water pressure in the sand layer, beyond $n>1.04$, it is possible to apply FEM. In this study the computer code PLAXIS was used (PLAXIS manual, 1998). In the FEM approach the critical situation is found by either decreasing internal friction and cohesion step by step or increasing the gravity, unit plastic failure occurs. In practice, however, a vertical safety factor under 1.04 is often found, rendering FEM not generally applicable. Moreover, as FEM is basically a stiffness approach rather than strength, additional parameters and schematizations are required – moduli, element type/size, initial stress state, acceptable error level – which makes results more subjective and it implies a limit to FEM's applicability as well.

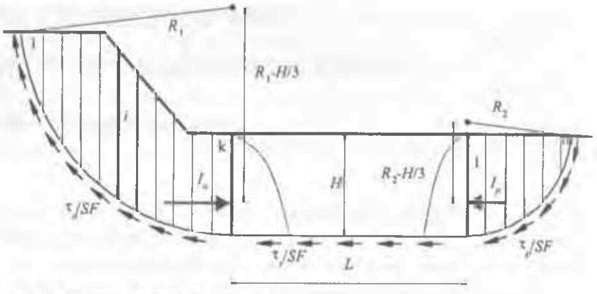
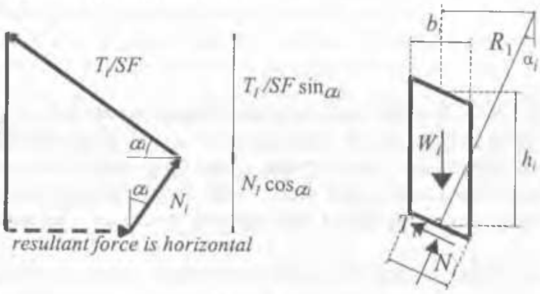


Figure 5. Scheme of Van's method



Figuur 6. Slice Forces (Bishop's and Van's method).

4 NEW ANALYTICAL METHOD FOR THE UPLIFT STABILITY PHENOMENA; VAN'S METHOD

In 1999 a new model is developed, referred to as Van's method, which is based on the following:

- the stability criterion should be identical to Bishop's method
- when the beam segment vanishes the stability factor should coincide with Bishop's method
- the model suites a probabilistic approach, which means analytical and quick.

According to Bishop's method (Bishop, 1955) the safety criterion applies to the stability factor *SF* being the lowest denumerator of the shearstress τ along the sliding plane, that results in equilibrium (Fig. 5). The inter-slice horizontal forces I_a and I_p are supposed to act at 1/3 of the beam segment height above the sliding plane, in fact, a safe assumption. In Figure 6 the system of forces acting on the sliding body are presented.

The moment equilibrium of the active segment yields the following formula.

$$I_a = \frac{\sum\limits_{i=1}^{k} \gamma_i \cdot h_i \cdot b_i \cdot \sin\alpha_i \cdot R_1 - \sum\limits_{i=1}^{k} \frac{\tau_i}{SF} \cdot \frac{b_i \cdot R_1}{\cos\alpha_i}}{R1 - \frac{H}{3}} \tag{1}$$

Here, *SF* is the unknown stability factor. The vertical slice equilibrium yields

$$N_i \cos\alpha_i + \frac{T_i}{SF}\sin\alpha_i = \gamma_i h_i b_i \tag{2}$$

with

$$N_i = \sigma_{ni}\frac{b_i}{\cos\alpha_i} = (\sigma'_{ni} + u_i)\frac{b_i}{\cos\alpha_i} \tag{3}$$

$$\frac{T_i}{SF} = \frac{\tau_i}{SF}\frac{b_i}{\cos\alpha_i} \tag{4}$$

Substitution of (4) and (3) into (2) gives

$$\sigma'_{ni} = \gamma_i h_i - u_i - \frac{\tau_i}{SF} \tan \alpha_i \tag{5}$$

The shear strength τ_i according to Mohr-Coulomb's material model states

$$\tau_i = c_i + \sigma'_{ni} \tan \phi_i \tag{6}$$

Substitution of (5) into (6) yields

$$\tau_i = \frac{c_i + (\gamma_i \cdot h_i - u_i) \tan \varphi_i}{1 + \dfrac{\tan \alpha_i \cdot \tan \varphi_i}{SF}} \tag{7}$$

Here, u_i is the local pore pressure. Substitution of (7) into (1) provides I_a. In a similar manner I_p is found. The friction force along the beam segment is expressed by

$$F_s = -\frac{\tau_s}{SF} \cdot L \tag{8}$$

The stability factor SF is obtained by considering the horizontal equilibrium: $I_a+I_p+F_s=0$. Substitution yields

$$SF = \frac{\left[\dfrac{\sum_{i=1}^{k} \left(\tau_i \cdot \dfrac{b_i}{\cos \alpha_i} \right)}{1 - \dfrac{H}{3R_1}} + \dfrac{\sum_{j=1}^{m} \left(\tau_j \cdot \dfrac{b_j}{\cos \alpha_j} \right)}{1 - \dfrac{H}{3R_2}} + \tau_s \cdot L \right]}{\left[\dfrac{\sum_{i=1}^{k} \left(\gamma_i h_i b_i \sin \alpha_i \right)}{1 - \dfrac{H}{3R_1}} + \dfrac{\sum_{j=1}^{m} \left(\gamma_j h_j b_j \sin \alpha_j \right)}{1 - \dfrac{H}{3R_2}} \right]} \tag{9}$$

Since SF appears implicitly (also τ_i and τ_j), the solution is found by iteration. Convergence proceeds without complications. For $R_1=R_2$ and $L=0$ a completely circular slip plane is obtained. Formula (9) reduces then to Bishop's method and SF corresponds precisely to Bishop's stability factor.

5 MODEL VALIDATION FOR 10 REPRESENTATIVE DUTCH POLDER DIKES

Van's method is an improved stability method for the uplift phenomenon. It results in new stability factors, different from previously found ones by other methods. Hence, new model factors are to be applied. These model factors must comply to the integral safety philosophy concerning inundation risk by river dike instability (Van & van Hoven, 2000).

To determine these model factors 10 typical well-investigated (bench mark) river dike sections have been considered. Stability factors have been calculated for various uplift conditions using different methods (Fig. 7). Results are compiled in Figure 8, showing Van's method versus MLift (old), Spencer's, Bishop's and PLAXIS (FEM). In this presentation no model factors have been included except for MLifl, because they were required to make a fit to Bishop's method. Results coincide reasonably well. Detailed information is compiled in Table 1. The final conclusion is that compared to previous evaluations (MLift, Bishop's method) the actual stability factor is 7% higher. This provides a significant release to required dike improvements in the Krimpenerwaard; many houses could be saved from abolishment.

Table 1. Comparison different models

comparison	$\Delta(\mu)^1$	σ^2
MLift versus Van ($n>1.2$)	0%	5.5%
MLifl versus Van ($n<1.2$)	7%	7%
Spencer versus Van	1%	1%
Bishop versus Van	5%	8%
PLAXIS versus Van[3]	-6%	8%

[1] relative difference in average SF [2] standard deviation

[3] PLAXIS generates higher plastic zones

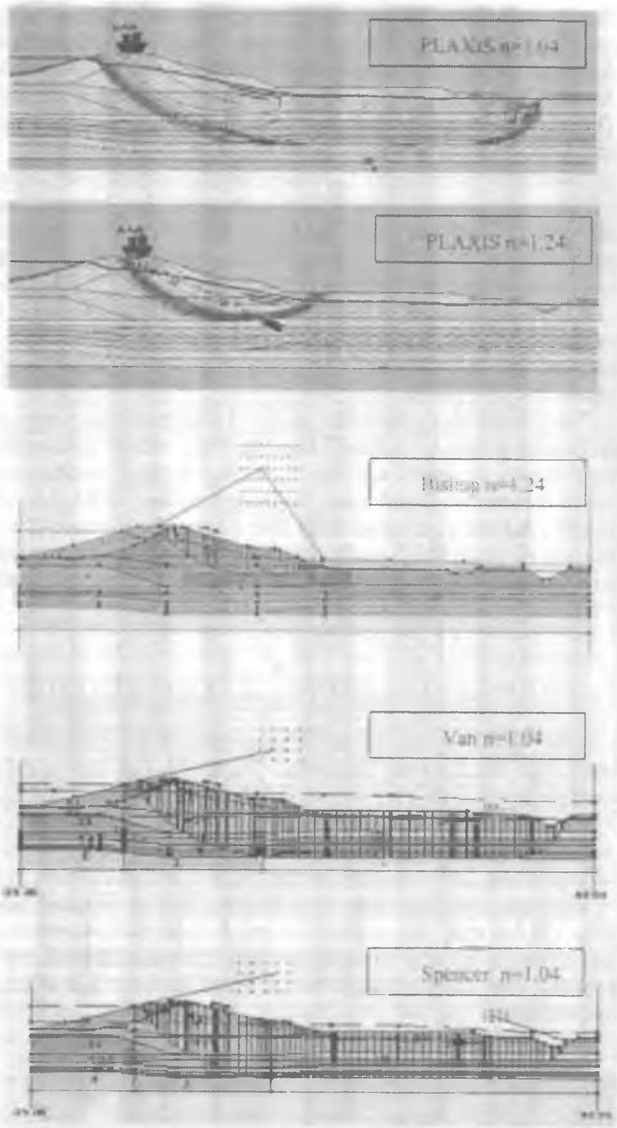


Figure 7. Results of different stability methods

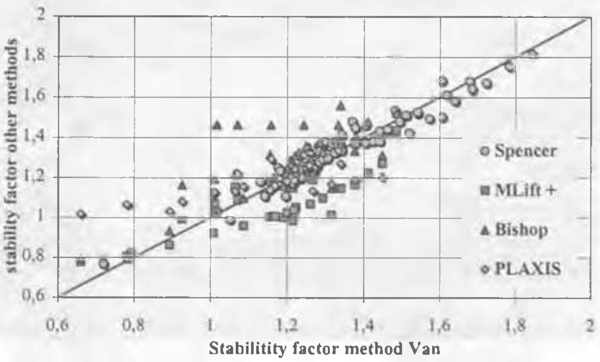


Figure 8. Comparision of different models for 10 cases

Table 2. Model factors

model	model factor
Bishop	1,10
Van	1,05
PLAXIS	1,00

6 SAFETY ASPECTS

The adopted model factors which include the uncertainties in the modeling approach of the uplift induced failure mechanism are presented in Table 2. Based on the results described in the previous section a model factor of 1.05 is chosen for Van's method. This gives a suitable agreement with the Bishop and PLAXIS approach, which are commonly applied in the Netherlands.

It is obvious that the uplift failure mechanism is best modeled by a FEM approach, i.e. PLAXIS, as it also includes deformations and two-dimensional stress distribution. However, proper parameters should be available. Soil stiffness has a significant effect, in particular the Poisson ratio (Rozing & Van, 1999). Because the corresponding parameters are difficult to determine, it is appropriate to appreciate the qualitative value of the trend between stability factors and observed safety, rather than the apparent absolute values.

The present-day safety philosophy is based on a long experience with Bishop's method. Therefore, the safety philosophy with regard to macro-stability including damage, model and material factors is based upon the Bishop model. In this respect stability factors determined with Bishop's method for $n>1.2$ are considered realistic. For $n<1.2$ the ideal case should coincide with the trend by PLAXIS and for $n>1,2$ to Bishop's method. Van's model suites these conditions.

7 VALIDATION BY CENTRIFUGE AND FIELD TESTING

For the validation of the uplift phenomenon an experimental centrifuge test has been performed (Figure 9). For the carefully designed test model the numerical failure was predicted at 90 g. The test model collapsed according to the uplift mechanism at 100 g. A precise analysis of the measurements and a reevaluation of parameters from a test model autopsy will yet take place.

In the large field pilot test of an existing dike at Bergambacht (Fig. 10) the uplift induced failure mechanism will be modeled and observed in order to validate Van's method and establish a together with the centrifuge test a sound base for the chosen model factor.

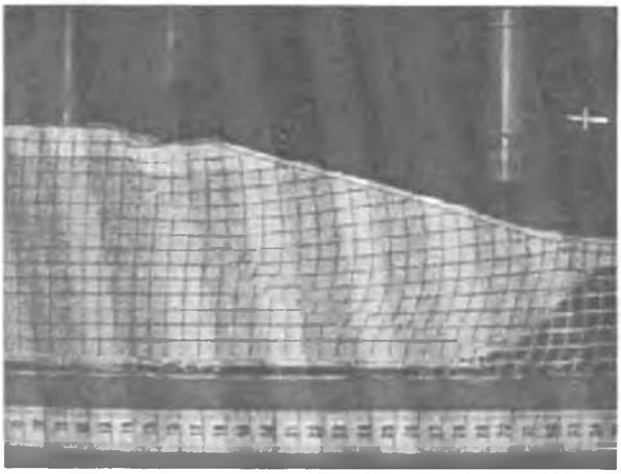


Figure 9. Active sliding planes in centrifuge modeling

Figure 10. Test site at Bergambacht

8 CONCLUSION AND RECOMMENDATION

In the Dutch lowlands the uplift phenomenon is a frequently occurring mechanism, that seriously jeopardize a river dike's stability. Consequently costly countermeasures are required, and existing houses have to be abolished in order to establish a proper safety against inundation. The method proposed by Van in this paper describes the uplift mechanism consistently and it conveniently suits the safety philosophy commonly used for dike stability in the Netherlands. Furthermore, Van's method is compatible to the application of bank constructions at the dike's lee side.

The method has been validated by a comparison with other common evaluation methods for a representative set of typical Dutch dikes and a geocentrifuge test. The method is simple and quick. The conclusion is justified that Van's method is a significant improvement of the state of the art on dike stability analysis. Moreover, it is easily applicable to a probabilistic approach. Actually the method has been accepted already for the Dutch practice and is available in a new version of the computer code MLift. Also a probabilistic version has been developed.

A real size validation is being executed; results are due in 2002. One of the adventitious and economic options is to install short sheetpiling at the Holocene-Pleistocene interface, as it may save local houses and infrastructure. The standard sheetpiling analysis does not apply in this case. How to incorporate this element in a state of the art sliding mechanism is a topic of research.

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