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STABILITY OF THE INNER SLOPE OF THE POLISH DREDGDIKES RESEARCH DIKE AT STATIONARY FLOW

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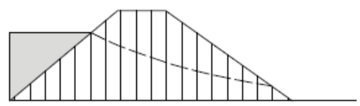
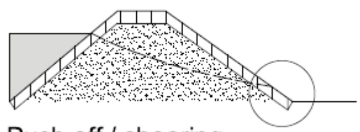
Abstract. For long duration of the flood the water table can appear on the slope with a problem of out-wash in the case of sand type dike. If the dike corps is covered with less permeable layer some additional push-off forces and shearing can rise in the cover. In both cases the micro stability of the inner slope should be considered at normative high water for homogeneous sand type dike or sand type dike with less permeable covers. The analyses were performed taking into account the geometry and soil parameters from the test dike in Gdańsk. The dike is formed with ash-dredged material mixture, characterized with relatively high permeability coefficient. The outer slope (water side) of the test dike corps is covered with clay while the inner slope is covered with fly ash product – sand mixture. The stability of the dike is calculated without cover and including cover on the slope. The stability against wash-out and shearing was calculated. Additional parametric studies were undertaken including different slope inclination, effective cohesion of the mixture. Micro-stability of the dike was analysed and the overall stability of the dike was also considered using analytical, FEM and limit state approach.

Keywords: dredged material, bottom ash, clay cover, local slope stability, seepage, push up

1. Introduction

The stability of the dike slopes is the main issue to be considered in design. Here, one can distinguish the case of the outer (water side slope), where the complex actions (water and ice erosion, wave loads, infiltration and seepage) acting on the revetment should considered. These requirements for the revetment are often contradictory and difficult to fulfil, Pilarczyk (1998). The other case is stability of the inner slope subjected to erosion, infiltration and seepage, which will be discussed in this paper. The attention will be focused on seepage and its influence both on the global and micro-stability. The latter relates to the stability of soil layer with limited thickness on the slope surface under the influence of the ground water flowing through the dike (Fundamentals, 1998). Very local instabilities may compromise the global stability of the dike. Usually, when micro-stability is assured, macro-stability is not a problem, provided that there is no weak soil layer within the dike or in the subsoil. Three typical cross-sections of dikes with phreatic lines are given in Table 1. When clay dike is considered the micro-stability makes no problem.

Table 1 Micro-stability mechanisms for different dike types

Type of dike	*Micro-stability*
Clay dike	 No problem
Sand dike	 Out-wash
Sand dike with clay covering	 Push off / shearing

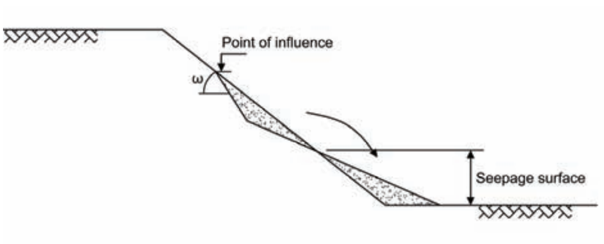


Fig 1. Slope profile after wash-out

In sand type dikes the high phreatic line and exiting water make the out-wash of the soil particles appear on the inner slope. It may occur when the permeability of the top layer is similar to that of the dike corps. The washed out material will be deposited a short distance away and a new equilibrium slope profile will be established as a result of erosion and deposition (see Fig 1). The typical inclination of such slope is 1:5. Failure of the water defence occurs when the point of encroachment reaches a minimum crown height, TAW, 1989.

The second failure mechanism in sand type dyke occurs in the form of shallow sliding planes in the sandy upper layer. The effective stress in the soil is reduced under the influence of the water, which is expelled. Shallow sliding of slopes under seepage conditions depends on the flow direction and hydraulic gradient, particularly near the ground surface, CIRIA (2013). For infinite slope stability model, the slip surface is assumed to be a plane parallel to the slope and the end effects are neglected. The slope element is subjected to both seepage force (F_w) and gravity (W) in a bloc stability approach. The forces acting on the sliding block near the slope surface are given on Fig 2. The hydraulic gradient can be derived as a function of seepage direction (λ) and slope angle (β). This exit gradient is defined as:

$$i = \frac{\sin\beta}{\sin\lambda} \tag{1}$$

It can be shown, CIRIA (2013), that equilibrium condition of the sliding mass with a block width (b) can be expressed in terms of slope geometry parameters and effective shear strength parameters of the soil on the slope:

$$\sin\beta + i\frac{\gamma_w}{\gamma'}\sin\lambda \le \frac{c'}{\gamma' D\cos\beta} + \left(\cos\beta - i\frac{\gamma_w}{\gamma'}\cos\lambda\right)\tan\phi' \tag{2}$$

where:
D – vertical soil depth [m]
β – inclination of the slope from the horizontal [º]
λ – inclination of the seepage direction from the normal to the slope
c’ – soil effective cohesion [kPa]
’ – soil effective angle of internal friction [º]
γ’ – unit weight of submerged soil [kN/m^3]
γ_w – unit weight of water [kN/m^3]

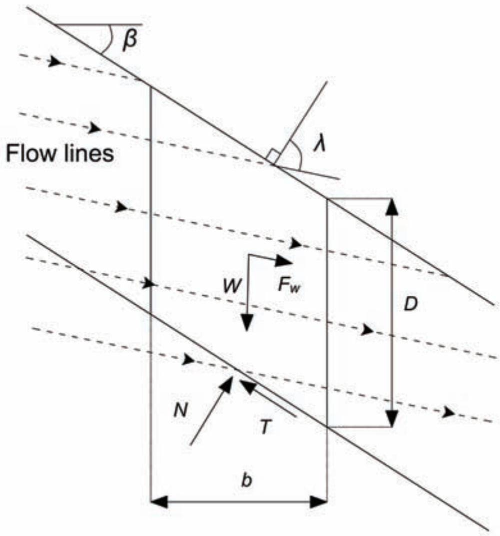


Fig 2. Infinite slope model with parallel flow lines, CIRIA (2013)

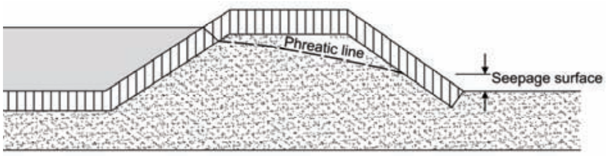


Fig 3. Push-off slope revetment scheme

If a less permeable top layer lies on the well permeable dike body some additional hydrostatic pressure generates under the clay cover. The water pressure mobilized under covering may push off less permeable top layer (see Fig 3). In this case no significant water flow is assumed through the clay cover. Once the revetment is lifted up, the soil particles under the cover may be washed out. The drop of the effective normal stress in the contact between the sand body and clay cover may result in the decrease of shearing resistance between these two bodies and stability loss in sliding. The shearing may occur even if the hydrostatic pressure is not large enough to produce cover push-off. The action of the push-off and shearing mechanisms is usually combined, TAW, 1989.

2. Test dike

The test dike was constructed near Gdańsk within DredgDikes program to study its stability under flood conditions (see DredgDikes web page). The dike body is built from compacted bottom ash – dredged material mixture, which mechanical parameters are given in Bałachowski and Sikora (2013). The dike cross section is shown on Fig 4. The dike is built on compacted clay as an isolation layer. The total height of the dike is 3m with slope inclination 1:2 on both sides. The water level in the measuring section can be maintained at 2.5 m above the ground level. The inner slope is covered with fly ash product-sand mixture, called Tefra. The parameters of the three soil layers are given in Table 2.

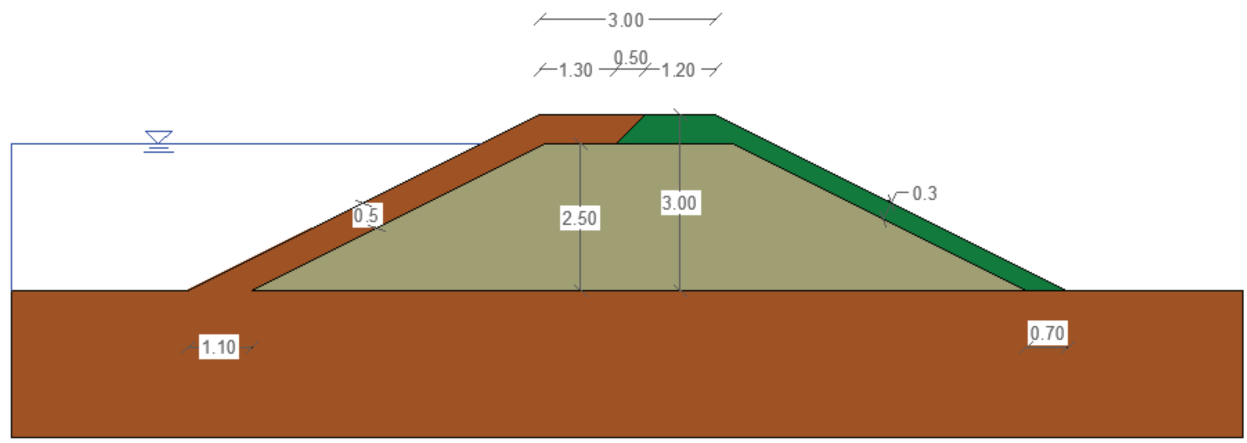


Fig 4. Cross section of the test dike, Pasetto (2014)

Table 2 Soil layer parameters

Materials		CLAY	TEFRA	MIXTURE
Unit Weight	γ [kN/m^3]	18	16	13
Saturated Unit Weight	γ_{sr} [kN/m^3]	21	20	16,3
Permeability coefficient	k [m/s]	1 e -7	1 e -7	1 e -3
Void Ratio	e [-]	0,79	0,64	0,69
Undrained shear	c_u [kPa]	50	30	-
Effective cohesion	c'[kPa]	30	50	5
Effective friction	' [°]	25	20	37
Young's Modulus	E [kPa]	15 000	30 000	22 500
Poisson's Ratio	υ [kPa]	0,35	0,30	0,25

3. Sand type dike stability

Let us assume the model made of bottom ash – dredged material mixture with the same size as the test dike and consider the inner slope stability. Three different slopes (1:2, 1:3, 1:3.5) and effective cohesion of the mixture varying from 5 to 20 kPa are taken into account.

3.1 Micro-stability

3.1.1 Wash-out conditions

The most dangerous situation for the micro-stability of the slope is when the water is expelled horizontally. The maximum slope inclination, when wash-out is considered above water table, should satisfy:

$$\tan\beta \le \sqrt{\frac{\gamma - \gamma_w}{2 \cdot \gamma_w}} \tag{3}$$

which means that the slope should be less steep than 1:2 to avoid washing out.

If the inner slope is partly under the water, the fluid is considered to be expelled perpendicularly to the slope and the following condition should be satisfied:

$$\cos\beta \le \frac{2 \cdot i \cdot \gamma_w}{\gamma - \gamma_w} \tag{4}$$

where *i* is the exit gradient to be determined in flow net analysis and factor 2 is safety coefficient.

3.1.2 Shearing on the slope

Shearing on the sandy slope should be checked for the water expelled perpendicularly to the slope. For simplified conditions, when effective cohesion is omitted, the following condition should be fulfilled:

$$\tan\phi' \ge \frac{\gamma \cdot \sin\beta}{\gamma \cdot \cos\beta - \dfrac{\gamma_w}{\cos\beta}} \tag{5}$$

This lead to very high, unrealistic values of effective angle of internal friction.

3.2 Analytical solution

Let us consider the water flow parallel to the slope. In this case hydraulic gradient is equal:

$$i = \sin\beta \tag{6}$$

An infinite slope model is considered. One should notice the advantage of the equilibrium condition in Eq 2, which takes into account the granular soil with some effective cohesion. Such approach enables the analysis of the bottom ash - dredged material mixture, with a small effective cohesion increasing with time due to cementation effect. Left side of the Eq 2 can be formulated:

$$L = \sin\beta \cdot \left(1 + \frac{\gamma_w}{\gamma'}\right) \tag{7}$$

Right side of the Eq 2 can be rewritten:

$$R = \frac{c'}{\gamma' D \cos\beta} + \cos\beta \cdot \tan\phi' \tag{8}$$

For cohesionless soils (c'=0 kPa) the Eq 2 reduces to well-known solution:

$$\tan\beta \le \frac{\tan\phi'}{1 + \frac{\gamma_w}{\gamma'}} \tag{9}$$

In this case the slope inclination should be higher than 3.5 to achieve the proper stability, Andrzejuk (2013).

The effective cohesion significantly contributes to the slope stability, CIRIA, 2013. Left and right sides of the Eq 2 were calculated for different slope inclination and effective cohesion for a given vertical soil depth *D=1m* (see Fig 2). One should mention that the choice of the vertical soil depth, where the slippage occurs, is important for the slope stability in cohesive soils. It is assumed that the ratio length of the slope over D should exceed 20 in order to consider infinite slope length. The calculated ratio right to left side (*R/L*) is given in Table 3.

The results indicate a good stability of the considered slopes, assuming flow parallel to the slope. Additional analysis should be taken into account for the water exit zone, where the flow lines are less inclined (more dangerous situation) and the requirements should be more strict.

Table 3 *R/L ratio* in cohesive soils for *D=1m*

Effective cohesion	1:2	1:3	1:3.5
c'=5kPa	1.37	1.93	2.22
c'=10kPa	2.12	2.93	3.36
c'=20kPa	3.63	4.94	5.64

3.3 Numerical analysis

Some numerical analyses of steady state flow through the dike were performed using SLIDE 5.0 and PLAXIS 8.2 programs for FEM analysis. Calculations were made for homogeneous dike built from ash-dredged material mixture and for the covers on the slope. These analyses were performed with the soil parameters from Table 2. The phreatic line (see Fig.5) exits on the slope at elevation 1.62m for 1:2 inclination. A very similar result was received for 1:3 and 1:3.5 slopes. The traditional slope stability analyses were checked using Bishop method. For a given slope inclination the shape of phreatic line obtained in FEM calculation was introduced to the model analysed with Discontinuity Layout Optimization (DLO), Smith and Gilbert (2007). The latter is a new numerical method (see Limit state manual) which automatically identifies the critical configuration of sliding soil blocks at failure. It finds the true critical slip-line failure mechanism for any geotechnical problem. The calculation can be performed for adequacy factor on load or adequacy factor on strength. The latter approach was used for slope stability calculation. Here, both effective angle of internal friction and effective cohesion are divided by the strength adequacy factor *F* to identify the critical slip line – failure mechanism.

The results of DLO analysis with sliding blocks at failure for different slope inclination and effective cohesion are given in Fig 6, 7 and 8. General failure conditions are observed when the overall stability is satisfied (see Fig 6b and 6c). When unstable slope is detected (adequacy strength factor F less than or close to 1) unrealistic bloc sliding mechanism is observed (Fig 6a, Fig 7a, Fig 8a).

The sliding block pattern does not enter the compacted clay substratum due to its high strength resistance. The sliding occurs on the roof of clay layer. For soft clays deep failure mechanism should be observed. DLO analyses confirm the weight of effective cohesion within the dike body on the failure mechanism

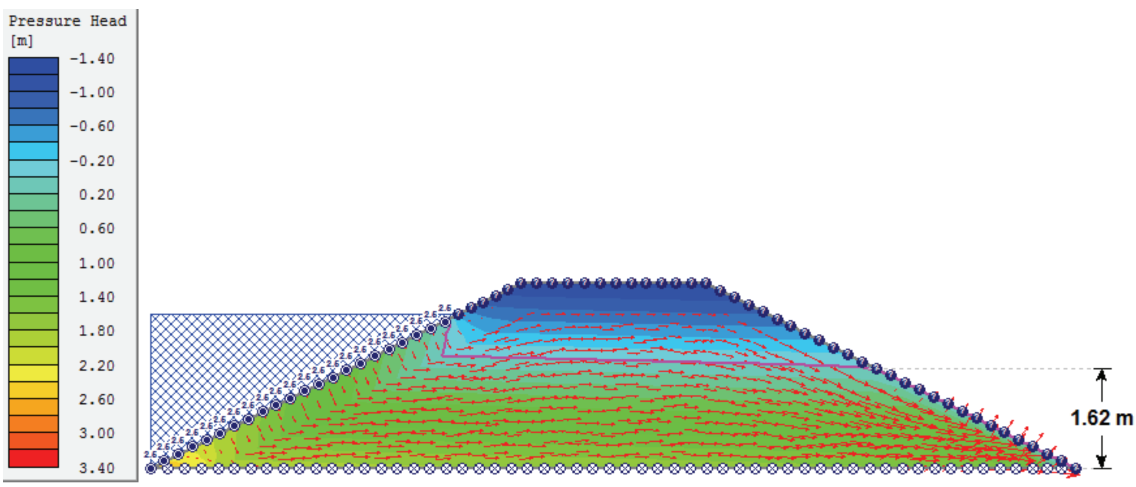


Fig 5. Steady state flow analysis, Pasetto (2014)

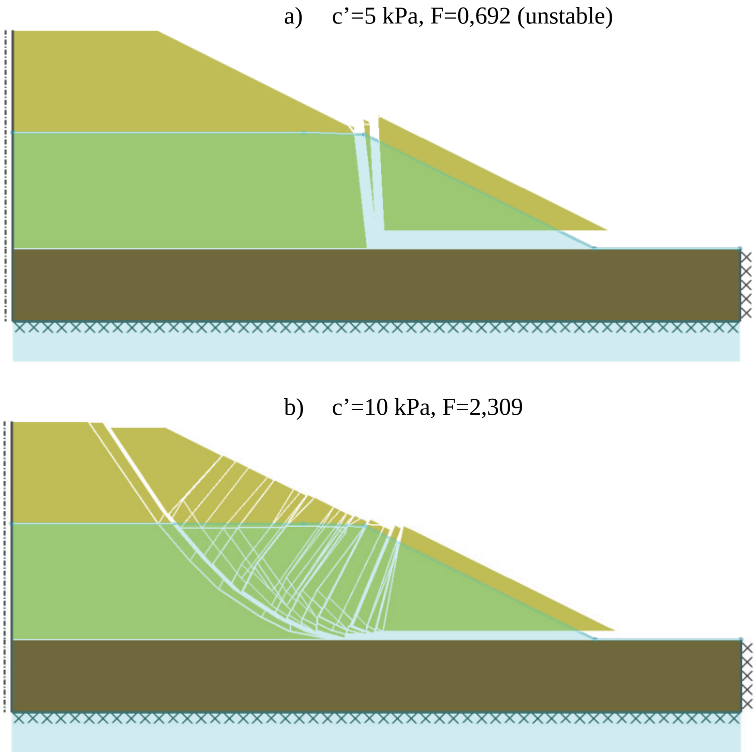


Fig 6. Slope 1:2, strength adequacy factor F

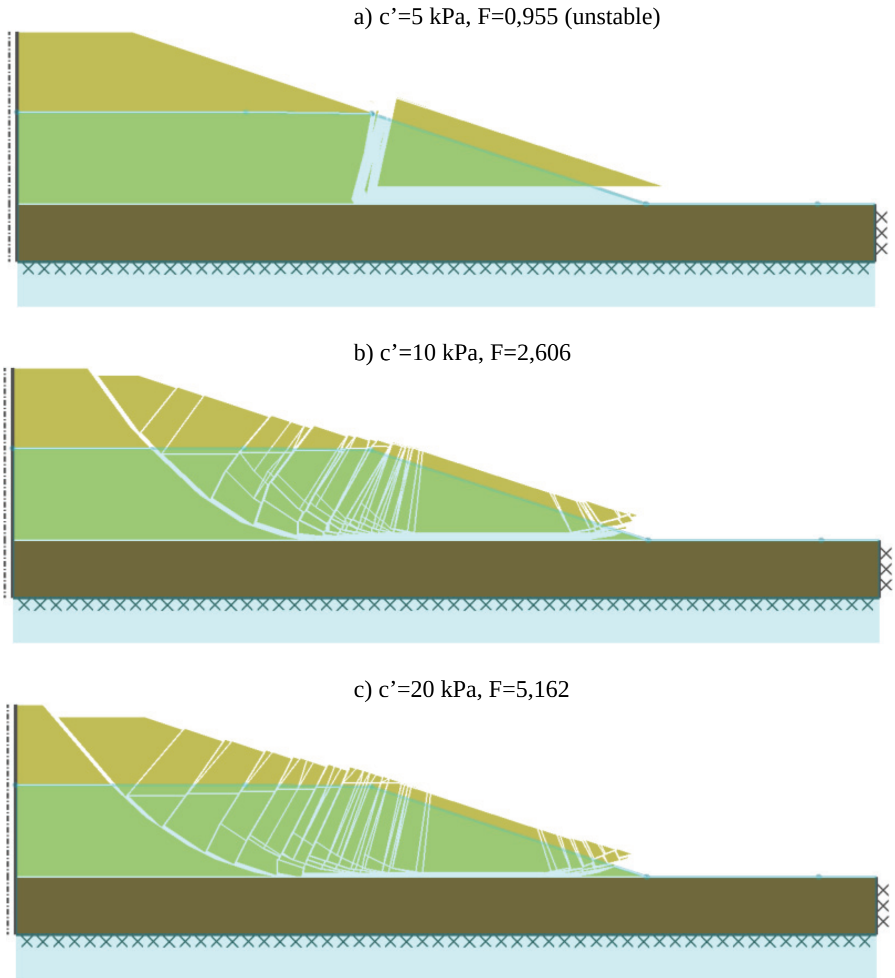


Fig 7. Slope 1:3, strength adequacy factor F

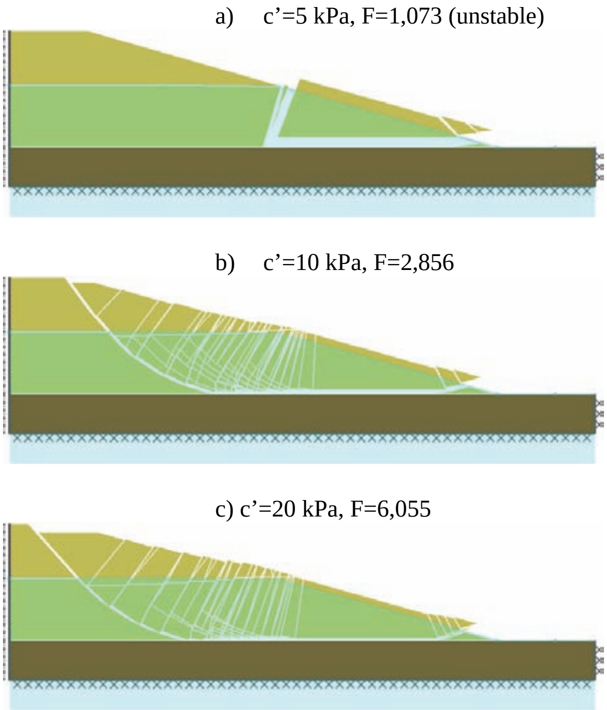


Fig 8. Slope 1:3.5, strength adequacy factor F

and the dike safety. The influence of the inner slope inclination is also important. For a small cohesion, i.e. c’=5 kPa, all dikes present unstable behaviour, regardless the considered slope inclination. This finding is contradictory with analytical solutions for unconstrained slope (compare Table 3). Similar levels of safety are obtained for higher cohesion. Failure mechanisms are however completely different in both cases.

4. Conclusions

1. The inner slope stability mechanisms were discussed for homogeneous sand type dike and dike with cover using some analytical and numerical analysis.
2. Global stability as well as micro-stability of the dike was considered mainly for homogeneous dike section.
3. In slopes constituted from granular soils the contribution of the cohesion is even more important that the slope inclination.
4. Cementation process may increase the slope stability of a dike made of ash-sand mixtures.
5. The minimal slope inclination was determined with micro-stability analysis, analytical solutions and numerical analysis. The results of all these methods are generally convergent for the considered dike section.

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