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TECHNICAL NOTE

STABILITY OF A LEVEE MADE OF BOTTOM SEDIMENTS FROM A DAM RESERVOIR

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Abstract: Stability analysis of a levee made of the bottom sediments from Czorsztyn-Niedzica Reservoir is presented in the paper. These sediments were classified as silty sands and, based on the authors' own research, their geotechnical parameters were beneficial, so the possibility of using this material for the hydraulic embankments was considered. Stability and filtration calculations were carried out for a levee that had the same top width – 3 m, slope inclinations 1:2 and different heights: 4, 6 and 8 m. Two methods were used: analytical and numerical. Calculations were carried out without and with a steady and unsteady seepage filtration. Based on the analysis carried out it was stated that the levee made of the bottom sediments is stable even at the height of 8.0 m, although because of the seepage on the downstream side it is recommended to use a drainage at the toe of the slope.

Key words: *bottom sediments, hydraulic embankments, stability*

1. INTRODUCTION

A siltation process occurs in every dam reservoir, it is a sedimentation of the bed load, transported by tributaries, and materials from the bank abrasion. Siltation has a negative influence on the functioning of the reservoir – it leads to a decrease in the capacity of flood protection reserve, additionally sediments cause water opacity, they can be polluted and they have a negative influence on the quality of the drinking water [2]. Operation problems can occur the earliest in the backwater region, at the mouth of rivers and streams, where the coarsest grains are deposited. This leads to a decrease in the free surface slope in the upper part of the reservoir and because of that the end section of the backwater is moving upstream. Deposited sediments change the shore line, the backwater area is getting shallower and a delta is created [3]. This process can be reduced by preventing erosion in the catchment area, trapping sediments before they enter the reservoir or routing the sediments through the reservoir. When there are significant siltation problems sediments can also be removed from the reservoir mechanically, by dry excavation, hydro-suction or hydraulic dredging. After that the sediments are usually treated as waste and put on a heap, which is not good for the environment, thus determining possible ways of their usage is very important. As a geotechnical material they may be used for earthwork purposes, for building levees or road embankments.

2. BOTTOM SEDIMENTS FROM THE BACKWATER OF CZORSZTYN-NIEDZICA RESERVOIR

Czorsztyn-Niedzica is one of the biggest reservoirs in Poland, its dam is the highest earthen dam in this country (56 m). The main purpose of the reservoir is to prevent flood, but apart from that it is also a power plant and a tourist attraction. During sixteen years of operating, the backwater area of the reservoir has become shallow and full of sediments because of the siltation process, therefore the possibility of their dredging was considered.

Samples of the bottom sediments were taken from the whole area of the backwater, especially along the foreland, consisting entirely from gathered sediments, at the mouth of the Dunajec river. A detailed description of the tests carried out and geotechnical parameters of each sediment sample can be found in the author's publication [3]. In the case of using sediments for earthwork purposes parameters of the averaged material, which was prepared by mixing all the samples, are more important. This material was classified as silty sand, organic matter content allowed it to be classified as mineral (Table 1). Permeability was low and shear strength parameters were relatively high, so the possibility of using this material for earthwork purposes was considered.

Table 1. Geotechnical parameters of bottom sediments [3]

Parameter	Value
Fraction content [%]: • sand 2–0.063 mm • silt 0.063–0.002 mm • clay <0.002 mm	 74.87 24.37 0.76
Name acc. to [3]	siSa
Uniformity coefficient	11.8
Specific density	2.663 g·cm^{-3}
Sand equivalent	30%
Organic matter content	1.44%
Optimal moisture content	14.8%
Maximum dry density	1.653 g·cm^{-3}
Permeability coefficient at: • $I_s = 0.90$ • $I_s = 1.00$	 $6.63 \cdot 10^{-6}$ m·s^{-1} $1.98 \cdot 10^{-6}$ m·s^{-1}
Angle of internal friction at: • $I_s = 0.90$ • $I_s = 0.95$ • $I_s = 1.00$	 31.1° 31.5° 33.7°
Cohesion at: • $I_s = 0.90$ • $I_s = 0.95$ • $I_s = 1.00$	 24.3 kPa 14.9 kPa 11.4 kPa
Bearing ratio after 4-days of soaking	11.0%

Based on the usability evaluation of the sediments it was stated that they can be used as a construction material for the embankments [3]. In order to determine the height of the levee at which it is stable, multivariant stability calculations were made.

3. METHODOLOGY

Two methods were used in stability calculations: analytical (classic Bishop's equilibrium method) and numerical (Finite Element Method). Bishop's method assumes the shape and position of the slip surface and the factor of safety is calculated as the ratio of forces resisting movement to the forces driving movement. Calculations were carried out using Geoslope programs – SLOPE/W for stability calculations and SEEP/W for filtration.

Slope failure in the finite element model occurs "naturally" through the zones in which the shear strength of the soil is insufficient to resist the shear stresses [1]. In FE method Z.SOIL.PC program was used [7]. The behavior of the soil medium was described using the Mohr–Coulomb model and the factor of safety was determined using strength reduction method [6]. Filtration calculations were carried out for steady and unsteady seepage flow.

Stability calculations were carried out for embankments on the ground from permeable medium sands of high thickness and impermeable layer of clay below them (Fig. 1). In Bishop's method two variants were assumed – without water filtration and with steady state flow, whereas in FE there were three – without seepage flow and with steady and unsteady seepage flow (simulating flood wave). The width at the top of the embankments was 3.0 m, inclination 1:2 and height 4.0, 6.0 and 8.0 m. Maximum level of water table was 1.0 m below the top of the levee. For simulated flood wave it was assumed that the water level rises for two days, it is stable for three and then

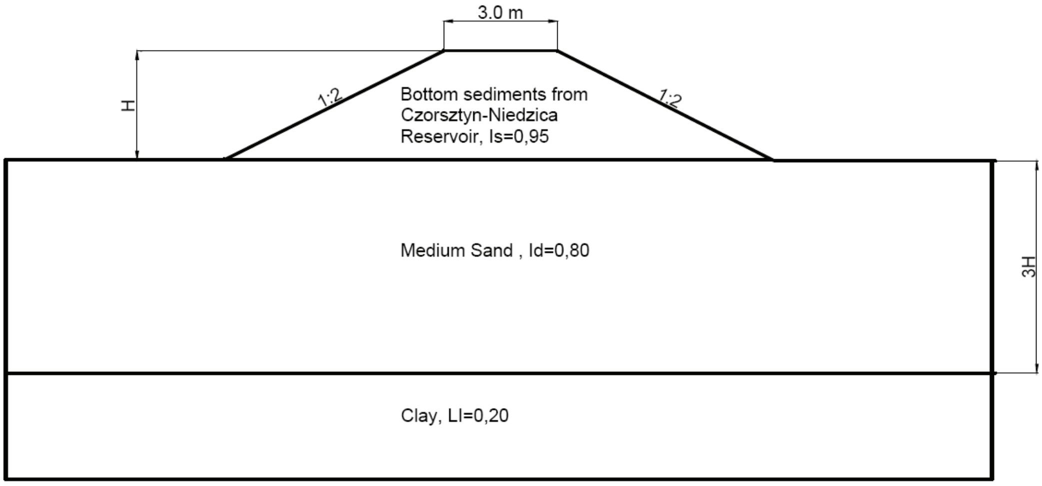

Fig. 1. Cross-section of the levee analysed

Table 2. Geotechnical parameters of bottom sediments and soils used in calculations

Parameter	Material		
	Bottom sediments Silty sand (compaction index $I_S = 0.95$)	Medium Sand (relative density $I_D = 0.80$)	Clay (liquidity index $I_L = 0.20$)
Angle of internal friction, φ [°]	31.1	35.0	18.0
Cohesion, c [kPa]	14.9	0.0	30.0
Unit weight, γ [kN·m^{-3}]	17.0	18.6	21.0
Permeability coefficient, k_{10} [m·s^{-1}]	$3.60 \cdot 10^{-6}$	$1.0 \cdot 10^{-4}$	$1.0 \cdot 10^{-10}$
Void ratio, e [–]	0.694	0.565	0.242

drops for the next two days. Geotechnical parameters of bottom sediments (Table 2) are based on the author's own tests, whereas for the soil in the ground typical values of a given soil type were accepted.

4. RESULTS OF CALCULATIONS USING BISHOP'S METHOD

The results of calculations carried out without water filtration show that both slopes of the levee were stable at every height assumed (Table 3). The factor of safety decreased along with the increase of the levee height from 2.71 at 4.0 m down to 2.24 at 8.0 m. Therefore, they were higher than the value recommended by Polish Regulation [5] for the 3rd and 4th class of embankments.

In the case of steady-state seepage flow calculations showed significant differences in the safety factor values for upstream and downstream slopes. These values were around 3.6 for upstream slope and from 2.07 down to 1.62 for the downstream slope (Fig. 2). Differences between these values increased along with

Table 3. Stability calculation results using Bishop's method

Height of the levee [m]	Slope	Factor of safety FS [–]	
		without filtration	Steady state filtration (water level 1.0 m below the crown of the levee)
4.0	upstream	2.710	3.602
	downstream		2.065
6.0	upstream	2.404	3.634
	downstream		1.756
8.0	upstream	2.239	3.629
	downstream		1.620

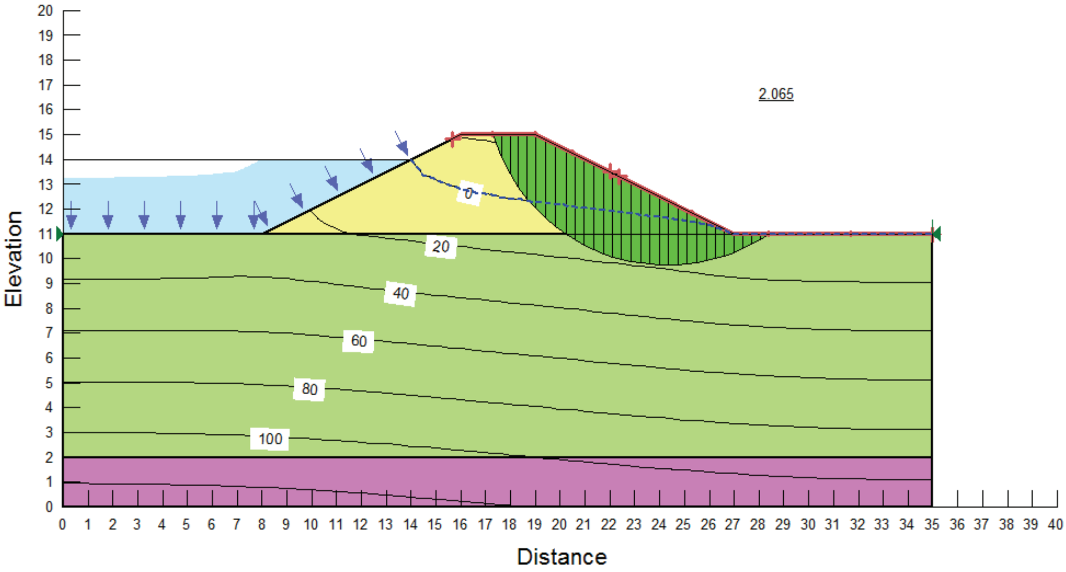

Fig. 2. Contour lines of the pore pressure, the critical slip surface and the factor of safety of a downstream slope (levee 4.0 m in height)

the height of the levees and were 1.5 at the 4.0 m up to 2.0 at the 8.0 m.

It can be stated that the slopes of the levee from bottom sediments were stable at each height assumed. The lowest factor of safety was at the height of 8.0 m – 2.24. In the case of steady-state filtration factors of safety for upstream side were higher, which was caused by the pressure of water, additionally supporting the slope. Because of the seepage pressure significantly lower values of the factor of safety were obtained for downstream slopes. These values were decreasing along with the increase of height of the levee, the lowest value was for the height of 8.0 m – 1.62.

Seepage which occurred at the toe of downstream slope each time is dangerous because of a possible seepage-failure, piping and then landslide. Therefore while using bottom sediments from Czorsztyn-Niedzica Reservoir for a levee, a sealing or drainage at the toe of downstream slope should be designed.

5. RESULTS OF CALCULATIONS USING FE METHOD

In the case of a levee without water filtration is was stable regardless of the levee height. The factor of safety decreased from 2.8 to 2.3 along with the increase in the height from 4.0 to 8.0 m (Table 4).

Stability conditions were significantly worse when a constant damming of water up to the level of 1.0 m below the top of the levee was assumed. As a result of

Table 4. Results of calculations using FEM

Conditions		Factor of safety FS [–] at the height of		
		4.0 m	6.0 m	8.0 m
without seepage flow		2.80	2.49	2.29
steady state seepage flow (water level 1.0 m below the top of the levee)		2.20	1.96	1.81
unsteady-state seepage flow	at the maximum water level (5th day)	2.23	2.00	1.83
	after drawdown (7th day)	2.56	2.28	2.08

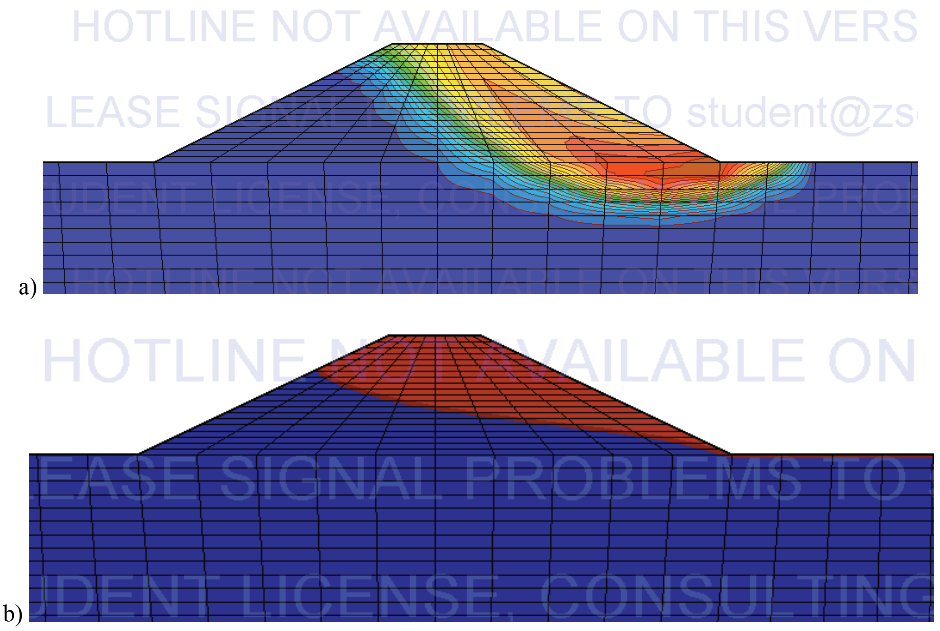

Fig. 3. Displacement amplitude isolines (a) and a seepage line (b) for a levee of 4.0 m in height at the steady seepage flow

Table 5. Results of filtration calculations

Conditions	Maximum seepage Q [m^3/d·m] at the height of					
	4.0 m		6.0 m		8.0 m	
	slope	ground	slope	ground	slope	ground
Steady seepage flow	0.042	6.865	0.109	15.223	0.150	21.492
Unsteady seepage flow	0.067	6.678	0.102	15.053	0.118	20.775

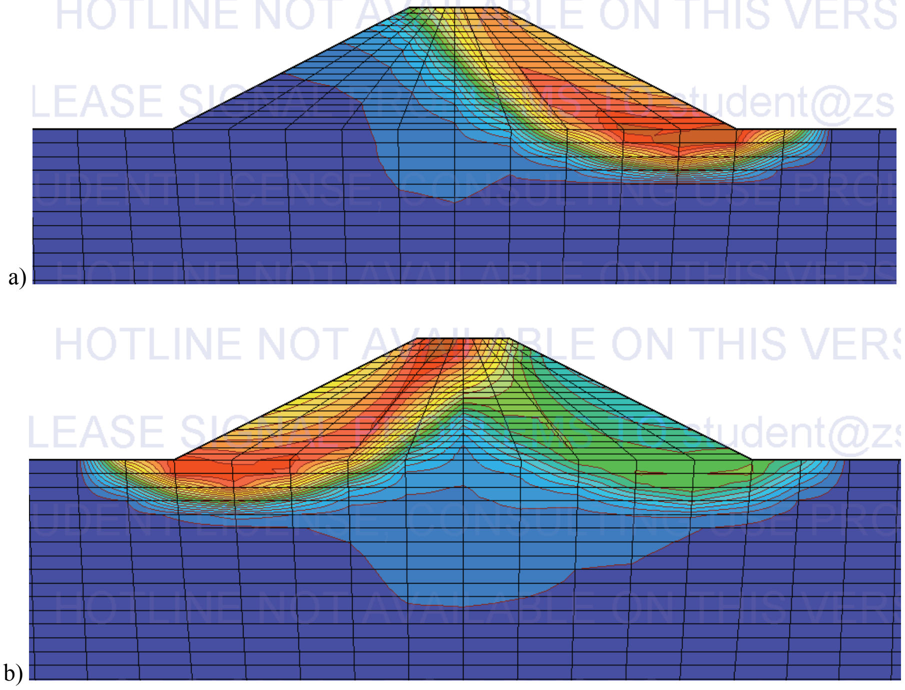

Fig. 4. Results of the slope stability calculations for the unsteady seepage flow: at maximum water level (a) and after drawdown (b) (levee 4.0 m in height)

seepage pressure the factors of safety for the downstream slope were decreasing from 2.2 at the height of 4.0 m down to 1.8 at the height of 8.0 m (Fig. 3). Based on the filtration calculations a position of the filtration curve and the value of seepage on the downstream slope and ground were obtained (Table 5). On the downstream slope there were slight seepages, whereas they were much bigger in the ground. The value of seepage increased from about 6.9 to 21.6 m^3/d·m along with the increase in the levee height from 4.0 to 8.0 m.

Results of calculations with the flood wave simulation showed that the slopes were stable at each height (Fig. 4). During maximum water level (5th day) filtration through the embankment was steady, thus potential slip surfaces were occurring on the downstream slope (values of safety factor were from 2.2 to 1.8 depending on the height), whereas after water level dropped (7th day) they were on the upstream slope (where factor of safety values were a little bit higher, from 2.7 to 2.0). The highest factors of safety were calculated for a levee without damming and the lowest when there was a constant water level. The amount of seepage increased from about 6.7 to 20.9 m^3/d·m along with the increase of the levee height from 4.0 to 8.0 m, although seepage in the slope was slight.

Without water filtration the levee was stable at any height. The obtained values of safety factor were high and over 2.3. Because of the seepage pressure lower values were obtained when steady seepage flow was taken into account during calculations. These values were decreasing along with the increase in the height of the levee, although they fulfilled the requirement set by [5] that factor of safety should be over 1.3. Seepage through the slope and ground on the downstream side, depending on the height of the levee, was from 7 to over 21 m^3/d·m. Calculations with simulation of flood wave passing showed that the levee was also stable, both during the maximum water level and after it dropped. The factors of safety were high and also fulfilled the aforementioned requirement FS $\geq$ 1.3. Seepage on the downstream side occurred at every height and these were slightly smaller than when there was a constant water level. This shows that, like in the case of calculations using Bishop's method, while using bottom sediments from Czorsztyn-Niedzica Reservoir for a levee that will constantly dam water, using sealing or drainage at the toe of the downstream slope should be considered.

6. CONCLUSIONS

Sometimes for dams with significant siltation problems dredging of the stored sediments is the only solution. When it happens these sediments have to be dispense, using them as a construction soil for earthwork purposes can be important from ecological and economical points of view. Before planned dredging tests and usability evaluation should be carried out in order to decide whether sediments can be used for embankments or levees.

Bottom sediments from the backwater of Czorsztyn-Niedzica Reservoir were classified as silty sands, with low permeability, small organic matter content and relatively high values of strength parameters [3]. Calculations of stability and filtration confirmed its usability for levees. Values of safety factor were relatively high, dependent on the height of the embankment and seepage flow. It should be emphasized that even at the height of 8 m the slopes were stable. Although because of seepage on the upstream side a sealing or drainage should be used to keep the line of seepage from emerging on the downstream slope.

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