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CAN MATERIAL PITS IN THE VICINITY OF A POLDER THREATEN ITS SAFETY?

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ABSTRACT

The frequent occurrence of floods recently has motivated discussions by experts on reviewing the safety of flood protection structures. The simulation of flood discharges belongs among transient flow tasks. Due to the randomness of the phenomenon, as well as the often unknown geological composition of the environment in which the flooding occurs, this question has become very complicated. The finite element method (FEM) is one of the methods for reviewing risk factors endangering the stability of hydraulic structures. In this article the application of FEM is mentioned in assessing the stability of the subsoil of the Borša polder in Slovakia.

KEY WORDS

- Flood,
- polder,
- subsoil,
- uplift,
- filtration velocity,
- safety,
- finite element method.

1. INTRODUCTION

Floods have threatened humans for centuries, and their devastating effects often result in the loss of human lives. They also can threaten the quality of life and the environment by inundating houses, apartments, parcels, local roads, state roads, landslides, etc. The evacuation of affected or endangered populations is also not unusual. Therefore, states and municipalities now take several steps to improve this situation and implement flood control measures. One way to accumulate flood discharges is the construction of polders. The Borša polder was built for this purpose. The Borša polder is situated in the East Slovakia lowland, in the district of Trebišov, near the village of Borša at the confluence of the Borša creek with the Bodrog river (Fig. 1).

Fig. 1 Situation.

2. BORŠA POLDER

The purpose of the Borša polder is to catch water from nearby rivers and thus protect the surrounding villages from flooding. Due to changing hydrological conditions in recent years, the polder has become an insufficient capacitive. For example, we quote the SME newspaper dated 24th April, 1998 (translation from the Slovak): “A large inflow from the Borša creek filled the polder (reserve reservoir), and there was a risk of overtopping a flood dyke near the village of Borša. With the consent of the District Flood Commission, the flood protection dyke was therefore breached at a place where the water does not threaten homes.” Negative events (uneven settlement, overtopping of the dyke, seepages, failure of the spillway, breaching of the Borša stream dyke, etc.) were recorded during flood discharges on the circumferential dykes of the polder, on the dykes of the Borša stream as well as on the appurtenant structures. Therefore, in 2007, the reconstruction of the Borša polder, including its circumferential dyke, was proposed (Fig.2). For the proposed reconstruction, a material pit was identified in the space of the existing polder for excavating materials. The material pit's location is apparent from the scheme in Fig. 2. The aim of this article is to present the lessons learned from the risk assessment of the threats to the safety of the polder dykes and the adjacent area due to the mining of the soils from the proposed material pits. The solution was carried out using the FEM. A detailed analysis is provided in Bednářová – Grambličková, 2007.

Fig. 2 Layout of the site.

3. SOLUTION TECHNIQUES

The mathematical solution of the transient flow of the underground and seepage water utilizes the continuity relation and Darcy's law. Three-dimensional numerical models are very difficult to construct from the point of view of creating the model itself and also very time consuming, mainly due to the need to solve multiple alternative tasks. Therefore, a solution in a vertical or horizontal plane is often substituted. For approximating a plane model the following formula for non-stationary groundwater flow is applied (Thomas - Yuan, 1996)

$$\frac{\partial}{\partial x} \left(k_x b \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_y b \frac{\partial h}{\partial y} \right) = (S_v + b S_s) \cdot \frac{\partial h}{\partial t} - q \quad (1)$$

where h is the pressure head (m), b is the saturated thickness (m), k_x , k_y are the filtration coefficients in the direction of the x and y axes respectively ($m \cdot s^{-1}$), t is the time (s), S_v is the specific yield for unconfined aquifers, S_s is the specific storage (m^{-1}), and q is a sink or source term ($m \cdot s^{-1}$). Note that the sign convention for q is positive for a recharge and negative for a discharge.

The finite element method, with the use of SEFTRANS software to permit the simulation of two-dimensional problems in a cross-section, was employed (SEFTRANS, 1996). Simple rectangular 4-node elements were applied. The discretization of equation (1) was applied according to the Galerkin method. The Gauss elimination technique was used to arrive at a solution. The unequivocalness of the equation's solution is determined by the boundary conditions on the border of the area investigated. In the case of an unsteady flow, it is necessary to extend them with the initial conditions. The initial conditions for an unsteady flow may be started from a programme set, which is produced in advance during the computations or ordered directly in the task simulation.

4. ASSUMPTIONS OF THE CALCULATIONS

In Fig. 3 a cross section of the polder together with the arrangement of the structures is presented. The circumferential dyke of the polder is 578 m long; its 3 m wide crest reaches an elevation 100 m above sea level; the inclination of the slopes is 1:2. The distance of the material pit from the right flood dyke of the Bodrog river is 160 m, 25 m from the circumferential dyke of the polder, and about 65 m from the left dyke of the Borša creek. The expected depth of the material pit is 1.8 m (96 m above sea level), with a slope inclination of 1:2.

The surface layers of the area studied (the subsoil of the Bodrog dyke, the circumferential dyke of the polder, and the bottom of the polder) are generally composed of silts and clays with classes MS, CL, and CS. Their thickness is variable, and the filtration coefficient is around $5 \cdot 10^{-8} m \cdot s^{-1}$. Below them loamy sand (SM) is situated, which sometimes changes into fine-grained sands (SF) with

Fig. 3 Characteristic cross section, assumptions of the calculations and safety risk factors for the dyke and adjacent area.

a filtration coefficient at the borders of $1.6 \cdot 10^{-5} \text{ m.s}^{-1}$ to $5.10^{-6} \text{ m.s}^{-1}$. Analyses of the available grain curves demonstrate their susceptibility to suffusion.

The water table is in a direct hydraulic connection with the water level in the Bodrog river. According to the results of the hydrogeological investigation in the area studied, the steadied groundwater level is at a depth of about 2 m below the surface, and on average about 96 m a.s.l. The backwater considered is 4 m above the average water level with a flood duration of 40 days.

As a result of the excavation of the soil from the bottom of the dry polder to a level of about 96 m a.s.l., the existing seepage conditions of the environment will change. Impervious overburden layers with a relatively low filtration coefficient (about 10^{-8} m.s^{-1}) will be excavated at the material pit to a depth of about 1.8 meters; therefore, the seepage paths in the subsoil of the polder will shorten locally. Thus, to assess the safety of the flood protection dyke and the adjacent territory, it was necessary to verify the impact of the designed material pits on the filtration stability for two load cases:

- Under extreme flood conditions in the Bodrog river during floods (towards the dry polder), it was necessary to analyse

the seepage conditions of the right flood protection dyke and its subsoil. The stability of the dry reservoir's bottom with the inlet of the seepage water to the material pits was also observed. The solution was made in profiles "I" marked in Fig. 2 with a dashed line.

- Under an extreme hydrodynamic load (full reservoir of the polder), it was necessary to analyse the seepage conditions in the circumferential dyke of the polder, its subsoil, and the material pits. The solution was made in the profiles "II" marked in Fig. 2 with a dotted line.

5. ANALYSIS OF THE RESULTS

The geological composition of the subsoil (contact of the nearly impermeable overburden layer with the semi-permeable layer) indicates the following potential risk factors (Fig. 3):

- The risk of breaking the overburden caused by the uplift. The matter touched on both the extreme hydrodynamic loading

Fig. 4 Loading of the overburden with the uplift (profile "I", $k_f = 1.6 \cdot 10^{-5} \text{ m.s}^{-1}$).

of the bottom of the polder with the flood discharges in the Bodrog (sections "I") as well as the loading of the overburden layers near the circumferential dykes of the polder during its filling from the Borša stream (sections "II"). Fig. 3 illustrates the most exposed areas of the uplift for the first load state with the numbers 1, 2, and 3; for the second load cases, it is the location labelled "4".

- The risk of suffosion (Fig. 3), given the confirmed presence of sandy soils in the subsoil *susceptible to suffosion*. The analysis of the intensity of the filtration flow was focused in the areas of the Bodrog dyke's subsoil, the bottom of the material pits (profiles "I") and the subsoil of the circumferential dyke of the polder - towards the background - where, as a result of the excavation of the soil in the immediate vicinity of the dyke, the existence of a shortened seepage path is implied.

Uplifts were observed with regard to the height of the backwater and the duration of the flood discharges. In this context, the dominant period is the termination of the flood discharges. The filtration

velocities are due to the maximum intensity of the hydrodynamic loading, which is especially crucial in the early stages of flood discharges; therefore, the analysis of their development was focused on this period.

5.1 Load state – extreme flood discharges in the Bodrog riverbed – profile "I"

The engineering-geological and morphological conditions of the adjacent area considered are shown in Fig. 3. The crest of the Bodrog flood protection dyke is at an elevation of 101.80 m a.s.l.; the predicted flood level in the Bodrog is at 101.30 m a.s.l. Its height above the surrounding terrain is about 3.3 m; according to the available documentation, the inclination of the upstream and downstream slopes of the dyke is 1:2. The bottom of the material pit is at an elevation of about 96 m a.s.l. The development of the underground and seepage water flow was analysed, assuming the coefficient of the permeability of the aquifers in the border $k_f = 1.6 \cdot 10^{-5} \text{ m.s}^{-1}$ to $5 \cdot 10^{-6} \text{ m.s}^{-1}$. Fig. 4 shows the developments over time (10 days, 40 days) of the uplifts acting on the overburden. The overburden's permeability coefficient is $k_f = 1.6 \cdot 10^{-5} \text{ m.s}^{-1}$, which is the

Fig. 5 Time development of the underground and seepage water levels (profile "I", $k_f = 1.6 \cdot 10^{-5} \text{ m} \cdot \text{s}^{-1}$).

most unfavourable situation. The results of the development of the uplift pressure line as compared to the critical pressure horizon (the dashed line) indicate that even under these conditions, conditions do not originate that threaten the stability of the overburden against its breakage. This risk does not arise near the downstream slope of the right-hand dyke of the Bodrog (in Fig. 4, the area marked as "1"), nor does it arise in the area of the material pits (in Fig. 4, the areas marked as "2" and "3"), where the original thickness of the overburden due to the excavation of the soil to a depth of about 1.8 m significantly decreased.

The development of the seepage water levels indicates (Fig. 5) that, during extreme discharges in the Bodrog, a slight increase in the water level can be expected after the tenth day above the bottom of the material pit. This was confirmed by providing the filtration coefficient of the sandy soils as $k_f = 5 \cdot 10^{-6} \text{ m} \cdot \text{s}^{-1}$.

The analysis of the filtration flow at the initial stage of the extreme hydrodynamic loading of the soils was focused on the risky sub-regions, i.e., under the flood protective dyke of the Bodrog and in the vicinity of the material pits. The numerical results indicate that in the assumed geological composition of a subsoil with a filtration coefficient of sandy soil $k_f = 1.6 \cdot 10^{-5} \text{ m} \cdot \text{s}^{-1}$, gradients of less

than 0.2, which are less than the specified critical value of $i_{\text{krit}} = 0.4$, mainly occurred in the subsoil of the flood protection dyke of the Bodrog. A short-term local risk was registered under the upstream toe of the dyke. The reason for this local phenomenon is not the existence of the material pits, but the geological, hydrological and morphological conditions in the area studied. Presumptions of the origin of the internal suffosion were not confirmed in the area of the material pits. The hydraulic gradients calculated here reached values of less than 0.008.

5.2 Load state – full reservoir of the polder – profile "II"

In the profile "II", the parameters of the filtration flow provided by the full reservoir in the subsoil of the polder and its circumferential dykes are analysed, with the water at an elevation of about 99.60 meters a.s.l. As a result of the excavation of the soil from the polder area and the creation of the material pits to a depth of about 1.8 below the current ground level, i.e., to about 96 m a.s.l., the seepage conditions will change. The shortening of the seepage paths from the polder into the adjacent areas underneath the circumferential dyke may result in undesirable phenomena that need

Fig. 6 Loading of the overburden with the uplift (profile "II", $k_f = 1.6 \cdot 10^{-5} \text{ m.s}^{-1}$).

to be explored. They include consideration of the risk of breaking the overburden near the downstream toe of the circumferential polder dykes (area "4" in Fig. 3) and a risk assessment of any internal suffusion.

It should be mentioned that the results of the engineering-geological survey in this area confirmed the local presence of an impervious overburden of a lesser thickness. This weakness has a negative impact on the filtration mode in the subsoil. Moreover, during the excavation of the soil for the reconstruction of the polder, the breaking of the impermeable overburden layer in the area of the bottoms of the material pits can be real. For the reasons outlined, we gave this issue more attention with negative, but realistic, assumptions.

Fig. 6 shows the time developments of the uplifts acting on an overburden, if there is the presence of sandy soils in the subsoil with a filtration coefficient of $k_f = 1.6 \cdot 10^{-5} \text{ m.s}^{-1}$, assuming a water level in a polder at an elevation of 99.60 m a.s.l. When considering the composition of the subsoil and the position of the proposed material pits, the risk of exceeding the critical pressure horizon during a 40-day flood is at the limit of acceptability. In the case of subsoil without material pits, the pressure horizon calculated is well below the critical values. The increase in uplifts in the subsoil to the ac-

ceptance limit is therefore evidence of the influence of the construction of the material pits.

Similar results were also achieved from monitoring the groundwater and seepage water levels. An undisturbed overburden layer of a polder is sufficient protection against the wetting of the downstream toe of a circumferential polder dyke under extreme hydrodynamic stress. With the excavation of material pits, conditions arise for their partial wetting if the duration of a flood discharge is 40 days. This is documented in Fig. 7.

The analysis of the filtration flow indicated that in the subsoil of the circumferential dyke of the polder, locations with the possible risk of internal suffusion occur in the inlet parts of the designed material pits (Fig. 7). The hydraulic gradient here exceeds the permissible value for about 2 days.

The hydraulic gradients calculated did not exceed the critical values in the subsoil of the circumferential dyke of the polder and in the region of the downstream toe of the dyke.

6. CONCLUSIONS

The aim of the presented article is to assess the impact of the excavation of the material pits in the area of the Borša polder on the

Fig. 7 Time development of the underground and seepage water levels (profile “II”, $k_f = 1.6 \cdot 10^{-5} \text{ m.s}^{-1}$).

changes in the filtration mode at the site under an extreme hydrodynamic load. The results of the numerical analysis confirm that due to the excavation of the material pits, the stability of the overburden loaded with the uplift is not threatened during flood discharges in the Bodrog. The thickness of the overburden as well as the location of the material pits is sufficient to guarantee the elimination of this risk. The trend in the development of the filtration velocities and gradient indicates only a local short-term risk to the filtration stability of the subsoil under the toe of the Bodrog dyke. Due to its size, duration (a few minutes) and unlikely conditions for the transport of fine-grained particles to the subsoil, this risk can be considered as almost unrealistic.

On the other hand, the negative impact of the excavation of the material pits on the development of the filtration regime in the subsoil of the circumferential dyke of the polder and the outside of the material pits was confirmed. When the polder is filled, the *risk of the breaking of the overburden layers caused by an uplift* originates on the downstream side of the circumferential dyke. Its elimination can ensure the distance of the material pits from the axis of the circumferential dyke. Given the results obtained, this should not be less than about 30 m.

If the polder is filled to the maximal level with a duration of 40 days, it is highly probable that it is the origin of the *wetting of*

the downstream toe of the circumferential dyke of the polder. The drainage system along the downstream toe was designed to preserve the stability of the downstream slope of the circumferential dyke. Its purpose is to eliminate the risk of the wetting of the downstream toe of the dyke. The results of the numerical analysis also confirmed the existence of the potential risk of internal suffosion generated in the inlet parts of the material pits. Given the verified susceptibility of the sands to suffosion as well as the risk of repeating such loading, the gradual degradation of the material pit slopes towards the upstream toe of the circumferential dyke of the polder cannot be excluded. This should be respected, so the material pit should be excavated with respect to the thickness of the overburden layer or the excavated material pits should be improved to exclude this risk (measures against suffosion).

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