Assessment of the Influence of Mountain Flood Control Reservoir Operation on the Floodplain Stability During an Extreme Flood

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ABSTRACT

Construction of Mountain Flood Control Reservoir is an effective method of flood protection on mountain rivers. The Flood Control Reservoir works under the extreme condition of rapid water level rising and falling. The regime of intensive water level change affects the floodplain stability. Simulation of water penetration into the depth of soil, formation of the seepage curve under transient conditions during water rising and falling was carried out by Midas GTS NX software. A slope stability analysis was conducted for the floodplain of the Irshava River, flood of 1% probability (return period of 100 years) was assumed. Numerous simulations showed that the influence of the mechanical and hydraulic properties of the soil depends on the slope angle. The stability of the floodplain slope depends on the cohesion and hydraulic conductivity for steep slopes greater than 26°; if the slope is less than 26°, the stability is considerably dependent on cohesion, and the hydraulic conductivity practically has no influence. Thus, floodplain with the angle greater than 26°, additional geological surveys are required to determine the soil composition, mechanical and hydraulic properties for each layer. For the slopes lesser than 26° it is sufficient to determine the mechanical and hydraulic properties for the engineering and geological elements of soil, according to the national building regulations. Numerical simulation allows reducing the total volume of geological survey by minimizing survey of the slopes with an angle of less than 26°, which is 30% of the floodplain perimeter. The slope stability analysis showed that the slopes with the angle greater than 26° require stabilization structures in the lower part of floodplain before the Mountain Flood Control Reservoir construction.

Keywords: mountain flood control reservoir, seepage curve, unsaturated seepage, transient seepage analysis, slope stability.

INTRODUCTION

The settlements in the Tisza River Basin (territory of Ukraine) periodically suffer from extreme floods. The peculiarity of the Tisza river flood is the significant flow rate lasting 3–5 days. The average rate of the level rising during flood is 0.5–0.7 m/day for small rivers and 1.5–3.5 m/day for medium and large ones. The water level falls slower than it rises. The construction of Mountain Flood Control Reservoir is proposed to protect the settlements in the Tisza River Basin, which transform the destructive flood flow of 1% probability to Channel-Flow. Channel-Flow is estimated as flow of 5% to 35% probability for the Tisza River

Basin [Obodovskyi et al. 2019]. The principle of the Mountain Flood Control Reservoir operation is that the flow which is less than Channel-flow, pass through the dam without transformation and most of the time the Reservoir stays dry. During the extreme floods, part of the runoff stores in the Reservoir for a short time of not more than 8-10 days, during which the reservoir is gradually emptied [Velychko et al. 2014].

The flood water level rises and then drops rapidly. Thus, the water penetration into the soil of the floodplain banks will be partial, the steady state seepage will not have time to form, and transient seepage will take place. The depth of water penetration into the soil will affect the stability of

the floodplain banks when the water level drops. When the water level drops in the saturated soil, a decline curve is formed because of water lag time, and excess pore pressure can lead to the bank destruction [Alfatlawi et al. 2020]. A slope stability decrease is noted also in the works by [Xue et al. 2016, Acharya et al. 2016, Duong et al. 2019, Liu et al. 2015] that is related to the penetration of water into unsaturated soil during the rain. Water penetration into the soil depends on the geological structure of floodplain banks. The bank with low water permeability loses stability if it contacts with water for the long time, if the bank soil has higher water permeability, the pore pressure increases and decreases rapidly making these soils less stable [Tofani et al. 2006].

The dangerous landslide processes criteria are the physical and mechanical parameters of soils, hydraulic conductivity, soil infiltration rate, slope and the water level drop rate [Mao et al. 2019].

The transient seepage analysis requires additional parameters of unsaturated soil: water content function, hydraulic conductivity function, residual water content. Finite element simulation enables to realistically describe the pore pressure change during the transient seepage analysis and estimate the slope stability. Not all soil parameters make a significant impact on the slope stability in unsaturated soils, but the pore pressure fluctuations influence the slope stability and cause slope destruction [Li et al. 2019, Hu et al. 2019]. In the work [Nam et al. 2014] it was noted that the hydraulic conductivity has a significant impact on the location of phreatic surface, unlike the volumetric water content function, which can be determined by the particle size distribution of the soil without losing the accuracy of calculations. In the work [Huang et al. 2017], the factor of safety was studied for the soil with different hydraulic conductivity and water level drop rates: the factor of safety decreased significantly at low hydraulic conductivity (0.004 m/hour), but almost did not depend on the water level drop rate, if the hydraulic conductivity was higher than 0.2 m/hour; the slower water level reduces the more stable slope. Studies conducted by the authors in different ranges of physical and mechanical properties of local soils and slopes allow us to identify the general trends, but to predict the slope stability under transient conditions, it is necessary to use numerical simulation.

Forecasting the possibility of dangerous landslides during Mountain Flood Control Reservoir operation with intensive rising and then dropping of water level in the Carpathians Mountains is an urgent task that will ensure reliable flood protection.

The purpose of the work was to analyze the factors influencing the slope stability of the floodplain, and to assess the possibility of dangerous landslides in the Mountain Flood Control Reservoir under the conditions of water penetration into unsaturated soils with the next seepage during water level dropping in the Carpathian Mountains.

MATERIALS AND METHODS

Model and soil properties

The Mountain Flood Control Reservoir is planned to be located on the Irshava River in the Transcarpathian region. The slopes forming the Irshava River floodplain are mostly gentle with angle of 5–10° on the left bank and with the maximum angle of 33° on the right side. The area of floodplain was divided into sections with similar soil properties and thickness of the alluvial-diluvial deposits. The right bank has the largest angle of 33° near the dam, the farther from the dam, gentler the slope becomes, up to 26°. The left bank is more sloping, the maximum angle is 18°, the example of the floodplain section is shown in Figure 1.

The bedrock is andesite, basaltic andesite and tufa (shown (3) in Fig. 1), it is cracked on the top. The bedrock is covered with Quaternary deposits of 1 to 5 m depth. There are modern alluvial boulder-pebble deposits (shown (1) in fig 1) in the river channel, and there are clay layers (shown (2) in Fig. 1) on the floodplain banks. Clay soils are classified as SC according USCS. The mechanical soil properties were obtained as a result of field survey and laboratory processing of the samples. The samples taken from the floodplain banks have homogeneous structure: specific gravity of 19.6 kN/m³, the porosity is 0.58, the cohesion is 25–16 kPa, the internal friction angle is 23°, hydraulic conductivity is 0.07 m/day. Visual inspection of the floodplain banks did not reveal any landslides on the area of the Mountain Flood Control Reservoir. In order to study the effect of hydraulic conductivity and cohesion on slope stability, the samples of silty sands soil were taken below the dam with hydraulic conductivity of 0.48 m/day, the cohesion is 8 kPa, which is classified as SM.
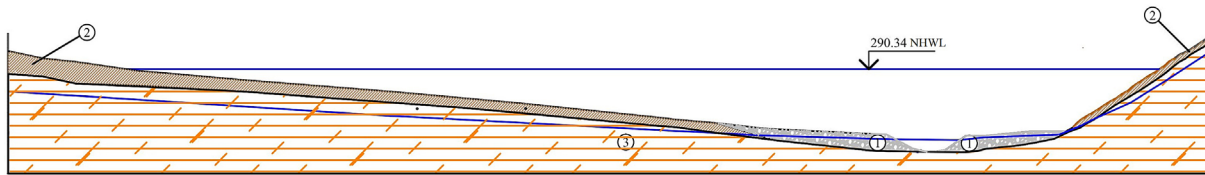
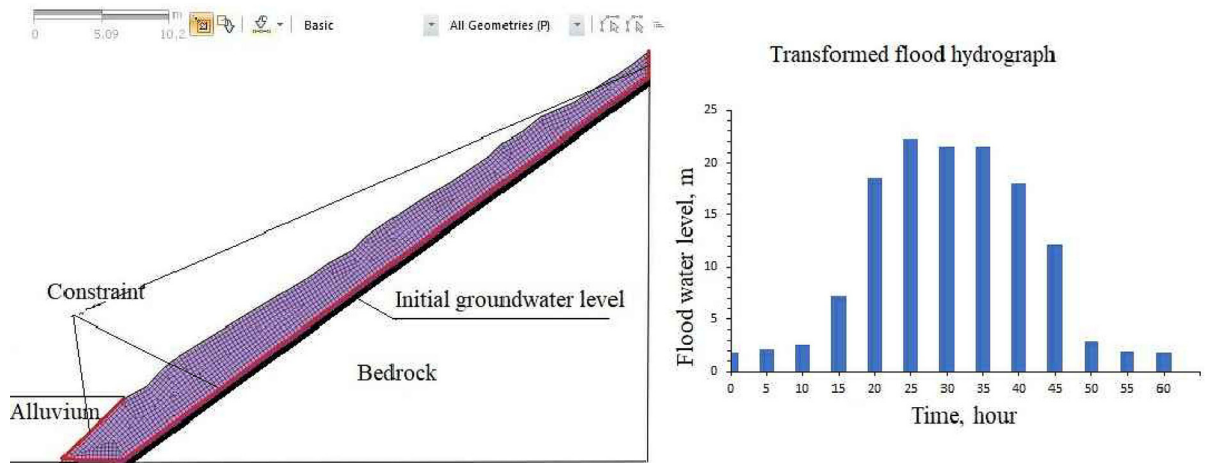**Figure 1.** Cross section of floodplain near the dam

Figure 2. 2D model of floodplain bank and its boundary conditions

The floodplain banks with angles of 33°, 26° and 18° were created in a 2D model, the slopes with angles less than 18° are stable in clay soils and have not been considered in the work. The floodplain banks were divided into finite element mesh with the size of 0.3×0.3 m (Fig. 2).

In order to simulate the flood phenomena on the Irshava River, a hydrograph of the flood flow of 1% probability (return period of 100 years) was taken in calculations with the maximum flow of 181 m³/s.

The water level rising from low water to the maximum occurs in 12.4 hours, the water level falls somewhat slower. The transformed water level stays at the maximum levels for a period of 15 hours, after which it begins to fall during the Reservoir operation. The transformed flood water levels in the Reservoir are shown in the Figure 2.

Some assumptions were made:
- the slope collapses as a single layer;
- soil model is Mohr–Coulomb;
- the boundary condition of constraint is located on the top of the bedrock and the border of alluvium deposits;
- the soil is homogeneous and isotropic, which is quite acceptable for clay and loam soils according to research [Yeh et al. 2018];
- the bedrock was taken as not deformed and saturated, the initial groundwater level was situated on the top of the bedrock;
- the water level fluctuation in the Reservoir was taken as transformed flood hydrograph (shown in Fig. 2) and was applied to the surface of the soil bank;
- the unsaturated soil properties were based on the hydraulic conductivity function and water content function, which were taken the same for slopes with different angles;
- infiltration into the soil of the floodplain banks was transient.

Simulation of the Mountain Flood Control Reservoir operation under transient condition

Transient seepage analysis in the banks soil was performed by using the Midas GTS NX software package using semi-coupled Seepage-Stress-Slope analysis. In this software package, the Darcy's Law is solved by means of the finite element method:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial H}{\partial y}\right) = \frac{\partial \theta}{\partial t}, \qquad (1)$$

where: H – total head, m;

k_x, k_y – hydraulic conductivity in the horizontal and vertical directions, respectively, m/s;

Q – boundary discharge, m³/s;

θ – volumetric water content, m³/m³;

t – time, s.

The soil-water characteristic curve (SWCC) can be determined on the basis of experiments [Elkady et al. 2017; Peranych et al. 2018], or determined using theoretical models: Carsel and Parrish [Carsel et al. 1988], Van-Genuchten [Van Genuchten, 1980], or by Fredlund and Xing`s method using grain size distribution [Fredlund et al. 1994]. The main unsaturated soil properties, which were taken for the transient seepage analysis are presented in Table 1.

Since the sliding surface along the bedrock cannot be cylindrical, it is possible to use either Limit Equilibrium method with the polygonal potential failure surface or the Strength Reduction Method (SRM) to assess the slope stability. The SRM enables to model close to the real form of failure surface without predefined potential failure surface that is an advantage over other methods [Seyed-Kolbadi and al. 2019].

The floodplain slope stability was evaluated by using the Strength Reduction Method based on a gradual reduction of the strength parameters until the slope reaches limit equilibrium state. The minimum value of the Safety Factor (SF) was determined using the Mohr-Coulomb yield criterion:

$$SF = \frac{c + \sigma_n tg\varphi}{\frac{c}{SRF} + \sigma_n tg\varphi_f} \qquad (2)$$

$$\varphi_f = tg^{-1}\left(\frac{tg\varphi}{SRF}\right) \qquad (3)$$

where: *SF* – Safety Factor;
φ, φ_f – original and reduced internal friction angle, respectively, °;
c – original cohesion, kPa;
SRF – Strength Reduction Factor.

In order to avoid overestimation of the Safety Factor due to the negative pore pressure, the metric suction limit equal 0 kPa was accepted.

RESULTS AND DISCUSSION

The seepage curve locations in the heavy clay soil (SC) slope with the saturated hydraulic conductivity of 0.07 m/day are shown in Fig. 3A, C, E during the period of the water level dropping in the Mountain Flood Control Reservoir. The simulation results for silty sand soil (SM) with the saturated hydraulic conductivity of 0.48 m/day are shown in Fig. 3B, D, F. The simulations show that in heavy clay soils with low penetration, that are typical for floodplain of the upper part of the Irshava River, moisture occurs in the top soil layer and the water obtain the sliding surface, which is located at the contact of the bedrock, only in the lower part of the slope. The steeper the slope, the smaller the contact area of the water and bedrock: if the slope angle is 33°, the contact area is 20% of the slope; and for the slope angle of 26° and 18° the contact area is 35% of the slope height. In the soils with the saturated hydraulic conductivity of 0.48 m/day, water quickly penetrates into the soil and saturates the slope during the period of water rising, the soil saturated rate is not dependent on the slope angle.

The results of the Safety Factor calculations by SRM are shown in Figs. 4, 5, 6 for the steep slope near the dam, for the slopes with the angles of 26° and 18°, respectively. As can be seen from Fig. 4 for the floodplain slope of the Irshava river with the angle of 33° and the cohesion of 25–16 kPa with the hydraulic conductivity of 0.07 m/day the slope is stable and the minimum SF is 1.44. The presence of silty sands (SM) in the slope with lower values of cohesion of 8.0 kPa leads to the slope sliding. The SF increases slightly when the water rises in the Reservoir at the beginning of the flood and drops to the initial values when the water falls in the Reservoir. The higher value of the hydraulic conductivity leads to full saturation of the slope soil and reduces the stability of the slope.

The slope stability is almost independent of the hydraulic conductivity and largely depends on the soil mechanical properties (cohesion) if the slope angle is less the 26° (Fig. 5), the majority of the floodplain banks inside Mountain Flood Control Reservoir have such slope angle.

Table 1. Hydraulic soil properties

Material properties	Type of soil SC	Type of soil SM
Volumetric water content, θ_s, m³/m³	0.396	0.434
Residual volumetric water content, θ_r, m³/m³	0.13	0.218
Empirical constant, α, 1/m	2.4	2.0
Empirical constant, n	2.06	2.76
Saturated hydraulic conductivity, m/day	0.07	0.48
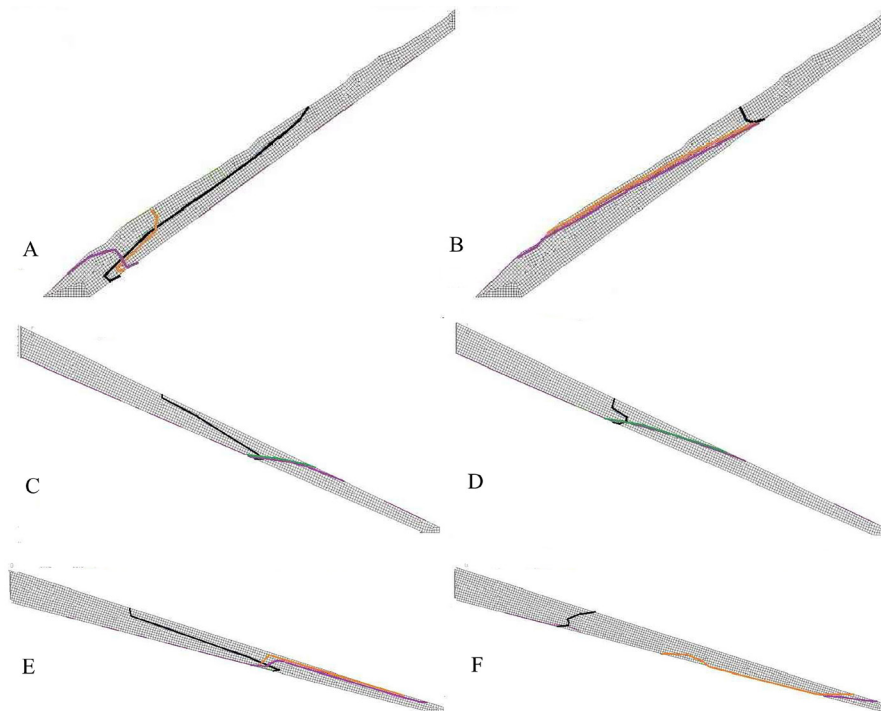
Figure 3. The seepage curves position in the slope during the period of water dropping in the Reservoir for two soil types: with hydraulic conductivity of 0.07 m/day (A, C, E) and 0.48 m/day (B, D, F) the slope angles of 33° (A, B), 26° (C, D) and 18° (E, F): 40 hours of the flood (black line), 50 hours (orange) and 60 hours (violet)
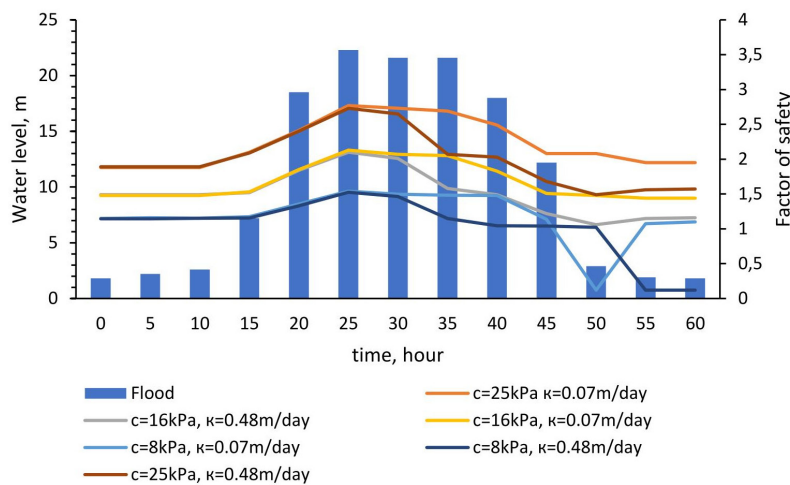
Figure 4. Safety Factor for the slope with angle of 33° depending on the cohesion and the hydraulic conductivity

The soil with low cohesion has minimum Safety Factor of 1.13. The slope angle reduction to 18° leads to the SF increase, the stability of the slope is provided even for the soils with high hydraulic conductivity up to 0.48 m/day (fig. 6). Slope stability is almost independent of the hydraulic conductivity. As the water rises, SF increases due to the stabilizing force of the hydrostatic water pressure on the slope.

Thus, the analysis of the slope geometry, hydraulic and mechanical properties of floodplain showed that the soil cohesion, the hydraulic conductivity and the slope angle have a significant impact on the slope stability. The steep slopes with angle greater than 33° are dangerous, especially if they are composed of silty sand layers. The slope stability decreases sharply at 50 hours of the flood, when the water level in the Reservoir drops to low position, the sliding surface is formed in the lower part of the slope at a height of 1.0–2.5 m above the level of alluvial deposits (Fig. 7). For such slopes, it is necessary to
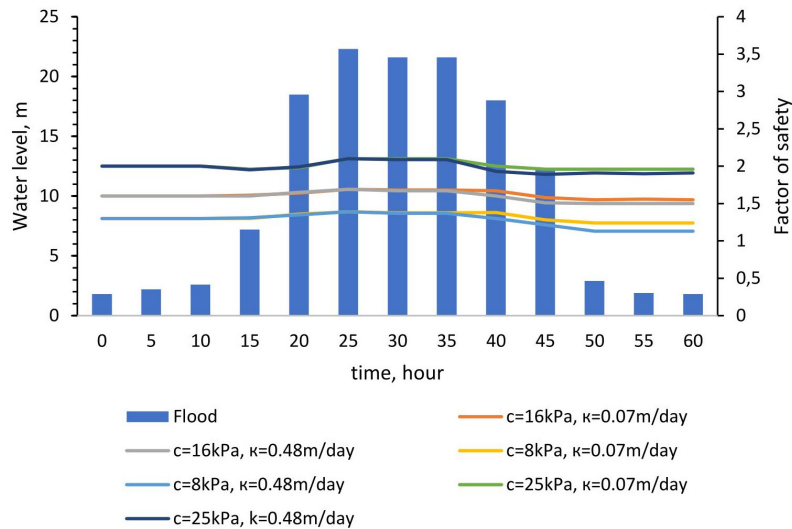
Figure 5. Safety Factor for the slope with angle of 26° depending on the cohesion and the hydraulic conductivity
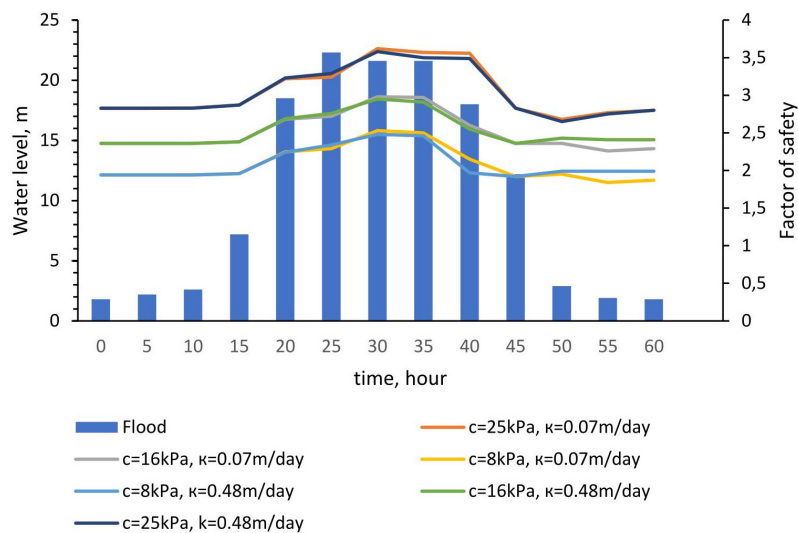

Figure 6. Safety Factor for the slope with angle of 18° depending on the cohesion and the hydraulic conductivity

perform additional surveys along the length of the slope to identify weak soil layers and its hydraulic conductivity as well as to perform calculations based on the updated data.

The slope stability with angles less than 26° does not depend on soil hydraulic conductivity, and is caused by the mechanical properties of soil; therefore, it is necessary to investigate the existence of weak soils which can influence stability of the slope, and if necessary, to stabilize the lower part of the floodplain bank.

The slopes with the angle of less than 18° are stable even in the presence of soils with high hydraulic conductivity, so their hydraulic and mechanical properties can be generalized and do not require additional surveys and calculations, which will reduce the cost of geological survey work.

CONCLUSIONS

On the basis of the presented simulation, the following conclusions can be drawn:

Flood water seepage into the floodplain soil during the Mountain Flood Control Reservoir operation is transient, so the soil hydraulic properties should be taken into account for the correct simulation of the seepage.

The most dangerous sliding surface is situated on the contact area between the clay soil and the bedrock. The Mountain Flood Control Reservoir operation affects the slope stability, but due to short-term water rise and fall in soil with the hydraulic conductivity of 0.07 m/day, water does not have time to penetrate deep into the soil and reach the sliding surface, so SF is reduced at the 45–50 hours of flood. The bottom of the sliding
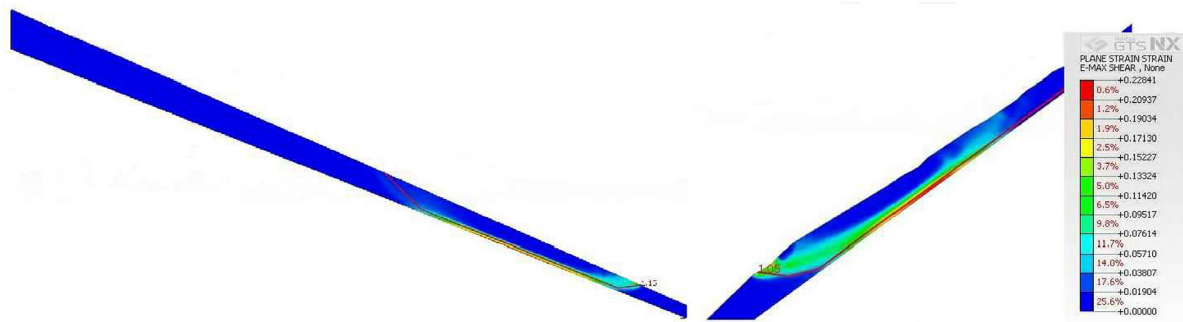
Figure 7. Sliding surface location on the slope with the angle of 26° (left) and 33°(right)

surface is located at the height of 1.0–2.5 m above the ground.

The sandy layer with hydraulic conductivity of 0.48 m/day leads to quick soil saturation, which reduces the Safety Factor. Particularly significant reduction of SF and slope destruction is observed for the slope with an angle of 33°. When the slope angle is less than 26°, hydraulic conductivity does not affect the slope stability of the floodplain banks.

Numerical simulation allows performing accurate slope stability analyses. Additional geological surveys should be carried out for floodplain slopes with the angles greater than 26° to identify weak layers with high hydraulic conductivity.

For the slopes with angles lesser than 26°, it is sufficient to determine the generalizing soil mechanical properties according to building regulations, as the stability of such slopes depends on soil cohesion.

Since the geological structure of the slope under natural conditions is not homogeneous, and silty sand layers with high hydraulic conductivity may occur in small quantities, the slopes with the angle greater than 26° need stabilization at the slope foot before the Mountain Flood Control Reservoir construction.

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