The Stability Analysis of a Cofferdam Using the Numerical Modelling

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Abstract. The foundation of the bridge pillars required the construction of cofferdams in the Danube River. The cofferdams protected the area of the excavation pit mainly against the effects of flowing water. The paper includes analysis of the cofferdam for the foundation of the main central pillar of the asymmetrical bridge. The cofferdam has the ground plan dimensions of 44 x 20 m. It’s constructed of the double-row sheet pile walls. The stability of the cofferdam was analysed using numerical modelling based on the finite element method using Plaxis geotechnical software. The level of backfilling inside the cofferdam, required for construction of the foundations, was 6 m above the bottom of the river. The depth of the excavation pit of the cofferdam was about 4 m below the river bottom. The numerical model included 15 construction phases, which corresponded to the procedure of the construction. The analysis were focused mainly on construction phases, such as, e.g., the total backfill of the cofferdam, the loading from the piling rig, creating the excavation pit inside the cofferdam and installation of struts, and the load from the maximum level of the Danube River. The analysis showed that there are two critical phases. The first critical phase represents the situation when the piling rig works near the edge of the cofferdam, and the Danube River is at a minimal level. The second critical phase occurs when the full excavation pit created, and the Danube River is at a maximum level.

1. Introduction

Cofferdams are temporary structures used in the foundation of constructions that are in the contact with water. Cofferdams made of sheet-pile walls are often used in the foundation of bridge piers in the river. The design of these structures is usually very difficult, and verification of their stability is given mainly by the interaction of various materials such as steel, concrete, soil, and water. Modelling the interaction of individual materials and their behaviour is one of the most difficult geotechnical tasks. Typical geometries of cofferdams were published by, e.g., [1]. An example of the design and construction of a cofferdam was presented by, e.g., [2, 3]. Analytical calculation models usually do not allow taking into account the construction of the cofferdam as one complex and selected parts of the cofferdam must be assessed individually. Typical verification includes verification of internal stability, verification of global stability, and verification of achieved deformations. The most appropriate method for designing the cofferdam structure is numerical modelling based on FEM (Finite Element Method). This method allows us to simulate the construction process and monitor changes in deformations and the stress state. Numerical analysis of a cellular cofferdam was presented by, e.g., [4, 5]. Hansen and Clough [4] were the first who applied the plane-strain analysis of a vertical slice cut...
through the cofferdam. Clough and Kuppusamy [5] analysed two-dimensional numerical modelling of a cellular cofferdam using the axisymmetric model, vertical-slice model, and generalized plane-strain model. They used Duncan-Chang hyperbolic material model [6] to simulate soil behaviour, which allowed for better interpretation of results. They also stated that the $E$-ratio concept provides a useful alternative approach to allowing increased horizontal flexibilities in the sheet-pile system. In general, it can be stated that the wrong modelling procedure and the use of simple material models, such as, e.g., linear elastic, or linear elastic-perfectly plastic, can lead to incorrect interpretation of the results obtained. A comparison of material models in the numerical modelling of retaining structures was presented by, e.g., [7]. The results of their study can also be assumed and interpreted for numerical modelling of the cofferdams. Current geotechnical software, e.g., Plaxis, allows the use of advanced material models, such as the Hardening Soil model [8] and Clay hypoplastic model [9]. The numerical analysis of the cofferdam using the Hypoplasticity Clay Model was presented by, e.g., [10].

The article deals with the numerical analysis of the cofferdam required for a foundation of a central pillar of the new bridge over the Danube River. The bridge has a length of 600 m and connects Slovakia with Hungary between cities Komarno and Komarom. The numerical modelling was done using Plaxis geotechnical software. The numerical analysis allowed verification of the cofferdam for all construction phases. Different lengths of the sheet-pile walls and different geometry of sealing of the bottom were also analysed to verify possible alternatives of the cofferdam geometry.

2. Geological conditions of the area of interest
The area of interest is formed by massive terraces formed by the stream of the Danube River. The subsoil consists mostly of fluvial sediments formed mica-silica sands with a low content of calcium. The geological survey was carried out for both pillars on the Slovak as well as the Hungarian side. Geological boreholes were also made directly in the Danube riverbed to determine depth of each soil layer. The subsoil consists of clays of firm consistency and cemented silts to a depth of about 4 m below the surface at the place of the central pillar. Below this soil layer, there is fine sand up to a depth of 16.5 m. Below a depth of about 16.5 m, there is a more stiff subsoil consists of sand, clays, and sandy silt. Beneath these consolidated sediments, which are to a depth of 20 m, there is grey sand with the content of organic clay. To a depth of 31.5 m, the soil was of the same character, penetrated by layers of grey clay. The geological survey used for the study was given by [11].

3. Design of the cofferdam
The cofferdam for the foundation of the central pillar had dimensions of 44 x 22 m. It was made of a double sheet-pile wall of a VL606 type. Outer and inner sheet-pile walls have an axial distance of 1.2 m and are connected using rods. The space between the outer and inner sheet-pile walls above the riverbed is filled with concrete. The inner sheet-pile wall has a length of 19 m, of which 6.5 m is embedded into the subsoil below the riverbed. The length of the sheet pile wall of 12.5 m was loaded by the water pressure and geostatic stress from the backfill. The outer sheet-pile wall had a length of 20.3 m to serve as protection against high water levels. The construction of the cofferdam was supported with struts installed in two layers. The axial distance of struts was 6.85 m. The subsoil of the cofferdam was improved using the jet grouting. The thickness of the improved soil was about 2 m. This layer increased the stiffness of the subsoil and prevented the inflow of water into the excavation pit. The stiffness of the sandy layer immediately below the excavation pit was also improved using a jet-grouting layer of a thickness of 1 m.

The first step of the construction of the cofferdam was the installation of the sheet-pile walls, their connection using rods, and concreting the space between them. The concreting was executed in four steps with a height of 1.7 m to prevent excessive deformations of sheet-pile walls. In the next step, the space inside the cofferdam was filled by a backfill made of coarse-grained soil. This allowed placing
the piling rig and the jet-grouting rig to create the pile foundations and the improved soil layers. A view of the cofferdam with the piling rig is shown in figure 1.

![Figure 1. The cofferdam with piling rig creating the pile foundations](image1)

The next step was creating the excavation pit inside the cofferdam for the foundation of the pillar. The excavation was executed in three steps. The struts were installed immediately after excavation steps 1 and 2. The water inside the cofferdam was pumped continuously together with the excavation of the soil. A view of the cofferdam with created excavation pit, during the concreting of a foundation slab, is shown in figure 2.

![Figure 2. The cofferdam after creating the excavation pit](image2)
The cofferdam had to be designed for two basic design situations, i.e., filling the cofferdam with the backfill and excavating the pit inside the cofferdam. These basic situations were the most critical for the design of all construction elements, but the numerical modelling included verification for all construction phases.

4. Verification of the stability of the cofferdam using numerical modelling

The numerical modelling was done using Plaxis 2D 2011 geotechnical software. The model was created as a plane strain model for a cross-section in the middle of the cofferdam. The dimensions of the whole model were 40 x 60 m. Because of the symmetry, only one side of the cofferdam could be modelled. The 15 node triangular elements were used. The soils were modelled using the hardening soil material model. The properties of soils were determined based on the results of the engineering geological survey. The properties of soil improved using jet grouting were determined on experiences from its previous practical applications in similar soils. The concrete was modelled only using a linear elastic material model, which was sufficient for a given type of material and estimated stresses. The properties used in numerical model are summarized in table 1.

| Material model | Concrete | CS | Jet-grouting | S-F | Stone backfill | Backfill |
|----------------|----------|----|--------------|-----|----------------|---------|
| Drainage type  | LE       | HS | drained      |     | drained        |         |
| \( \gamma \) (kN.m\(^{-3}\)) | 23       | 19 | 20           | 18  | 20             | 19      |
| \( \gamma_{int} \) (kN.m\(^{-3}\)) | -        | 19 | 20           | 18  | 20             | 19      |
| \( E \) (MPa) | 35000    |    |              |     |                |         |
| \( \nu \) (-) | 0.2      |    |              |     |                |         |
| \( E_{ult}^{ref} \) (MPa) |         | -  | 24.19        | 444 | 115            | 222     |
| \( E_{ref} \) (MPa) | -        | 72.57 | 1332       | 345 | 666            | 345     |
| \( m \) (-) | -        | 0.7 | 0.9          | 0.5 | 0.5            | 0.5     |
| \( c' \) (kPa) | -        | 15  | 35           | 0   | 0              | 0       |
| \( \varphi' \) (°) | -        | 24  | 40           | 30  | 40             | 35      |
| \( \psi' \) (°) | -        | 0   | 10           | 0   | 10             | 5       |
| \( k_s = k_t \) (m.day\(^{-1}\)) | -        | 0.0864 | 0.00864   | 0.0864 | 864            | 0.864   |
| Interface | 0.8      | 0.8 | 0.8          | 0.8 | 0.8            | 0.8     |

Each sheet-pile wall was modelled as an elastic plate with axial stiffness of 4200 MN.m\(^{-1}\) and bending stiffness of 110500 MNm\(^2\).m\(^{-1}\). The rod connecting the outer and inner sheet-pile walls was modelled as an elastic anchor with the stiffness of 103.1 MN and spacing 1.2 m. The struts were modelled as anchors with elastic axial stiffness of 2940 MN and spacing of 6.85 m.

The numerical model included 15 construction phases, which simulated the construction process. The cofferdam had two different functions. The first function marked as "backfill" represented the design situation when the cofferdam is filled by the backfill, and the piling rig works near the edge of the cofferdam. To verify the most critical situation, in this case, the Danube River was estimated at the lower level. The second function was marked as "excavation" and represented the situation when the excavation pit inside the cofferdam is created. The most critical phase represented the state when a full depth of the excavation pit is achieved, and the Danube River reaches the highest level. The two main design situations and corresponding construction phases were defined as follows:

- A, Design situation “backfill”;
  - Phase No. 1 - Initial stress state,
  - Phase No. 2 - Installation of the sheet-pile walls,
  - Phase No. 3 - Installation of rods between outer and inner sheet-pile walls,
  - Phase No. 4 - Concreting the space between outer and inner sheet-pile walls,
Phase No. 5 - Decreasing the level of the Danube River to its minimum level,  
Phase No. 6 - Filling the space of the cofferdam with the backfill,  
**Phase No. 7 - Loading from the piling rig (the most critical),**  
Phase No. 8 - Improvement of the subsoil using the jet-grouting.  

- B, Design situation “excavation”;  
  Phase No. 9 - Increasing the level of The Danube River to its average level,  
  Phase No. 10 - Excavation to the depth below the level of upper struts,  
  Phase No. 11 - Activating the upper struts,  
  Phase No. 12 - Excavation to the depth below the level of lower struts,  
  Phase No. 13 - Activating the lower struts,  
  Phase No. 14 - Excavation to the full depth,  
**Phase No. 15 - Increasing the Danube level to its maximum level (the most critical).**  

Scheme of the numerical model for phase No. 7, loading from the piling rig, is shown in figure 3. In the first verification of this phase, because of the loading from the piling rig, the sheet-pile walls had extensive deformations. Due to this reason, the stone backfill around the outer sheet-pile wall was designed. This caused a decrease in horizontal deformation of the sheet-pile wall from about 30%. The level of the Danube River was defined at its minimum level because the stress from the water acting favourably. The horizontal deformations determined using numerical modelling are shown in figure 4 (left). The deformed mesh (deformed model) is shown in figure 4 (right).  

Scheme of numerical model for phase No. 15, full excavation pit with increasing the Danube River level to its maximum level, is shown in figure 5. The level of The Danube River was defined at the maximum level to which the cofferdam must withstand. In the case of higher flood water level, the design considered the flooding of the cofferdam.

![Figure 3](image1.png)  
**Figure 3.** A scheme of the numerical model of the cofferdam for phase No. 7
The horizontal deformations determined using numerical modelling are shown in figure 6 (left) for phase No. 15. The deformed mesh (deformed model) is shown in figure 6 (right).
The numerical analysis of the cofferdam allowed for determining the internal forces for all structural elements in each construction phase, i.e., axial forces in rods and struts, and bending moments in sheet-pile walls. Horizontal deformations and bending moments of the inner sheet-pile wall, for selected phases, are given in figure 7. The phases Nos. 1 - 5 are construction phases when the deformations and forces are negligible.

Figure 6. Horizontal deformations of the cofferdam - left; deformed mesh (deformed model) - right; after construction phase No. 15

Figure 7. Horizontal deformations (left) and bending moments (right) for inner sheet-pile walls for selected construction phases
The deformations began to increase from phase No. 6, and the biggest deformations were achieved in phase No. 7 when the piling rig moved along the edge of the cofferdam. These deformations were in the direction out of the cofferdam. Subsequently, the subsoil was improved using jet grouting, and the construction pit was excavated. The deformations and forces gradually changed in each construction phase. Phase No. 14 represented the situation, which will occur the most time during the full excavation and construction of the pillar. Phase No. 15 represented the most critical situation, which can occur when the level of the Danube River increased. The maximal horizontal deformation of the inner sheet pile wall, in the direction out of the cofferdam, was about 67 mm - reached in phase No. 7. The maximal deformation in the direction into the cofferdam was about 38.4 mm - reached in phase No. 15. The highest value of the bending moment was about 295 kNm - reached in phase No. 15. The highest forces in struts were achieved in phase No. 15. The forces were equal to 1358 kN in the upper strut and 3911 kN in the lower strut.

5. Changes during the execution of the cofferdam

During the construction of the cofferdam, there were problems with the driving of the sheet-pile walls. Some sheet-piles could not be driven to the required depth, due to the high strength of the cemented layers of sand, which in some places had the character of sandstones. Because of this, it was necessary to verify the stability of the cofferdam under changed boundary conditions. Based on the expected changes, three alternative models were created for verification of the stability of the cofferdam. The schemes of the numerical models for these alternative models are shown in figure 8. Alternative A assumed that the sheet-pile walls would be 2 m shorter. The lower layer, improved by jet-grouting, was moved 2 m higher so that it was at the level of the bottom of the sheet-pile walls. Because the upper and lower layers improved by jet-grouting were close to each other, the modified shape of the soil improvement was verified. The modified shape of the soil improvement assumed that only the bottom layer of the soil improvement would be formed at a depth of 2 m. It was also recommended to improve the soil along the inner sheet-pile walls to prevent flowing of water into the space of the cofferdam in a place where the sheet-pile walls will not be deep enough. For this shape of soil improvement, the two alternative lengths of sheet-pile walls were verified, see alternatives B and C in figure 8.

![Figure 8. Horizontal deformations (left) and bending moments (right) for inner sheet-pile walls for selected construction phases](image)

The horizontal deformations of the inner sheet-pile wall, for alternative models A - C, are shown in figure 9. The deformations are presented only for the most critical phases (Nos. 7 and 15). Alternative A takes into account soil improvement in two layers as the original model. The results showed that the deformation of sheet-pile walls in phase No. 7 increased, but in phase No. 15 decreased, in comparison to the results of the original model. The results also showed that the change of shape of the soil
improvement has no impact to deformations in phase No. 7. The change of shape of the soil improvement caused that the subsoil inside the cofferdam is stiffer, and because of this, the deformations in phase No. 15 are smaller. The highest deformation for phase No. 7 was determined in alternative C. The highest deformation for phase No. 15 was determined in the original model geometry.

Figure 9. Horizontal deformations (left) and bending moments (right) for inner sheet-pile walls for selected construction phases

6. Conclusion
The temporary cofferdam for a foundation of the central pillar of the bridge, between Komarno and Komarom cities, was designed from double sheet-pile walls supported by struts in two levels. The stability of the structure was verified using the numerical modelling based on the finite element method. The numerical modelling was done using the Plaxis 2D geotechnical software. The numerical model included 15 construction phases, which corresponded to the construction process of the cofferdam. The cofferdam had two main design situations, which corresponded to its two functions. The first design situation represented the state when the cofferdam is filled by backfill and loaded by the piling rig (construction phase No. 7). The second design situation represented the state when the excavation pit inside the cofferdam is created (construction phase No. 15). The largest deformation of the sheet-pile wall, in the direction out of the cofferdam, was achieved in phase No. 7. The largest deformation of the sheet-pile wall, in the direction into the cofferdam, was achieved in phase No. 15. The highest values of bending moments and axial forces, for all structural elements, were achieved in phase No. 15. Three alternative models, which included changes of the lengths of the sheet-pile walls and the shape of soil improvement using jet grouting, were analysed. The results showed that shortening the length of the sheet-pile walls led to increasing the deformation in phase No. 7 for about 10 %. The deformation of the sheet-pile walls in phase No. 15 decreased by about 8 %. The change of shape of the soil improvement has no impact to deformations in phase No. 7. The deformations in phase No. 15 were smaller because the change of shape of the soil improvement caused that the subsoil inside the cofferdam is stiffer.

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