STATIC ANALYSIS OF AN ARCH GRAVITY DAM – A CASE STUDY

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Summary

The Janneh dam is designed as an arch-gravity Roller Compacted Concrete dam (H=157 m), currently under construction in Lebanon. It was initially designed as a straight-gravity dam. However, due to seismic reasons, its layout has been curved.

In the paper is performed numerical static analysis of dam Janneh, by spatial (3D) numerical models. Namely, the model consists of dam body and rock foundation. The analysis were executed by application of code SOFiSTiK.

The behaviour of the contact zone dam-foundation was simulated by interface elements of type spring, by specifying input parameters for non-linear behaviour of the zone.

The obtained results are compared with output results from executed analysis from different calculation codes.

Key words: arch-gravity dam, spatial (3D) model, static analysis.

СТАТИЧКА АНАЛИЗА НА ЛАЧНО ГРАВИТАЦИОНА БРАНА – СТУДИЈА НА СЛУЧАЈ

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Резиме

Брана Јанех е проектирана како лачно-гравитациона брана од валјан бетон (H=157 m), и моментално е во фаза на градба во Либан.. Првично била проектирана како класична гравитациона брана. Сепак, поради барања во однос на сеизмиката, браната била закривена во основата.

Во рефератот е извршена статичка анализа на браната Јанех, со примена на просторен (3D) нумерички модел. Имено, моделот се состои од телото на браната и карпестата основа под браната. За спроведување на анализите е применета програмата SOFiSTiK.

Однесувањето на контактанта зона брана-основа е симулирана со примена на спојни (контактни) елементи од типот спринг, со задавање влезни параметри за нелинеарно однесување на наведената зона.

Добиение резултати се споредени со резултати добиени со анализа на браната Јанех со примена на други пресметувачки програми.

Клучни зборови: лачно-гравигтациона брана, просторен (3D) модел, статичка анализа.

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1. INTRODUCTION

The construction of arch gravity dams under favorable conditions (shape of the valley, strength of the bedrock, availability of construction materials is a more and more competitive alternative.

More specifically, when Roller Compacted Concrete (RCC) is used, such alternative may be comparable to a Conventional Vibrated Concrete (CVC) arch dam in terms of costs of the project. Moreover, the higher overall thickness of the dam allows its construction on bedrocks of lower quality compared to that required for CVC arch dams.

In the present case study is analyzed the behaviour of Janneh dam (157m high, currently under construction in Lebanon), under static loading by numerical models.

The behavior of straight gravity dams on wide valleys is well known and several international guidelines may be used in order to assist their design:

- The dam withstands the water pressure by means of shear strength at the dam/foundation interface and at several weak planes in the dam body and/or within the bedrock;
- Crack opening at the upstream toe is generally only allowed for unusual and extreme load cases (occurrence of MCE type of earthquake).

Except for high-seismicity sites, 2D rigid block analysis is usually considered sufficient to assess the stability of arch gravity or gravity dams. In cases when the layout of a gravity dam is curved with a small enough radius of curvature, arch effect is triggered, even under normal operating conditions. The arch effect laterally transfers a part of the water pressure to the abutments of the dam. This leads to an offloading of the central blocks and an overloading of the bank blocks.

In the present case study is analysed the static behaviour Janneh dam (H=157m), currently under construction in Lebanon, thus applying spatial (3D) numerical models.

2. DAM/ GEOMETRY

The Janneh dam is designed as arch-gravity RCC dam. The dam was initially designed as a straight-gravity dam. However, due to seismic reasons, its layout has been curved.

The definition of the upstream and the downstream faces of the dam is cylindrical (simple curvature). The dam layout and typical cross sections A-A (at block B5) and B-B (at block B0) are displayed on Fig. 1. The maximal height of the dam above the excavation is designed at 157.0 m, with crest width of 10.0 m and length of 300.0 m. Maximal width at the dam base is designed to 66.0 m. The crest elevation is at 847.0 masl. Downstream slope from elevation 831.2 masl to elevation 752.4 masl is by slope 0.8H/1V.

3. DESCRIPTION OF THE CODE SOFiSTiK

3.1 General

The numerical analysis of dam Janneh is carried out by application of code SOFiSTiK, produced in Munich, Germany. The code is based on finite element method and has possibilities for complex modeling of the structures and simulation of their behavior. It also has possibility in the analysis to include certain specific phenomena, important for realistic simulation of dam's behavior, such as: discretization of the dam and foundation taking into account the irregular and complex geometry of the structure, simulation of stage construction, simulation of contact behavior by applying interface elements and etc. in order to assess the dam behavior and evaluate its stability. The code SOFiSTiK in its library contains and various standards and constitutive laws (linear and non-linear) for structures analysis. Moreover, the code SOFiSTiK has possibility for spatial (3D) modelling of the structures, most common applied in case of arch and arch-gravity dams.

Within the stage of numerical analysis, following steps must be undertaken, typical for this type of analysis: (1) choice of material parameters and constitutive laws (concrete. rock foundation and interface elements); (2) discretization of the dam and the rock foundation and (3) simulation of the dam behaviour for the typical loading states (as required in the topic formulation).

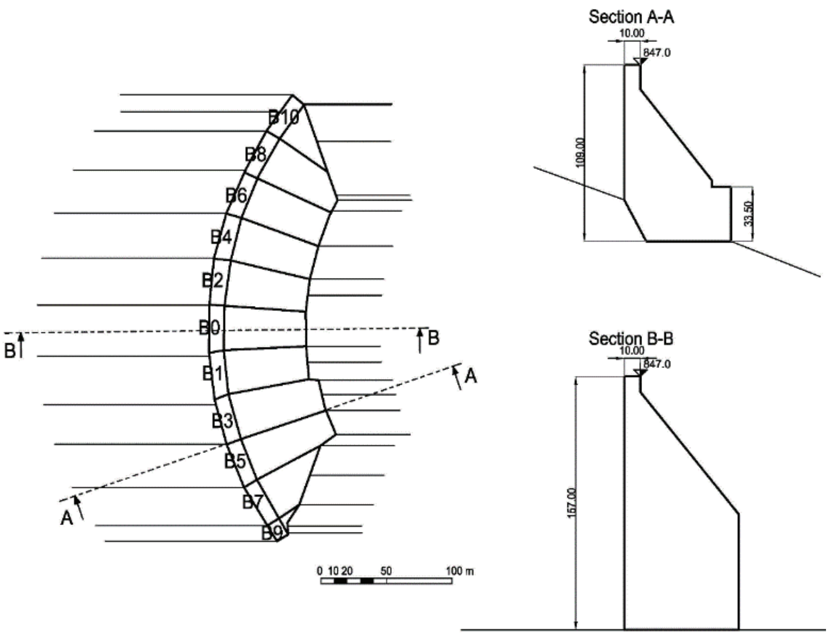


Figure 1. Plane view and cross sections A-A and B-B of Janneh dam.

3.1 Input parameters and constitutive laws for the materials

The choice of material parameters, as input data for the stress-deformation analysis is complex process, taking into account various factors and influences. The stress state of the rock foundation in the numerical model is taken into account as initial state. A linear constitutive law is applied for the rock masses in the foundation, with input data specified in Table 1 [1].

The dam body is planned to be constructed by Roller Compacted Concrete (RCC). The dam construction will be simulated by subsequent horizontal layers of approximately equal height. Total of 10 subsequent horizontal layers (groups) are applied in the numerical model. The constitutive stress-strain law for RCC is adopted linear, with input parameters also specified in Table. 1.

The water load is important specific phenomena in case of dams. In case of static loading the water is applied as water pressure on the upstream face of the dam.

Table 1. Material parameters.

Material	Density (kg/m3)	Static deformation modulus (GPa)	Poisson's ratio	c (kPa)	ϕ (°)	Tensile strength (MPa)
Concrete	2400	20	0.2			-
Bedrock	2800	25	0.25			-
Water	1000		0.499			-
Dam/ found. interface.	-	-	-	0	45	0

4. DISCRETIZATION OF DAM BODY AND FOUNDATION BY FINITE ELEMENTS

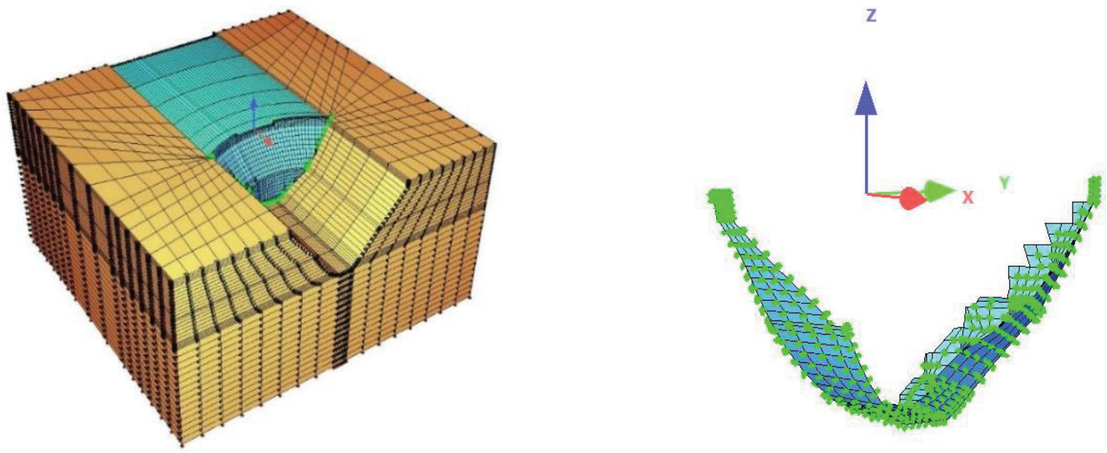
4.1 Applied finite elements

Numerical analysis in the report are performed by spatial (3D) model, where the dam body and the foundation are modelled with volume elements. A powerful and reliable finite element should be applied in case where an analysis of structure with complex geometry and behavior is required, having in consideration that the correctly calculated deformations and stresses are of primary significance for assessment of the dam stability. In this case, for discretization of the dam body and the rock foundation are applied quadrilateral finite element (as auxiliary elements, type quad, by 4 nodes), volume finite element (type bric, by 8 nodes) and interface element of type spring.

4.2 Numerical model

The model is composed of dam body, rock foundation and interface elements at contact dam-foundation. The rock foundation is modelled according to the prepared geometry by the task formulator. More precisely, the numerical model captures the dam body, limited by dam site shape apropos the rock foundation, with approximate length upstream of the central section 248.0 m and downstream of 265.0 m. The rock foundation below the dam is taken in consideration at approximate depth of 223.0 m. The length of rock foundation in the left bank is approximately 227.0 m, while in the right bank the length is 242.0 m. The spatial model has geometrical boundaries, limited to horizontal and vertical plane. In these planes are defined the boundary condition of the model (Figure 2a). The horizontal plane in the lowest zone of the model is adopted as non-deformable boundary condition, vertical planes perpendicular on X-axis are boundary condition by applying fixed (zero) displacements in X-direction and vertical planes perpendicular on Y-axis are boundary condition by applying fixed (zero) displacements in Y-direction. The discretization is conveyed by capturing of the zones of various materials in the model – concrete and rock foundation. The dam body is divided in 10 groups that will enable simulation of stage construction of the dam. Namely, for each layer is assigned group, thus enabling activation and deactivation in dependence of the loading state of the dam.

The behavior of the contact zone dam – foundation is simulated by interface elements (type "spring", Figure 2b). Namely the spring interface elements are used to model the contact foundation – dam, which enable differential displacements in the joint. Interfaces in principle, act as compressed ones, i.e. the relative displacement along the contact are in fact displacements in tangential direction of the spring. The behavior of the springs generally is described by two parameters: normal stiffness C and tangential stiffness Ct. On the current level of development in geotechnics, several approaches of shear strength testing are known, but there are still cases when it is very usual to adopt or assume them, and very often this problem is not even treated. Along with this, it is very difficult to conclude how close is the prognosis of the parameters to the actual conditions which are expected in the phase of exploitation of the structures. The theory and methodologies for determination of shear strength along discontinuities are also developed [1, 2]. Furthermore, there are some developed methodologies to define shear strength along interfaces concrete-rock mass in a phases of design for concrete dams [3, 4]. Some detail analyses of shear strength parameters in designing of fill dams can be found in Barton and Kjaernsli [5], while summarized overview is given by Tančev [6, 7]. The research of input data for the stiffness properties by specially arranged laboratory direct shear test can be done by applying the Hoek's apparatus [8]. In the present case there are no specified input data and for simulation of model of dam attached to the foundation are adopted high values for the stiffness strength parameters C=Ct=1×10^9 KN/m^3, and for simulation of non-linear behavior are adopted lower values C=1×10^8 KN/m^3, Ct=1×10^6 KN/m^3, based on previously executed analysis and experience, and also is applied input for no tension stresses occurrence along with input of friction and cohesion parameters, thus applying Mohr-Coulomb constitutive law for the contact zone behavior. Namely, the nonlinear behavior of the dam and contact zone is enabled by input of possibility for crack occurrence i.e. if tension stresses occur there is as possibility for crack generation in that zone, depending whether or not are exceeded the allowable tension stresses of the concrete.



a) b)

Figure 2. Numerical model of Janneh dam. a) Spatial model with boundary conditions, b) Interface zone dam-foundation.

4.3 Dam loading

The applied dam loading includes simulation of the dam loading state at full reservoir, for normal water level Znwl=849.0 masl. In order to simulate the specified state, firstly was simulated the dam construction in 10 horizontal layers, taken as initial state for the full reservoir with displacements reset to zero.

5. STATIC ANALYSIS

The numerical calculations are to be carried out by following a progressive approach: the subsequent stage is by increased complexity (from linear to non-linear model).

5.1 Linear analysis - Model no. 1

In the linear analysis, the dam is modelled as fix connected to its foundation in such a way that the input properties of the interface elements are with high values for the stiffness parameters. On Figure 3 are displayed horizontal displacements (X-direction upstream to downstream) in central block B0 and in bank block B5 for state at water elevation on 839.0 masl. The displacements are in downstream direction, with maximal values of 21 mm and 12 mm at the dam crest for both blocks accordingly.

On Fig. 4 are displayed arch stresses in central block B0 and in bank block B5 for state at full reservoir. Maximal arch stresses are located at approximately 50% of the blocks height at block B0 at upstream face, value of 1.3 MPa. In case of section B5 the maximal value of the stresses is approximately at 70% of the blocks height, value of 0.7 MPa, also at upstream face.

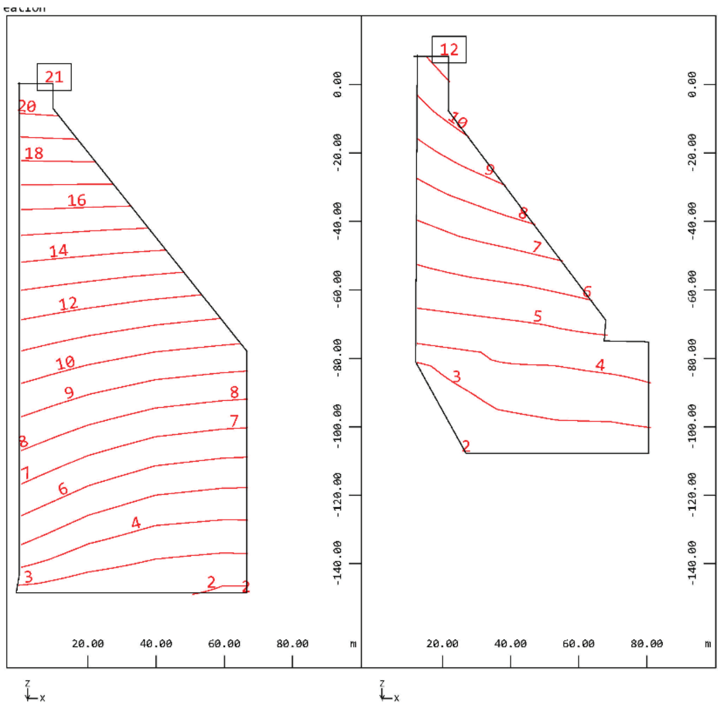


Figure 3. Horizontal displacements in cross section of the central block B0 and bank block B5 [mm] (“+“ denotes displacement in downstream direction) for model no. 1.

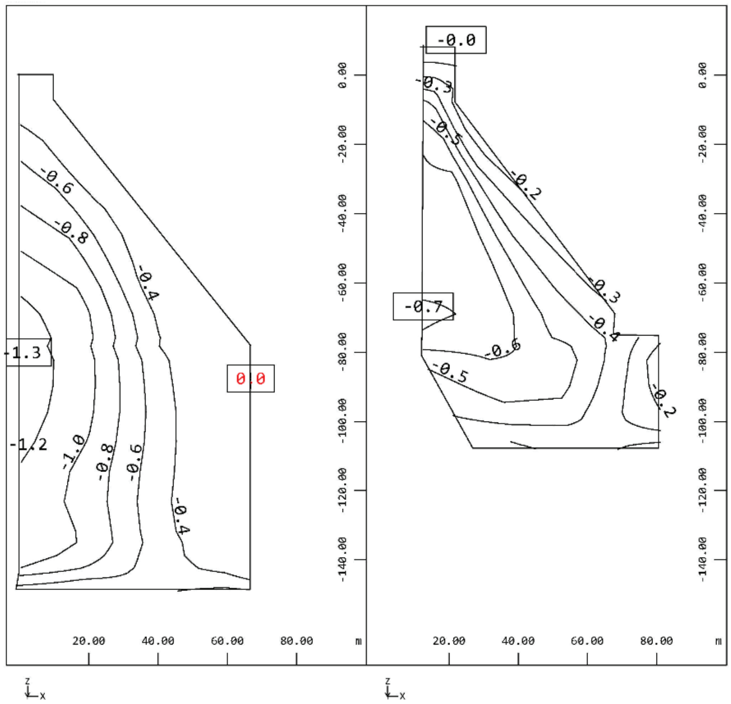


Figure 4. Arch stresses in blocks B0 and B5 at water elevation at 839.0 masl, model no. 1 [MPa].

5.2 Simplified non-linear analysis - model no. 2

In the simplified non-linear analysis, the dam is modelled by applying interface elements, following Mohr-Coulomb law and uplift simulated as loading on the dam foundation zone in full amount regarding the water level elevation. On Figure 5 are displayed horizontal displacements (X-direction upstream to downstream) in the central block B0 and bank block

B5 for state at water elevation on 839.0 masl. The displacements are in downstream direction, maximal value at dam crest of 23 mm and 13 mm respectively, by similar distribution and slightly increased values compared to model no. 1 (as stiffer model).

On Fig. 6 are displayed arch stresses in central block B0 and in bank block B5 for state at full reservoir. Maximal arch stresses are located at approximately 50% of the height at section B0, value of 1.4 MPa, at upstream face of the dam. In case of section B5 the maximal value of the stresses is approximately at 70% of the height of the section, value of 0.7 MPa, also at upstream face.

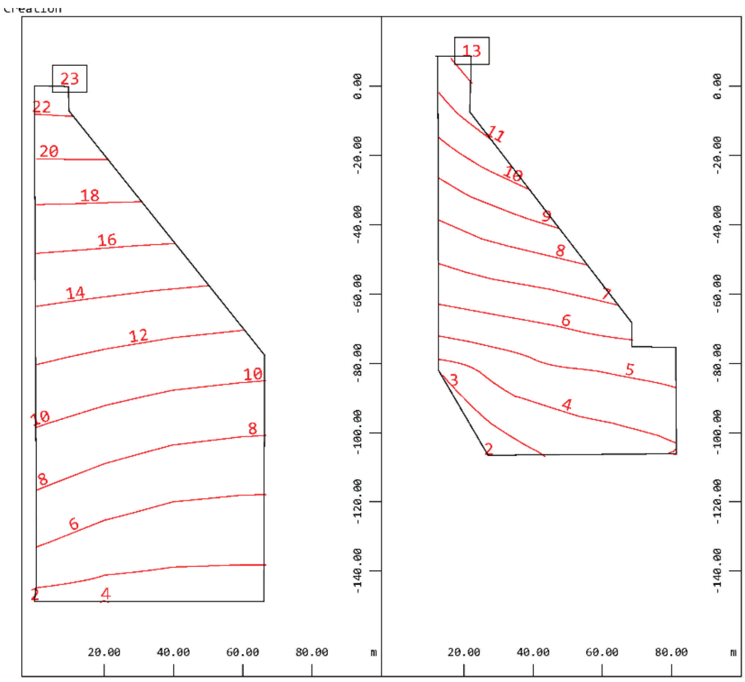


Figure 5. Horizontal displacements in cross section of central block B0 and bank block B5 [mm] (“+“ denotes displacement in downstream direction) for model no. 2.

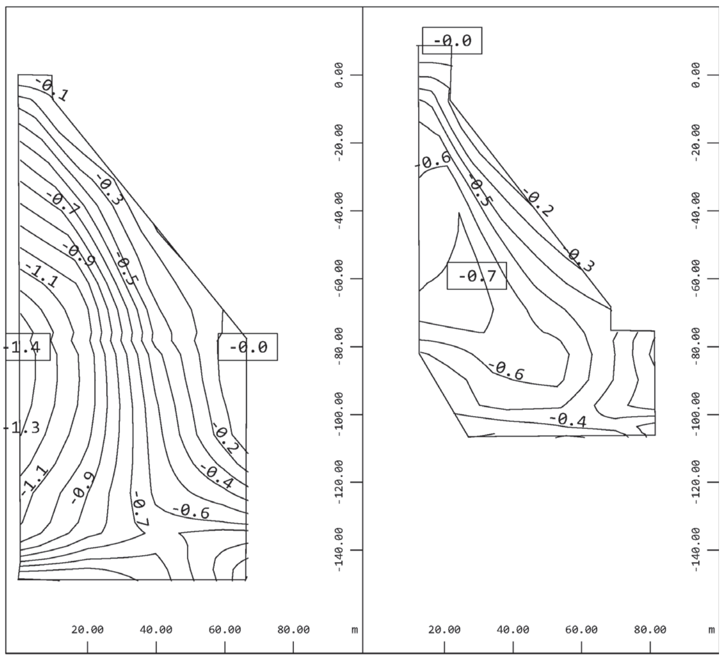


Figure 6. Arch stresses in blocks B0 and B5 at water elevation at 839.0 masl, model no. 2 [MPa].

5.3 COMPARISON OF RESULTS

The obtained results from the carried out analysis are compared with reference values for displacements and stresses. The reference model carried out by the formulators doesn't claim to be the optimum solution and its results are only given as a means of comparison.

On Fig. 7 are displayed horizontal displacements along the upstream face in central block B0 and bank block B5 at full reservoir for model no. 1 and the reference values. The comparation of the values for the displacements shows very good match for both sections B0 and B5.

On Fig. 8 are displayed horizontal displacements along the upstream face in central block B0 and bank block B5 at full reservoir for model no. 2 and the reference values. The comparation of the values for the displacements also shows very good match for both sections B0 and B5.

It is evident that model no. 2, whereas the contact zone dam-rock foundation is modeled by interface elements, slightly behaves more elastic, compared to model no. 1, modeled without interface elements.

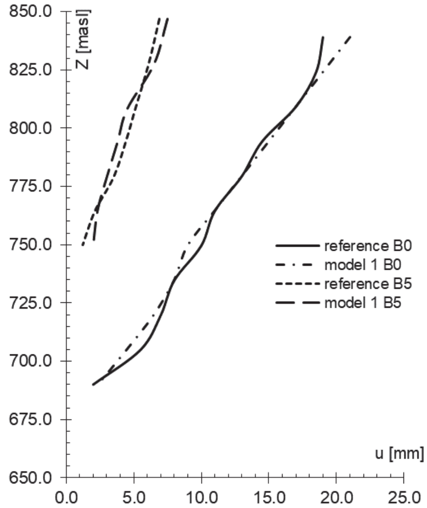


Figure 7. Horizontal displacements in cross section of the central block B0 and bank block B5 [mm] ("+" denotes displacement in downstream direction) for model no. 1.

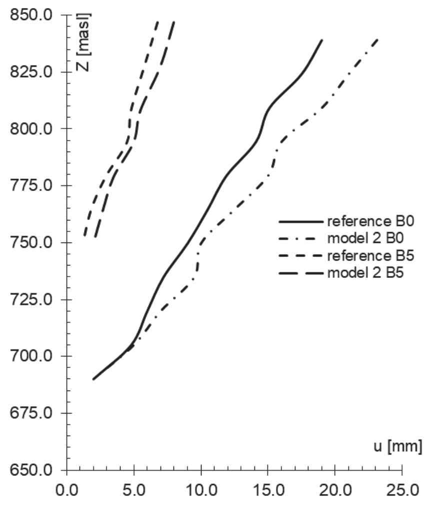


Figure 8. Horizontal displacements in cross section of the central block B0 and bank block B5 [mm] ("+" denotes displacement in downstream direction) for model no. 2.

On Fig. 9 are displayed arch stresses along the upstream face in central block B0 at full reservoir for model no. 1 and the reference values. The comparation of the values for the calculated and reference values for the stresses shows good match.

On Fig. 10 are displayed arch stresses along the upstream face in central block B0 at full reservoir for model no. 2 and the reference values. The comparation of the values for the calculated and reference values for the stresses is a good match for distribution of the stresses, with some differences regarding the obtained values.

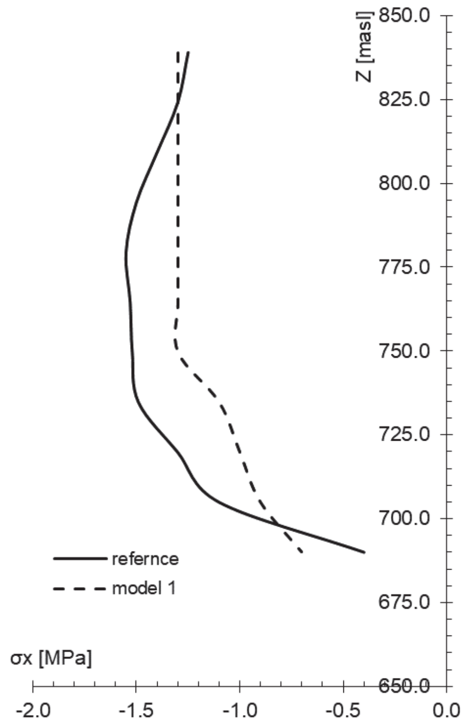


Figure 9. Arch stresses at upstream face for block B0 at water elevation 839.0 masl, model no. 1.

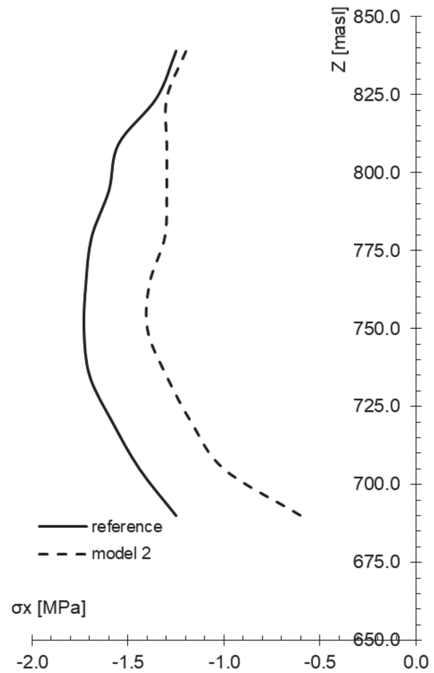


Figure 10. Arch stresses at upstream face for block B0 at water elevation 839.0 masl, model no. 2.

6. CONCLUSIONS

From the numerical experiment of simulation of the static behaviour of Janneh dam following conclusions can be drawn out:

1. The prediction of the arch gravity dam behaviour during construction, reservoir filling and service period by means of numerical calculation models is of primary importance.
2. The strength properties for contact zone dam-foundation, modelled by interface elements, should be determined by specific laboratory tests on shear strength along discontinuities (eg. by Hoek's apparatus), thus specifying the stiffness parameters and non-linear behaviour of the zone, in order more realistic simulation of the dam's behaviour.
3. The horizontal displacements at full reservoir in analyzed blocks B0 and B5 are mainly in downstream direction, with maximal values at dam's crest for both models.
4. The arch stresses at full reservoir in blocks B0 and B5 for both models have very similar distribution and values, with maximal values at upstream face of the dam at approximately 50% and 70% of the blocks height respectively.
5. The comparation of the calculated and reference values for the displacements shows very good matching of the values and the distribution.
6. The comparation of the calculated and reference values for the arch stresses shows generally good matching of the distribution and some difference in the values. Namely, additional calibration is required in the strength parameters of the interface zone.

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