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STATIC ANALYSIS OF A HIGH ARCH DAM

STATIČNE ANALIZE VISOKE LOČNE PREGRADE

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Abstract

The paper presents the design and static analysis of a high arch dam. A feasibility study was conducted on the dam in the 90s and a preliminary layout was designed. However, the dam's construction phase has been never started. In this paper, the design and layout of the dam under consideration are in accordance with the US manuals for the design of arch dams. The structure's three-dimensional model was entered into the program SAP2000 and three-dimensional solid finite elements were used to discretize the model. This paper considers the hydrostatic pressure of the water reservoir and concrete self-weight. The analysis was performed for both the maximum and the minimum designed water level and for the case when the reservoir is empty. Special attention is given to the boundary conditions of the dam at its abutments and foundation. The results show that the planned layout is good for the dam's construction. The arch dam's curve transfers the loads to the abutments. The significant role of the foundation rigidity and the reservoir water level in the stress distribution and nodal displacements within the arch dam is observed.

Keywords: Arch dam, static analysis, finite element, stress, displacement.

Izvleček

V prispevku predstavljamo zasnovo in izvedbo statične analize ločne pregrade. Študija temelji na tehnični zasnovi ločne pregrade iz predinvesticijskega elaborata in idejne zasnove iz 90. let prejšnjega stoletja. Dejansko do uresničitve projekta kasneje ni nikoli prišlo. Zasnova konstrukcije in njena prostorska umestitev sta bili izvedeni v skladu z določili ameriških priporočil za načrtovanje ločnih pregrad. Za pripravo numeričnega modela smo uporabili prostorski končni element in izvedli statično analizo z uporabo računskega programa SAP2000. V analizi smo upoštevali hidrostatični tlak vode v akumulaciji in lastno težo konstrukcije. V računu smo predpostavili skrajni možni obratovalni stanji, z maksimalno in minimalno gladino v akumulaciji, in računski primer, ko je zadrževalnik prazen. Posebno pozornost smo namenili analizi robnih pogojev na bokih pregrade, v točki vpetišča objekta in temeljne podlage. Rezultati so potrdili ustreznost konstrukcijske zasnove pregrade. Pri ločnih pregradah se obtežba z izkoriščanjem ločnega efekta prenaša neposredno v hribinsko podlago. Pri tem sta ključnega pomena togost hribinske podlage in obratovalna gladina, ki vplivata na porazdelitev napetosti v telesu pregrade in pomike konstrukcije.

Ključne besede: ločna pregrada, statična analiza, končni elementi, napetosti, pomiki.

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1. Introduction

Arch dams are solid concrete dams that are curved in their upstream plan (US Bureau of Reclamation, 1977). The curve transfers a part of the applied loads to the dam's foundation and abutments. The site's geometry is a crucial aspect for the selection of a dam type. Narrow valleys with steep abutments are perfect for arch dam construction. The contact surface of the dam should be capable of transferring loads to the abutment. This can be achieved by considering the critical role of the dam profile's contact angle with the abutment. Since arch dams have smaller foundation contact areas, the abutment and foundation rocks must have sufficient strength to withstand the large imposed bearing pressure.

The feasibility study for the construction of the present dam was done in the 1990s on the Komarnica River in Montenegro. Some preliminary layout was elaborated; however, construction has never gotten underway.

The arch dam in this paper was designed based on the US design manuals for arch dams composed by the US Army Corps of Engineers, 1994, and the US Bureau of Reclamation, 1977.

The design process of arch dams is iterative. A design should be developed and a preliminary static analysis conducted (Boggs et al., 1988). Results thereof will be evaluated and required modifications to the initial arch dam layout will be considered. The modification may apply to the shape, curvature, and the thickness of the arches in the different elevations based on the preliminary results of stresses and displacements. The next static analysis will be performed on the modified layout, with the process continuing until an acceptable design is acquired.

Various methods for designing and analysing arch dams have been developed. These include the trial-load method, developed before 1940 and widely used and improved later. Many existing dams were designed using this method. The method is based on the load distribution between the arch and cantilever units and the agreement between their deflections in the radial, tangential, and rotational directions (Ghanaat, 1993). The main restrictions on the use of this method were its complexity and the required time and efforts for a complete analysis. However, these limitations are partially solved by the Arch Dam Stress Analysis System (ADSAS), which was developed in the mid-1970s to run the trial-load method on a computer system (US Army Corps of Engineers, 1997). The efficiency of the trial-load method was approved by comparing the analysis results with structural behavior measurements (US Department of the Interior, 1968) and the results obtained from solving the finite element with a computer program (Nourani, 2016).

With the improvement in computational technology, discretization of the arch dam became easier and the Finite Element Method (FEM) was used for analyzing the arch dams. Various computational techniques based on the FEM were developed for stress and deformation analysis of arch dams. The Finite Element Method was employed in the thin shell theory by Bernardou and Boisserie (1982) to simulate arch dam behavior. Da Silva and Julio (1995) employed the finite element method for developing a computational technique based on the membrane method. One of the first programs for arch dam analysis was the Arch Dam Analysis Program (ADAP), developed by the University of California based on three-dimensional finite elements (US Bureau of Reclamation, 1977). Since then, the implementation of three-dimensional solid elements for arch dam analysis was developed in computational software. In this paper, we employed three-dimensional solid elements in SAP2000 software for analyzing the arch dam.

In the static analysis of the arch dam, we need to consider dead load (self-weight), hydrostatic pressure load, and the temperature load.

Two methods for modelling of the temperature load are available in SAP2000 software. The first method is assigning the temperature load on nodal joints of solid elements. This method will be extremely time-consuming due to the complex shape of the dam and the enormous number of the nodes, 9990 nodes. The second method is to assign uniform temperature directly on each three-dimensional solid elements. This method can be inaccurate. Because the difference in temperature of the adjacent elements will cause a temperature jump in the common nodes between the solid elements. The influence of the temperature loads is not considered in the scope of this paper.

The effect of the spillway and other voids such as conduits in the dam can be neglected in static analysis, except for large spillways or for tunnel spillways, which should be analyzed separately. Our study does not consider these effects.

2. Layout and computational model

The site's topography is presented in Figure 1. Based on the topography, the design and layout of the arch dam were drafted in AutoCAD and SketchUp Pro. We used a double curvature arch dam due to the canyon's asymmetric shape.

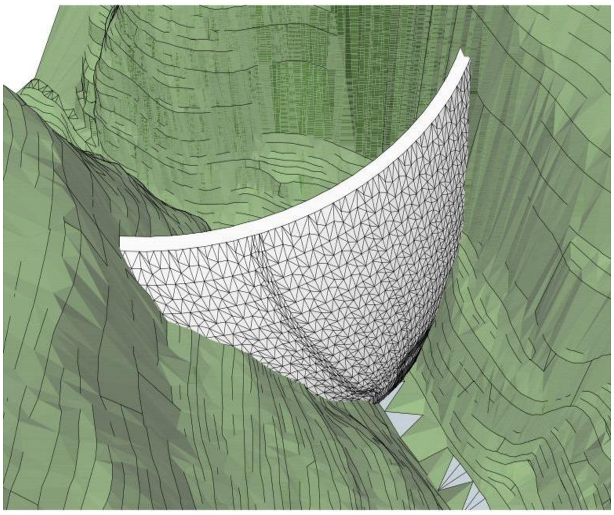

Figure 1: *Three-dimension model of the arch dam and its site.*

Slika 1: *Trirazsežni model ločne pregrade in lokacije.*

The river's bed is at an elevation of 665 m. The reservoir capacity should be determined to estimate the dam geometry. The dam's purposed function, the reservoir's design life, the site's hydrological and geological condition and the considered valley's topography are the crucial factors in estimating the reservoir capacity. Hydrological studies on the streamflow, flood, sedimentation, and groundwater are required for assigning the reservoir capacity.

Here, the reservoir's maximum water level was assumed to be to the elevation of 816 m, so we consider the dam's crest elevation to be 820 m. Considering sufficient excavation into the bottom foundation, a height of 166 m for the dam was acquired.

The dam's geometric properties are presented in Table 1.

Table 1: *The dam's general geometric parameters.*

Preglednica 1: *Splošni geometrijski parametri pregrade.*

Parameter	Value
Dam height at the crown (m)	166
Thickness at the crest (m)	5
Thickness at the base (m)	22
Maximum water level (m)	816
Minimum water level (m)	760
Axis radius (m)	120

USACE EM 1110-2-2201 (US Army Corps of Engineers, 1994) suggests empirical equations to determine the axis radius and the thickness of the arch dam at the crest and the base. These equations are a function of the dam height and the straight distance between the two excavated abutments.

Using these equations, the geometry of the crown cantilever in the reference plane was designed as can be seen in Figure 2.

The dam's plan view was obtained by drawing arcs from eight elevations in addition to the crest arch. The plan view of the dam is shown in Figure 3, which presents the arcs, their radius, the location of the centres, and the angles of the drawn arcs.

Table 2 presents the values of the geometric parameters indicated in Figure 2 and Figure 3.

In modeling the foundation we used the deformation modulus of the foundation instead of an elastic modulus, to consider the effect of joints, shears, and faults (US Bureau of Reclamation, 1977). Material properties of the concrete and rock foundation are presented in Table 3.

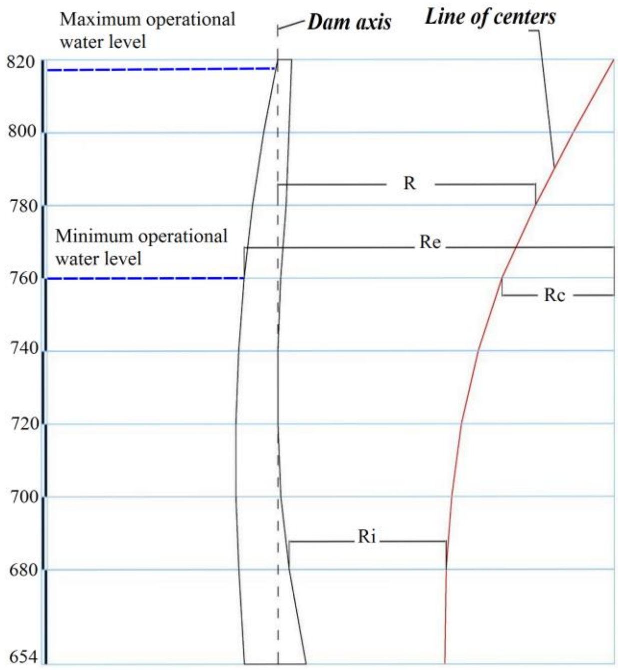

Figure 2: *Geometry of the crown cantilever in the reference plane.*

Slika 2: *Geometrijski parametri pregrade v referenčni ravnini.*

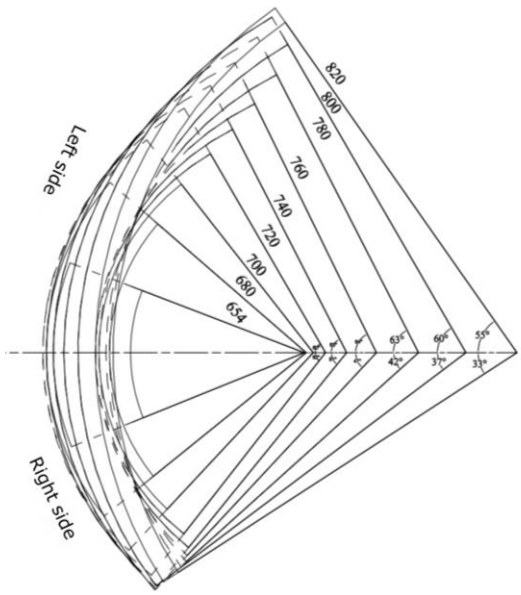

Figure 3: *The dam's plan view.*

Slika 3: *Karakteristični horizontalni prerezi po višini pregrade.*

Table 2: *Geometric parameters of the dam at crown cantilever and plan views.*

Preglednica 2: *Geometrijski parametri pregrade po višini.*

Elev.	Re [m]	Ri [m]	Rc [m]	$\emptyset_{right}$	$\emptyset_{left}$	R [m]
820	120	115	0	33	55	120
800	125	116	14.5	37	60	105.5
780	129	117	28	42	63	92
760	132	119.5	40	47	64	81
740	134	120	48.5	51	63	71.5
720	135	120	54.5	52	60	65.5
700	135	119	58	47	52	62
680	134	116	60	39	41	61
654	132	110	60.5	22	21	59.5

Table 3: *Material properties of the dam.*

Preglednica 3: *Materialne lastnosti pregrade.*

Parameter	Value
Concrete modulus of elasticity (MPa)	31000
Concrete Poisson ratio	0.2
Concrete unit weight (KN/m3)	25
Rock modulus of elasticity (MPa)	40000
Deformation modulus of rock (MPa)	30000
Compressive strength of concrete (MPa)	34

Two static load combinations were considered. In the first one, the water reservoir at the maximum operational level and the self-weight of the arch dam were applied. For the second combination, the minimum operational water level was combined with the self-weight. Both load combinations are classified as unusual static load combinations based on USACE EM 1110-2-2201 classification. The arch dam subjected to its self-weight with an empty reservoir was also considered.

The foundation of the dam was modeled with two approaches. In the first approach, we assumed that the dam is clamped to the foundation and that both the foundation and abutments are considered rigid. We restricted the contact joint from translation in any direction and rotation around any axis. However, we are aware that the arch dam is not perfectly clamped and that the foundation and abutment rocks are not perfectly rigid. We accordingly used linear elastic constitutive law for the foundation and abutment based on the deformation modulus of the rock in the second approach. For this reason, we assigned the simple area spring, which acts normally on the faces of the solid elements that are in contact with the abutment and foundation. Stiffness equal to 30000 MPa/m was assigned for the area spring, which was taken from the deformation modulus of the rocks to describe the boundary conditions more realistically.

The rigid model is presented in Figure 4, I and the flexible model can be seen in Figure 4, II.

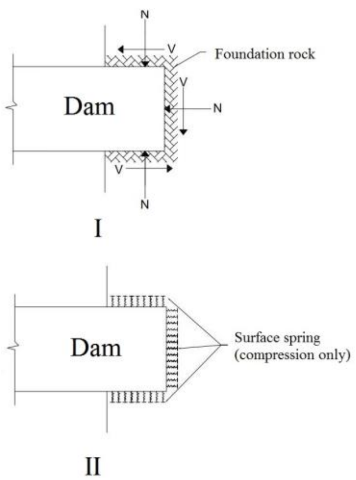

Figure 4: *Modelling the foundation and abutment.*

Slika 4: *Modeliranje vpetja konstrukcije pregrade v boke.*

The structure was modeled by three-dimensional solid elements as implemented in SAP2000 environment. Applied elements have eight nodes and six quadrilateral faces. Three translational degrees of freedom are sought at each node, while the rotational degrees of freedom are not members of primary unknowns (Computers & Structures Inc., 2016).

Very fine mesh with 7632 solid elements and 9990 nodes was used as demonstrated in Figure 5. The hydrostatic pressure loads were applied directly at the nodes and the analysis in the elastic regime was performed.

USACE EM 1110-2-2201 suggests the allowable stresses result from unusual static load combination and the safety factor against sliding. These values can be seen in Table 4, where f'_c presents design compressive stress and f'_t is design tensile stress.

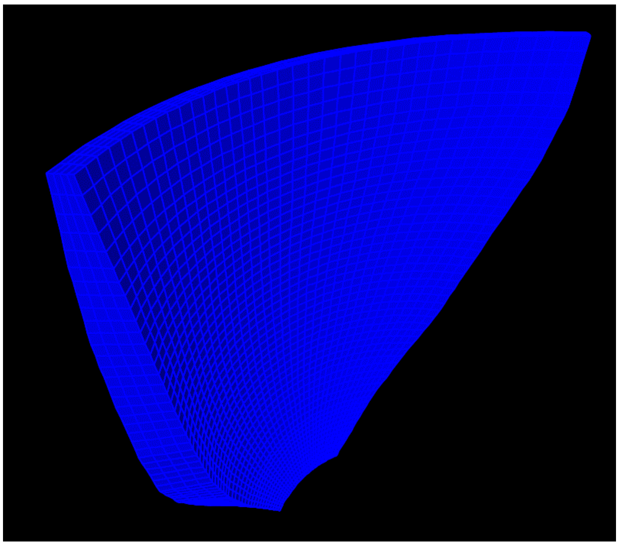

Figure 5: *SAP2000, discretization of the model into three-dimensional solid elements.*

Slika 5: *SAP2000 – diskretizacija modela z uporabo tridimenzionalnih končnih elementov.*

Table 4: *Allowable stresses and safety factor.*

Preglednica 4: *Dopustne napetosti in varnostni faktor.*

Parameter	Value
Allowable compressive stress	$f'_c/2.5$
Allowable tensile stress	f'_t
Factor of safety against sliding	1.3

3. Results and discussion

We present the nodal displacements and stresses for the arch dam due to applied load combinations LC1, LC2, and the self-weight.

LC1 = Self-weight + Maximum water level at elevation 816 m.

LC2 = Self-weight + Minimum water level at elevation 760 m.

Self-weight is considered in order to analyze the dam response at the end of the construction phase, while the reservoir is still empty. The results are presented for both rigid and flexible model of the foundation.

3.1 Displacements

The deformed shapes of the crown cantilever sections of the dam are shown in Figure 6. This figure presents the results for both rigid and flexible foundation due to applied load combinations LC1, LC2, and self-weight. To present the deformed shapes of the arch dam in the horizontal planes, four arches are presented at different elevations. Figure 7 and Figure 8 present the deformed shapes due to LC1 and LC2 load combinations respectively. The segments of the arch dam that are embedded into the abutment are indicated by the dashed lines. Nodal displacements of sixteen nodes chosen as presented in Figure 7 and Figure 8 are listed in Tables 5 and 6. Here, the displacements are presented based on the joints' local axis. The direction towards the downstream face is considered as positive x-direction, while the y-direction and z-direction are considered based on the right-hand rule as can be seen in Figure 7. *Ux*, *Uy*, and *Uz* present the nodal displacement of the joints based on their local axis relative to their initial location.

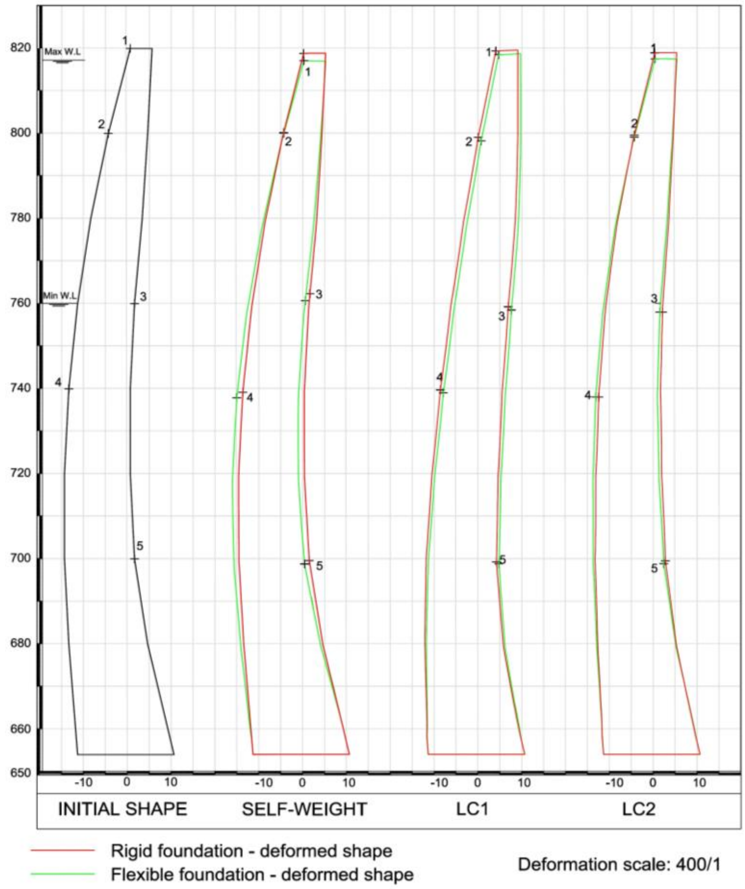

Figure 6: *Deformed shape of the crown cantilever.*

Slika 6: *Deformirana oblika prečnega prereza pregrade v temenu.*

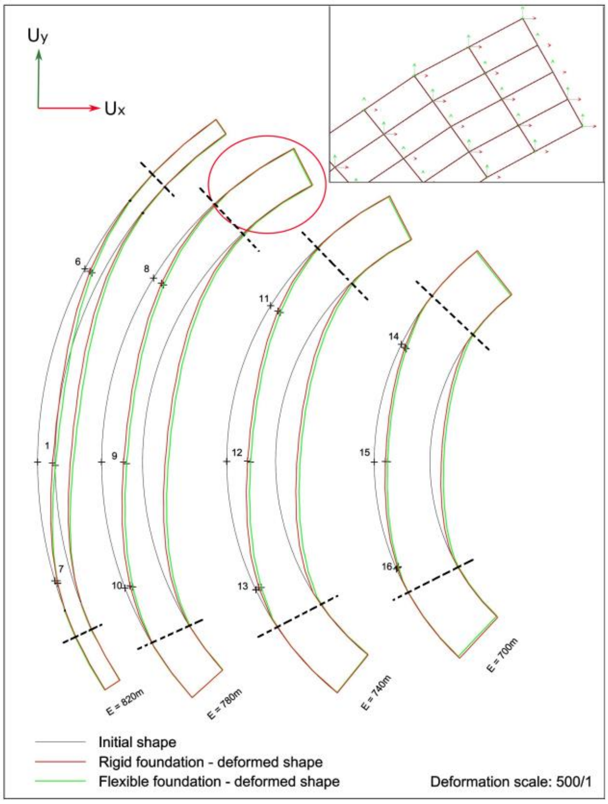

Figure 7: *Deformed shape of the dam in the arch plane due to applied load combination LC1.*

Slika 7: *Deformirana oblika prereza pregrade v horizontalni ravnini po višini, zaradi obtežnega primera LC1.*

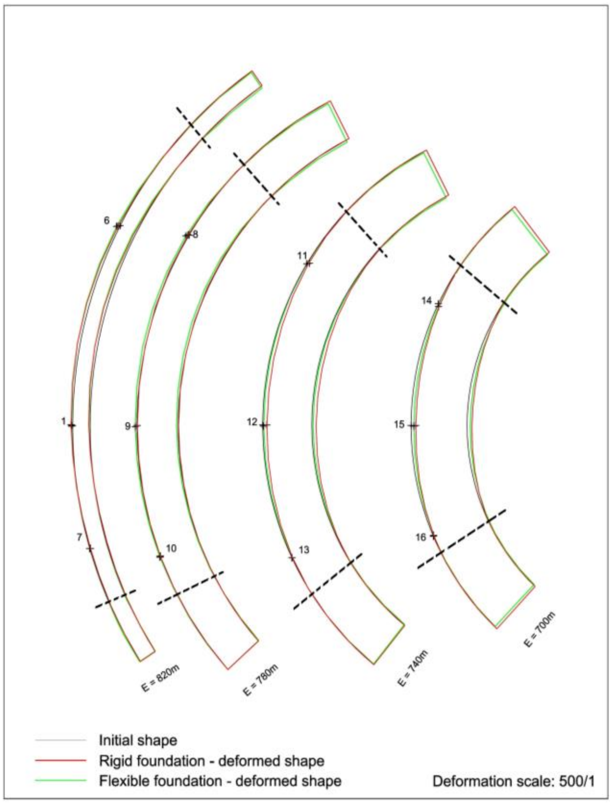

Figure 8: *Deformed shape of the dam in the arch plane due to applied load combination LC2.*

Slika 8: *Deformirana oblika prereza pregrade v horizontalni ravnini po višini, zaradi obtežnega primera LC2.*

It is evident that the foundation's rigidity has a significant role in displacement within the dam. Nodal displacements within the dam body are generally found to be bigger if the foundation is not rigid.

The largest displacement in the vertical direction occurs when the arch dam is only subjected to its self-weight. In the crest elevation, the vertical displacement is at its maximum value and gradually decreases with the depth of the arch dam. It should be mentioned that for the self-weight load case and LC2 load combination, in both the rigid and flexible foundation some negative horizontal displacement (displacement toward the upstream) were observed. These displacements are the results of vertical bending of the arch dam due to its self-weight.

Adding the hydrostatic load of water in the reservoir increases the horizontal displacement of the arch dam toward the downstream. In the LC1 combination, where the maximum water level at 816 m is applied, the arch dam has the maximum displacement in the x-direction due to high water pressure. By applying the hydrostatic load that is acting perpendicular to the self-weight the displacement in the vertical direction decreases, along with the vertical bending of the arch dam.

Table 5 presents the nodal displacement for the applied load combinations and the self-weight when the rigid foundation was considered. Table 6 presents displacement results for the case that the flexible foundation was used.

Table 5: *Displacements for the rigid foundation (Displacement values are highlighted from dark red for maximum positive displacements to dark blue for the maximum negative displacement).*

Preglednica 5: *Pomiki v primeru toge temeljne podlage (velikosti pomikov so označene: od temnordeče barve za največje pozitivne vrednosti, do temnomodre barve za največje negativne vrednosti pomikov).*

load	Self-weight			LC1 combination			LC2 combination		
Joints	Displacement[mm]			Displacement[mm]			Displacement[mm]		
	Ux	Uy	Uz	Ux	Uy	Uz	Ux	Uy	Uz
1	-1.08	0.49	-3.09	8.53	-0.53	-1.74	-0.82	0.45	-2.75
2	-0.82	0.15	-3.08	10.97	-0.21	-2.34	-0.39	0.15	-2.79
3	-0.72	0.08	-2.6	13.1	-1.5	-1.99	1.19	-0.15	-1.97
4	-0.79	-0.1	-2.21	11.89	0.22	-0.83	2.35	-0.02	-2.3
5	-0.4	0	-1.16	6.37	-0.76	-1.84	2.75	-0.34	-1.3
6	-1.26	-0.56	-2.06	2.88	-1.35	-0.85	-1.28	-0.31	-1.86
7	0.08	1.19	-1.67	1.28	0	-0.71	0.03	1	-1.47
8	-0.75	0.16	-2.01	4.53	-2.97	-0.64	-0.57	0.15	-1.83
9	-0.73	0	-2.85	12.56	-0.01	-2.25	0.18	0.02	-2.73
10	-0.17	0.1	-1.38	2.88	1.44	-0.83	-0.06	0.1	-1.23
11	-0.4	0.17	-1.6	4.11	-3.08	-0.02	0.58	-0.55	-1.41
12	-0.79	-0.1	-2.21	11.89	0.22	-0.83	2.35	-0.02	-2.3
13	-0.13	-0.11	-0.92	1.65	1.38	-0.28	0.29	0.24	-0.82
14	-0.15	0.09	-0.89	1.98	-1.71	0.47	0.84	-0.74	-0.41
15	-0.48	-0.09	-1.44	6.36	0.25	0.68	2.7	0.05	-0.74
16	-0.01	-0.08	-0.4	0.65	0.68	0.07	0.32	0.28	-0.21

Table 6: *Displacements for the flexible foundation (Displacement values are highlighted from dark red for maximum positive displacements to dark blue for maximum negative displacement).*

Preglednica 6: *Pomiki v primeru podajne temeljne podlage (velikosti pomikov so označene: od temnordeče barve za največje pozitivne vrednosti, do temnomodre barve za največje negativne vrednosti pomikov).*

load	Self-weight			LC1 combination			LC2 combination		
Joints	Displacement[mm]			Displacement[mm]			Displacement[mm]		
	Ux	Uy	Uz	Ux	Uy	Uz	Ux	Uy	Uz
1	-0.95	-0.37	-7.48	10.12	-1.94	-3.93	-0.65	-0.34	-6.3
2	-1.75	-0.63	-7.17	12.61	-1.3	-4.53	-0.96	-0.55	-6.14
3	-3.49	-0.19	-6.63	14.89	-2.13	-3.95	-0.42	-0.47	-5.18
4	-4.21	-0.71	-5.52	13.59	-0.35	-2.5	0.51	-0.61	-5.1
5	-3.05	0.03	-3.18	7.77	-0.88	-3.02	1.8	-0.46	-2.95
6	-2.25	-0.75	-7.33	4.02	-2.33	-2.64	-2.02	-0.48	-6.06
7	-0.06	0.23	-7.1	1.61	-1.47	-3.78	-0.16	0.1	-5.91
8	-2.52	-0.47	-7.09	5.77	-3.96	-2.43	-1.86	-0.41	-5.88
9	-2.64	-0.76	-6.65	14.27	-0.93	-4.37	-1.01	-0.66	-5.89
10	-0.62	-0.55	-6.6	4.38	0.75	-4.08	-0.3	-0.48	-5.55
11	-2.71	-0.45	-6.17	5.46	-3.94	-1.56	-0.74	-1.23	-5.07
12	-4.21	-0.71	-5.52	13.59	-0.35	-2.5	0.51	-0.61	-5.1
13	-0.95	-0.36	-5.56	3.09	1.31	-3.09	0.07	0.03	-4.66
14	-1.88	-0.62	-4.53	2.78	-2.55	-0.39	0.11	-1.62	-3.09
15	-3.31	-0.5	-4.35	7.6	0.13	-0.2	1.57	-0.36	-2.94
16	-0.69	0.22	-3.92	1.04	1.38	-1.75	0.13	0.66	-2.96

3.2 Stresses

In SAP2000 the stresses are presented according to the local axes. Initially, the local axes follow the same direction as x, y, and z-direction in the global coordinates. However, in arch dams the loads are transferred along the arch direction to the abutment and foundation. For this purpose, we have rotated the local axis of all solid elements into the cylindrical coordinates. For the modified coordinates, tangential stress (S_τ) presents the stresses along the arch direction and normal to the abutment surface, while the radial stress (S_R) presents the stresses towards the downstream direction.

The maximum of compressive and tensile stresses obtained should be smaller than allowable stresses by the safety factor provided in Table 4. In addition, the tensile stresses should be kept at the minimum level because sufficient tensile strength should be reserved in the case of an earthquake occurring (US Army Corps of Engineers, 1994).

For the downstream face, the presence of tensile stresses in the crown of the arch dam is not acceptable. The tensile stress can be reduced by increasing the dam's horizontal curvature or decreasing the thickness of the dam at the cantilever while the thickness at the abutment remains the same.

Since loads are transferred to the abutment due to curve action in the arch dam, the high compressive stress zones are expected at the abutments contact as seen in Figure 9.

Some results for tangential stresses are presented in Figures 10 through Figure 12. In the stress results, the parts of the dam body that are embedded into the foundation and abutments are greyed.

Comparing Figure 9 with Figure 10 shows that tangential stress formed the major portion of the compressive stresses in the arch dam. For all cases, the maximum compressive stresses are obtained in direction of the arch plane, normal to the abutment rocks (tangential stress). These stresses occurred in the vicinity of the arch dam's contact with the abutments as it can be seen in the figures.

Figures 10 and 11 present the stresses for the LC1 load combination for the flexible and the rigid foundation, respectively. The significant effect of foundation rigidity in the stress distribution will be cleared by comparing these two figures. In the arch dam with the rigid foundation, the stresses are concentrated highly in a small zone in both abutments and near the foundation. On the other hand, for the flexible foundation, a high reduction in the magnitude of the compressive stresses is observed for all applied load combination. The results show that the rigidity coefficient of foundation and abutment significantly influence the stresses magnitude and distribution.

The compressive stresses are mainly located on the arch dam's downstream side, as can be seen from figures. Some tensile stresses zones are observed, however, their magnitudes are smaller than allowable tensile stress. These tensile stresses are mainly located in the arch dam's upstream face, especially for the arches in the upper elevations.

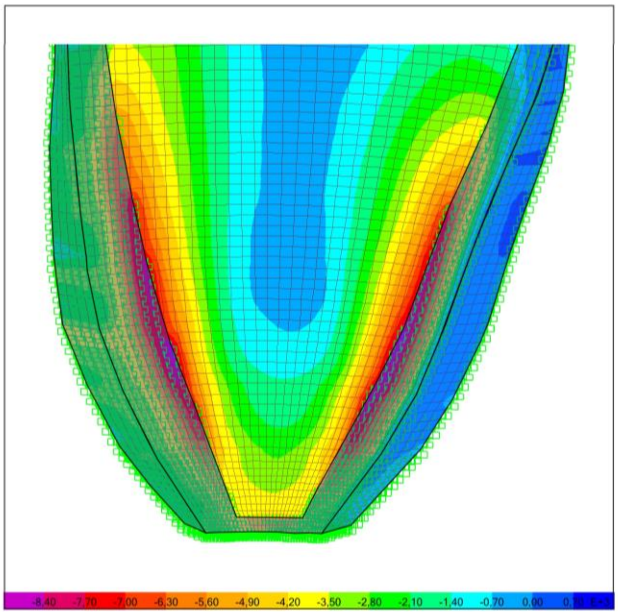

Figure 9: *Principal compressive stresses [kPa] due to LC1 load combination for the flexible foundation.*

Slika 9: *Glavne tlačne napetosti [kPa] pri obtežnem primeru LC1 v primeru podajne temeljne podlage.*

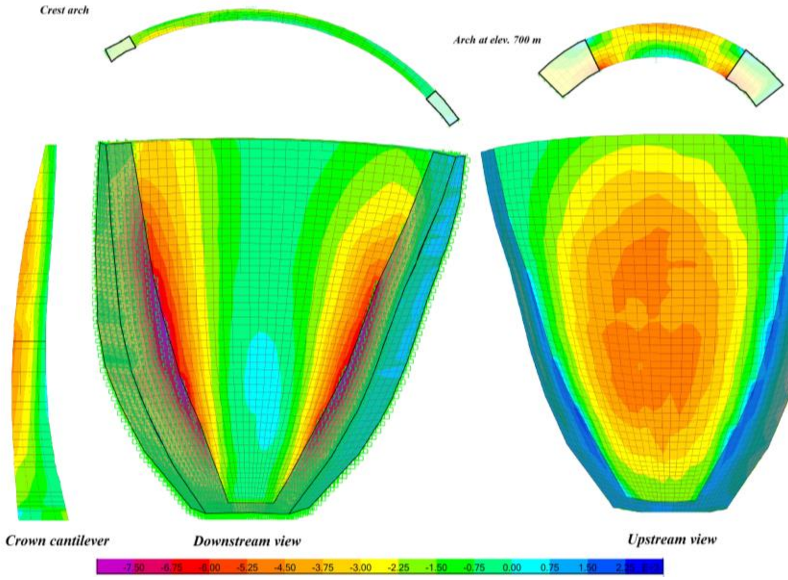

Figure 10: *Tangential stresses [kPa] due to LC1 load combination for the flexible foundation.*

Slika 10: *Tangencialne napetosti [kPa] pri obtežnem primeru LC1 v primeru podajne temeljne podlage.*

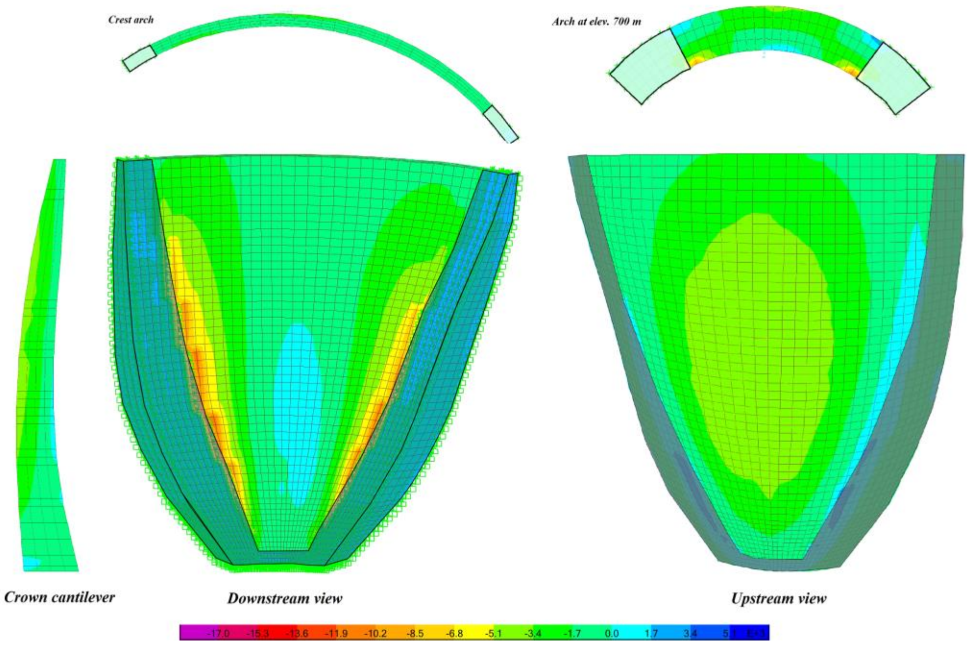

Figure 11: *Tangential stresses [kPa] due to LC1 load combination for the rigid foundation.*

Slika 11: *Tangencialne napetosti [kPa] pri obtežnem primeru LC1 v primeru toge temeljne podlage.*

Due to high water pressure, the compressive stress obtained from the LC1 load combination is higher than the other load combination. For the LC2 load combination where the minimum water level at 760 m is applied, the main compressive stress zones are obtained for the arch dam body below the reservoir water elevation, as can be seen from Figure 12. The magnitude of compressive stress is smaller compared to the LC1 load combination. The smallest magnitude of tangential compressive stresses is obtained in the case of the empty reservoir. However, the vertical compressive stress is maximized in this load case.

Since the real arch dam foundation is not completely rigid, the results obtained for the flexible foundation are more realistic.

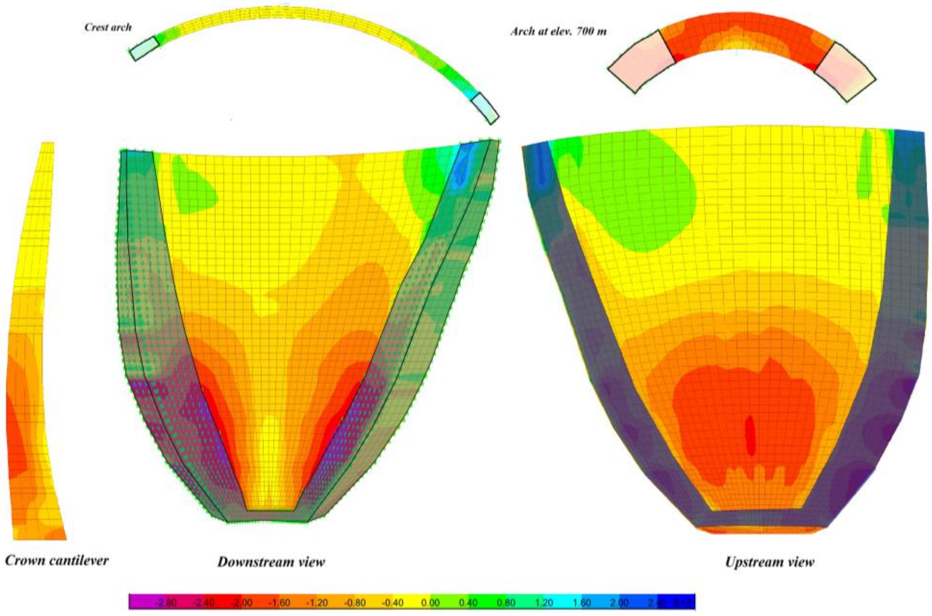

Figure 12: *Tangential stresses [kPa] due to LC2 load combination for the flexible foundation.*

Slika 12: *Tangencialne napetosti [kPa] pri obtežnem primeru LC2 v primeru podajne temeljne podlage.*

The stress results show that compressive stresses are located mostly at the central cantilevers on the upstream face, where the water pressure loads are applied at the joints. However, these compressive stresses are transferred by the arch action to the abutment vicinities on the downstream face.

4. Conclusion

The arch dam was designed based on the USACE EM 1110-2-2201 and static analysis was performed. A linear elastic analysis based on finite elements method was used. Three-dimensional solid elements as employed in SAP2000 were used to obtain the results.

The arch dam shape and curvature have a significant role in dam behavior and response. The curve action behavior in the arch dam is evident from the stresses distribution and deformation results. Loads were transferred by curve action to the abutments and the compressive stress zones are obtained in the vicinity of the dam abutments.

The distribution and magnitude of the stresses, as well as the deformation of the arch dam, is affected by the foundation and abutment stiffness.

For the arch dam with the rigid foundation, higher stresses and smaller displacements were obtained. The stresses are mostly concentrated at the contact area of the dam with the foundation and abutments.

In the case of a less rigid foundation, the stresses were distributed more widely through the entire body of the dam with lower magnitudes. In this case, some small displacement in the boundary nodes were obtained, while the magnitude of displacements for the arch dam body was bigger than for the rigid case.

Some tensile stresses were observed in the case of the minimum reservoir water level. In the arch dams, sometimes the maximum tensile stress can be a result of the low water level. Therefore, the minimum water level also should be considered in static analysis.

The concrete in arch dams should have sufficient strength to transfer the load actions to the abutment rocks. Also, the abutment materials must be strong enough to resist the transferred loads.

The static analysis of arch dam in this paper can be used as a primary step for arch dam designs. For the final design, consideration of the dynamic loads, temperature, and heterogeneity of material properties is required.

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