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Construction stages analyses using time dependent material properties of concrete arch dams

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Abstract. This paper presents the effects of the construction stages using time dependent material properties on the structural behaviour of concrete arch dams. For this purpose, a double curvature Type-5 arch dam suggested in "Arch Dams" symposium in England in 1968 is selected as a numerical example. Finite element models of Type-5 arch dam are modelled using SAP2000 program. Geometric nonlinearity is taken into consideration in the construction stage analysis using P-Delta plus large displacement criterion. In addition, the time dependent material strength variations and geometric variations are included in the analysis. Elasticity modulus, creep and shrinkage are computed for different stages of the construction process. In the construction stage analyses, a total of 64 construction stages are included. Each stage has generally 6000 m^3 concrete volume. Total duration is taken into account as 1280 days. Maximum total step and maximum iteration for each step are selected as 200 and 50, respectively. The structural behaviour of the arch dam at different construction stages has been examined. Two different finite element analyses cases are performed. In the first case, construction stages using time dependent material properties are considered. In the second case, only linear static analysis (not considered construction stages) is taken into account. Variation of the displacements and stresses are obtained from the both analyses. It is highlighted that construction stage analysis using time dependent material strength variations and geometric variations has an important effect on the structural behaviour of arch dams. The maximum longitudinal, transverse and vertical displacements obtained from construction stages and static analyses are 1.35 mm and 0 mm; -8.44 and 6.68 mm; -4.00 and -9.90 mm, respectively. In addition, vertical displacements increase from the base to crest of the dam for both analyses. The maximum S11, S22 and S33 stresses are obtained as 1.60MPa and 2.84MPa; 1.39MPa and 2.43MPa; 0.60MPa and 0.50MPa, respectively. The differences between maximum longitudinal, transverse, and vertical stresses obtained from construction stage and static analyses are 78%, 75%, and %17, respectively. On the other hand, there is averagely 12% difference between minimum stresses for all three directions.

Keywords: concrete arch dam; construction stage analysis; finite element analysis; time dependent material properties

1. Introduction

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Arch dams are one of the important engineering structures for public safety due to retaining a large quantity of water. In case the failure of these dams, economical and life losses can come into exist. So, arch dams have economical and strategically importance for the countries. Therefore, the identification of the structural behaviour of these structures under variable loads has to determine accurately using finite element analysis (USACE 2003; Lotfi 2004; Lotfi 2005; Karaton *et al*. 2006; Akköse *et al*. 2007; Aköse *et al*. 2008; Bayraktar *et al*. 2008; Bayraktar *et al*. 2009; Sevim *et al*. 2010). However, in the analytical solutions using finite element models, it is assumed that the structure is built and loaded in a second. But, this type of analysis does not always include the reliable solutions. Because, construction period of the important engineering structures such as dams, bridges, tunnels, and tall buildings carry on a long time and loads may be change during the period. In addition to these, the geometry of arch dams has doubled curvature in plan and elevation generally. They have two structural behaviours such as arch and cantilever. So, construction stages and time dependent material properties must be considered in the analysis for these types of structures.

Construction stage analysis using time dependent materials is a new method to obtain the realistic behaviour of engineering structures. These methods have been started to use since last decade. In the literature, some researches exist about the construction stage analysis and time dependent material properties of the structures. Cheng *et al*. (2003) carried out the wind induced load capacity of a long span steel arch bridge during two construction stages. Pindado *et al*. (2005) investigated the influence of the section shape of box girder decks on the moments during construction stages experimentally. Karakaplan *et al*. (2007) performed the construction stage analysis of a cable supported pedestrian bridge and a tall building considering time dependent material strength variations. Analysis results compared with each other and the differences are presented. Somja and Goyet (2008) studied about nonlinear finite element analysis of segmentally constructed cable stayed bridge. Time dependent effects including load history, creep, shrinkage and aging of the concrete considered in the analyses. Modification of the bridge topology has carried out using an efficient procedure for creating/removing elements. Cho and Kim (2008) carried out probabilistic risk assessment for the construction stages of the Hanbit suspension bridge. The bridge is under construction and will be one of the longest suspension bridges in Korea in 2010. The main span designed as 850 m with two side spans of 255 m and 220 m each. Tensile forces for main cables and deflections for stiffening girders are controlled for each construction stages. Altunışık *et al*. (2010) performed the construction stage analysis of Kömürhan Highway Bridge constructed with balanced cantilever method using time dependent material properties.

In this paper, it is aimed to determine the effects of the construction stages using time dependent material properties on the structural behaviour of concrete arch dams. Type-5 arch dam suggested in ‘‘Arch Dams’’ symposium in England in 1968 is selected as an example. The time dependent material strength variations and geometric variations are included in the construction stage analysis. Elasticity modulus, creep and shrinkage are computed for different stages of the construction process. The structural behaviour of the arch dam at different construction stages has been examined.

2. Formulation

The 3D finite element models of Type-5 arch dam are constituted using SAP2000 (2008) software. In the program, time dependent material properties of concrete such as elasticity modulus, creep and shrinkage are considered according to the CEB-FIB (1990). The formulations of the time dependent materials related to CEB-FIB (1990) are summarized below.

2.1 Compressive strength

The compressive strength of concrete at an age t depends on the type of cement, temperature and curing conditions. The relative compressive strength of concrete at various ages may be estimated by the following formula (CEB-FIP 1990);

$$f_{cm}(t) = ß_{cc}(t) f_{cm} \tag{1}$$

in which $ß_{cc}(t)$ is a coefficient with depends on the age of concrete and is calculated by

$$\beta_{cc}(t) = \exp\left\{ s\left[1 - \left(\frac{28}{t/t_1} \right)^{1/2} \right] \right\} \tag{2}$$

$f_{cm}(t)$ is the mean concrete compressive strength at an age of t days, f_{cm} is the mean compressive strength after 28 days, t is the age of concrete in days and s is a cement type coefficient.

2.2 Aging of concrete

The elasticity modulus of concrete changes with timely. For this reason, the modulus at an age $t \neq 28$ days may be estimated by

$$E_{ci}(t) = E_{ci}\sqrt{\beta_{cc}(t)} \tag{3}$$

where $E_{ci}(t)$ is the modulus of elasticity at age of t days, E_{ci} is the modulus of elasticity at an age of 28 days, $ß_{cc}(t)$is a coefficient which depends on the age of concrete.

2.3 Shrinkage of concrete

The CEB-FIP Model Code (1990) gives the following equation of total shrinkage strain of concrete;

$$f_{cs}(t,t_s) = \varepsilon_{cso} ß_s(t-t_s) \tag{4}$$

where ε_{cso} is notional shrinkage coefficient, $ß_s$ is the coefficient to describe the development of shrinkage with time, t is the age of concrete in days and t_s is the age of concrete in days at the beginning of shrinkage.

2.4 Creep

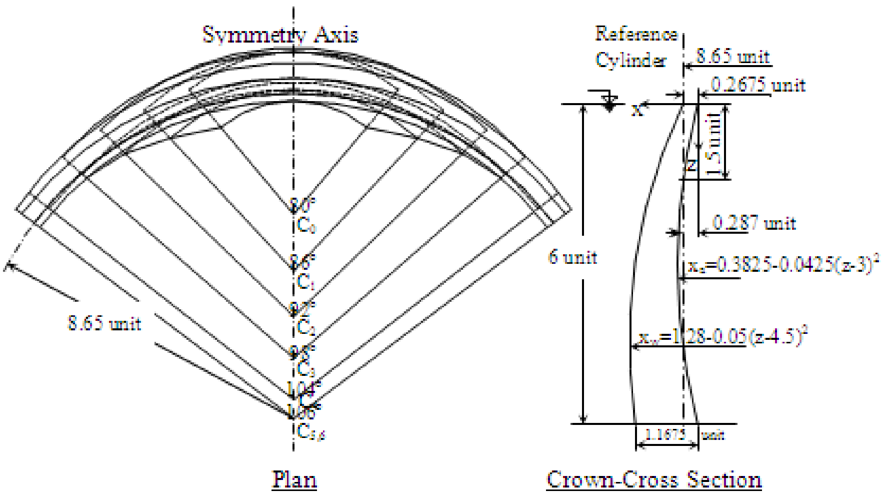
The creep effect is calculated using CEB-FIP Model Code (1990) creep model. For a constant stress applied at time to, this leads to;

$$E_{ci} \tag{5}$$

in which $\sigma_c(t_\sigma)$ is the stress at an age of loading to, $\phi(t, t_\sigma)$ is the creep coefficient and is calculated from

$$\phi(t, t_o) = ß_c(t - t_o)\ \phi_o \tag{6}$$

where $ß_c$ is the coefficient to describe the development of creep with time after loading, t is the age of concrete in days at the moment considered, to is the age of concrete at loading in days.



Level	C_0	C_1	C_2	C_3	C_4	C_5	C_6
Radius (unit)	3.67	5.29	6.64	7.72	8.54	8.80	8.50
Central Angle	80°	86°	92°	98°	104°	106°	106°

Fig. 1 The view in plan and vertical crown-cross section of Type-5 arch dam

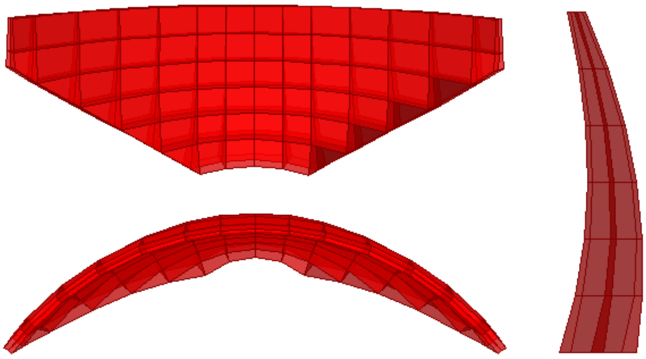


Fig. 2 3D Finite element model of type-5 arch dam

3. Description of rype-5 arch dam

A double curvature Type-5 arch dam suggested in ‘‘Arch Dams’’ symposium in England in 1968 is selected as a numerical example (Arch Dams 1968). The geometrical properties of Type-5 arch dam appear in Fig. 1. As seen in Fig. 1, Type-5 arch dam has a double curvature, variable radius and variable central angle. In addition, it has 6 unit height, 0.2675 unit thicknesses at the crest and 1.1675 unit at the base constant widths. In the finite element model, 1 unit is selected as 20 m. Therefore, the height of dam is computed as 120 m, and computed thickness of dam at the top is 5.35 m and at the base is 23.35 m. 3D finite element model of the dam is appear in Fig. 2.

4. Construction stage analysis

4.1 Modelling of the construction stages

In the construction stage analysis, some special points given below should be considered;

- All construction stages and their details should be determined from design to management,
- Working plan including construction durations of main structural elements of the arch dam should be prepared,
- Added and removed loads for each construction stages should be determined,
- To obtain the reliable solution, each stage results should be added to end of the each stage and next stage analysis is done,
- Non-linear solution parameters should be selected depending on the literature.

In the literature, there is not enough study related to constructed stage analyses of ach dams, so some acceptances in the analyses are considered by the authors. In the construction stage analyses of Type-5 arch dam, a total of 64 construction stages are included. Each stage has generally 6000 m^3 concrete volume. Total duration from the beginning to end of the construction is taken into account as 1280 days. Maximum total step and maximum iteration for each step are selected as 200 and 50, respectively. Firstly, a suitable formwork is placed to the related segment. Then, the segment (20m height) is concreted from the base to the crest of the dam. After the concreting, the formwork is moved using form carrier to the next segment and a new cycle is started. This sequence is averagely completed in twenty days. The operation sequence is summarized in Table 1. Fig. 3 shows some construction stages obtained from SAP2000 finite element analysis program according to procedure. In addition, some photos related to construction stages of arch dams appear in Fig. 3 as an example.

Table 1 The typical operation sequence of construction stages

Time	Working plan
1st-4th Days	Setting up and adjusting of formwork
5th-16th Days	Concreting of the segment
17th-20th Days	Removing of the formwork, moving the form carrier to the next position and starting a new cycle

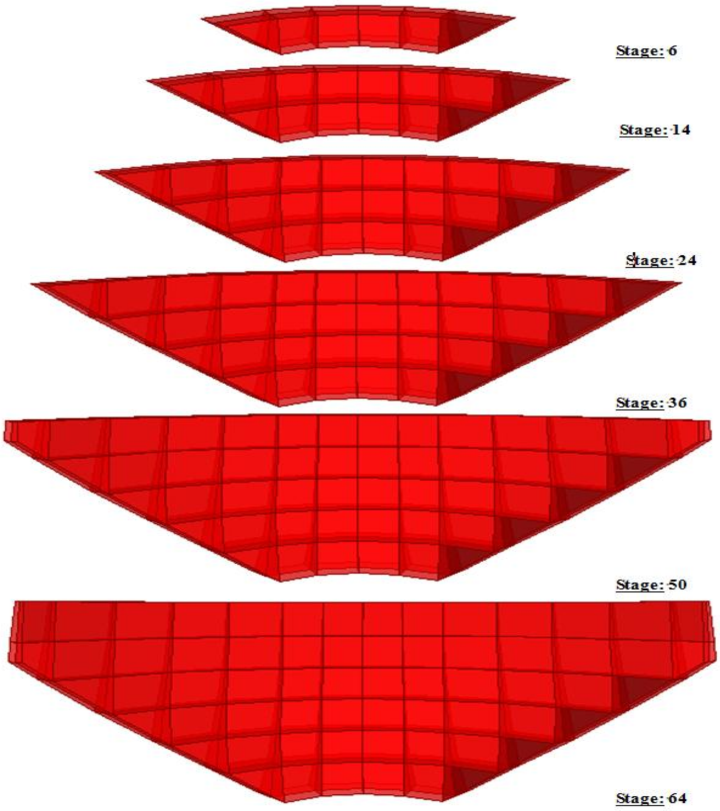


Fig. 3 Some construction stages of Type-5 arch dam

Fig. 4 Some photos related to construction stages of arch dams

4.2 Determination of the time dependent material properties

In the construction stage analyses of ach dams, time dependent material properties such as elasticity modulus, creep and shrinkage for concrete should be considered, because they are variable due to the climate during the construction. Time effects and cracking make analyses even more complex for concrete arch dams. Creep strains develop at early stages of the construction process and continue to evolve significantly after the structure is built. Depending on the construction method, restrained creep can appear and induce important stress redistribution in the structure. To accurately analyze structures both during their construction and along their entire life, engineers must have at their disposal appropriate design methods. The effects of geometry changes occur during construction of the structure cannot be taken into account using standard finite element codes since structural elements are added and removed at certain time instants. Analysis parameters for time dependent material properties are summarized in Table 2.

Variation of time dependent material properties used for concrete appears in Figs. 5 and 6. These parameters are selected from CEB-FIB design code (CEB-FIB 1990) in SAP2000. According to the parameters in Table 2, these graphics may be changed automatically. Total duration of the analysis from beginning the construction of the arch dam to nowadays is considered as 1280 days.

Table 2 Selected analysis parameters for time dependent material properties (CEB-FIB 1990)

Parameters		Arch dam
Material properties		Concrete (Isotropic)
Nonlinear material data	Hysteresis type	Kinematic
	Stress-Strain diagram	User defined
Time dependent properties	Elasticity modulus	✓
	Creep	✓
	Shrinkage	✓
	Creep analysis type	Full
	Cement type coefficient	0.25
	Relative humidity %	60
	Notional size	0.1
	Shrinkage coefficient	5
	Shrinkage start age	0

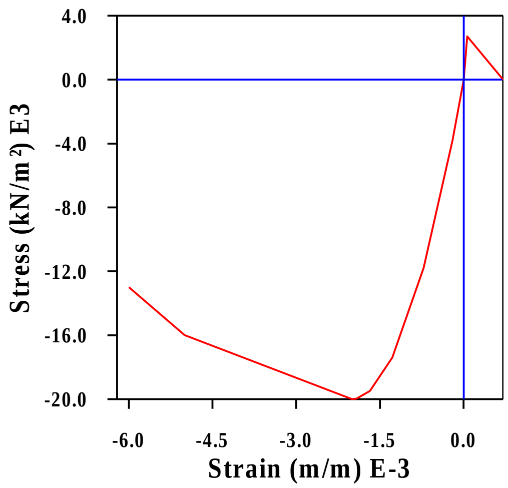
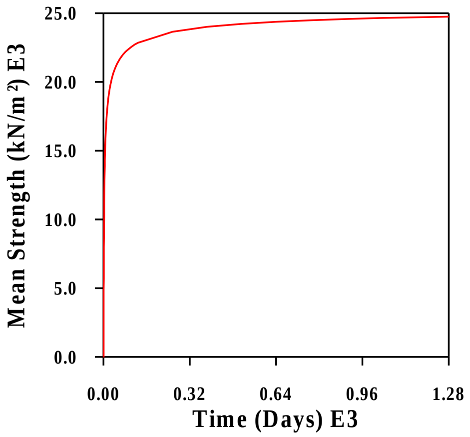
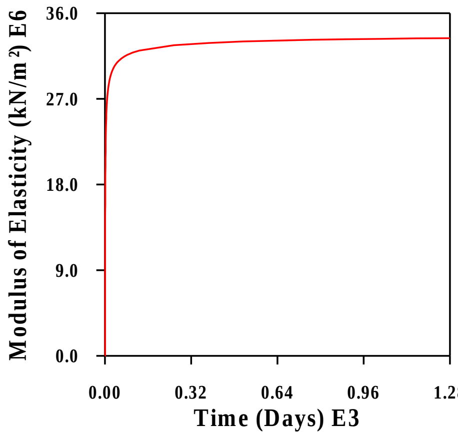


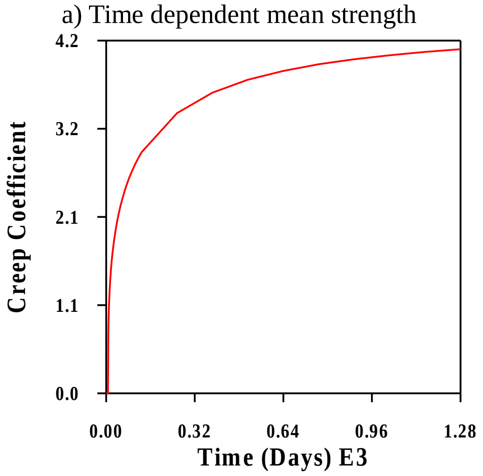
Fig. 5 Stress-strain diagrams used for concrete



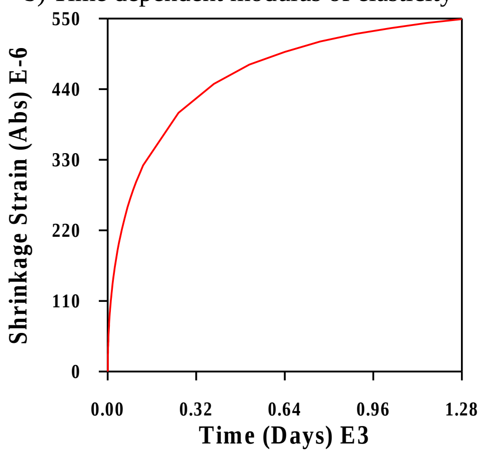
a) Time dependent mean strength



b) Time dependent modulus of elasticity



c) Time dependent creep coefficient



d) Time dependent shrinkage strain

Fig. 6 Variation of time dependent material properties for concrete

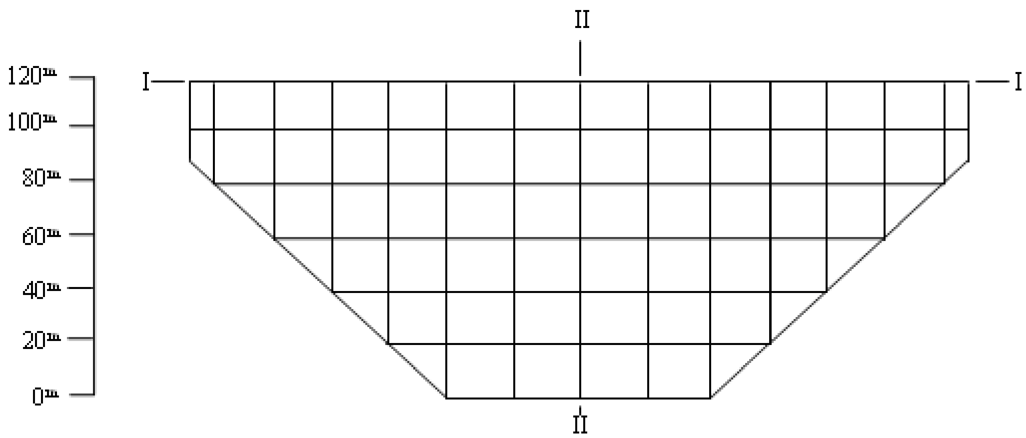


Fig. 7 Finite element mesh model of type-5 arch dam

4.3 Construction stage analysis using time dependent material properties

The construction stages using time dependent material properties effects on the structural behaviour of Type-5 arch dam are presented in this part of the study. Analyses are performed using SAP2000 program. Nonlinear staged construction and P-Delta plus large displacements options are selected as analysis type. In the analysis two different cases are considered to determine construction stages and time dependent material properties effects more pronouncedly:

- Case 1: Construction stages using time dependent material properties are not considered. Linear static analysis of the arch dam is performed.
- Case 2: Construction stages using time dependent material properties are considered.

Finite element mesh model of Type-5 arch dam and sections selected for comparison of both analyses results are shown in Fig. 7.

4.3.1 Deformation shapes and displacements

The deformations of Type-5 arch dam for some construction stages are plotted in Fig. 8. In addition, the maximum U1, U2 and U3 displacements are listed in Table 3. Here, maximum displacements occur in the middle point of the crest for the stages 6, 14, 24, 36, 50, and 64. The terms of the U1, U2 and U3 are used to imply the longitudinal, transverse and vertical displacements, respectively.

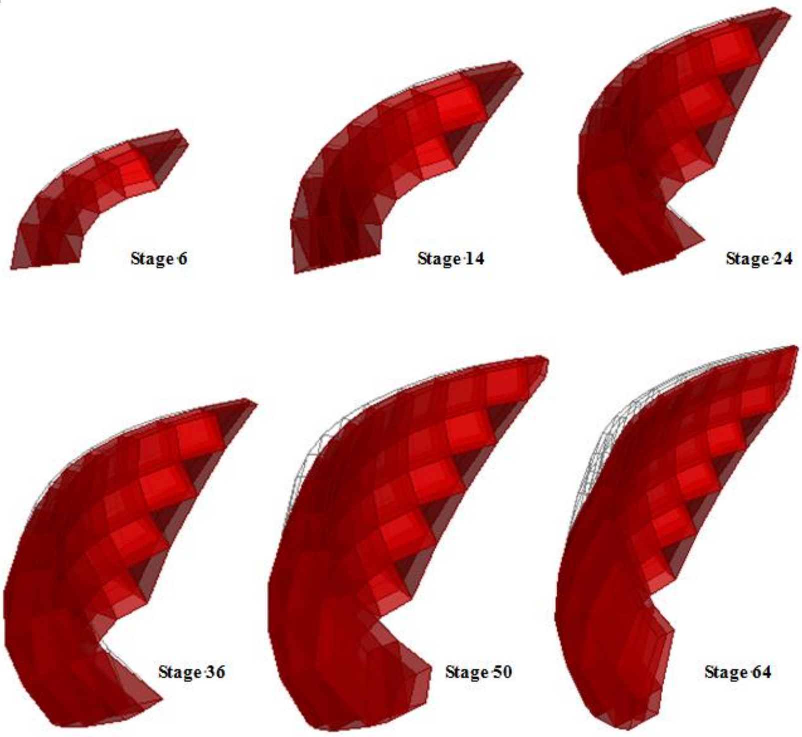


Fig. 8 Deformation of Type-5 arch dam during some construction stages (units in mm)

Table 3 Maximum U1, U2, and U3 displacements obtained from construction stage analyses

Stages	Maximum displacements (mm)		
	U1	U2	U3
6	0.24	0.22	0.53
14	0.52	1.21	1.30
24	0.86	1.71	1.69
36	1.21	0.49	1.95
50	1.35	2.87	2.49
64	1.01	8.44	4.00

Table 4 Displacements (mm) obtained from II-II section of Type-5 arch dam

Dam height	Construction stage			Static		
(m)	U1	U2	U3	U1	U2	U3
120	1.01	-8.44	-4.00	0	0.04	-9.90
100	1.35	-2.87	-2.49	0	4.33	-8.43
80	1.21	0.49	-1.95	0	6.64	-7.27
60	0.87	1.71	-1.69	0	6.68	-6.12
40	0.52	1.21	-1.30	0	4.72	-4.76
20	0.24	0.22	-0.53	0	1.66	-2.42
0	0	0	0	0	0	0

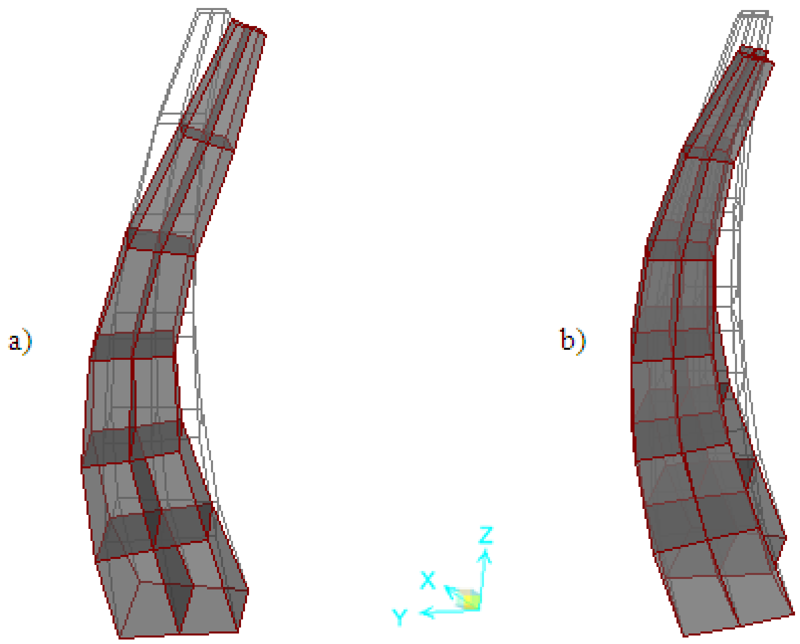


Fig. 9 Deformation shapes of Type-5 arch dam (a) considered construction stages and (b) not considered construction stages

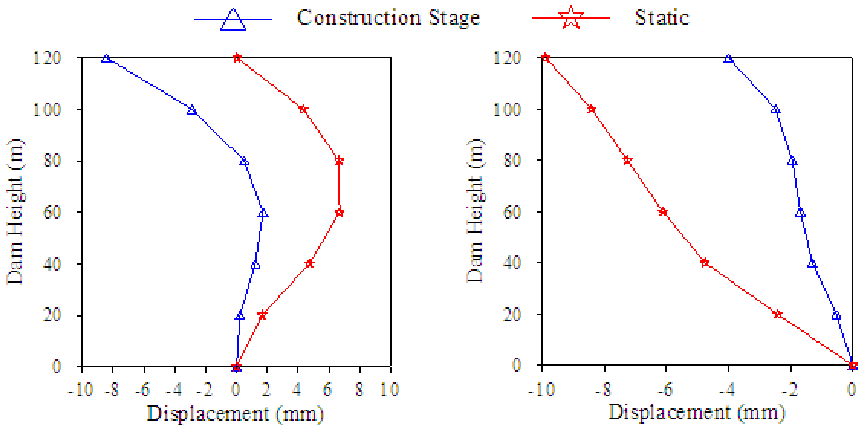


Fig. 10 Variation of (a) transverse, (b) vertical displacements along to II-II section

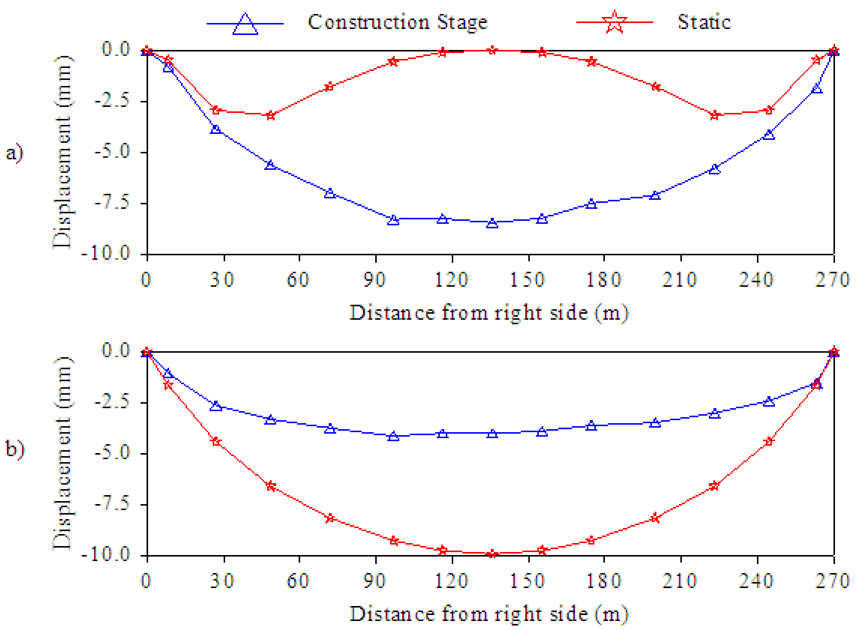


Fig. 11 Variation of (a) transverse, (b) vertical displacements along to I-I section

Deformation shapes of Type-5 arch dam obtained from construction stages and static analyses appear in Fig. 9. Displacements obtained from II-II section for both analyses are listed in Table 4. As seen in Table 4 that the maximum longitudinal, transverse and vertical displacements obtained from construction stages and static analyses are 1.35 mm and 0 mm; -8.44 and 6.68 mm; -4.00 and -9.90 mm, respectively. In addition, vertical displacements increase from the base to crest of the dam for both analyses. The variation of transverse and vertical displacements along to I-I and II-II sections for both analyses are plotted in Figs. 10 and 11, respectively. Figs. 10 and 11 show that the construction stage analysis has important effects on the displacements of Type-5 arch dam compared to static analysis results.

4.3.2 Stresses

The maximum longitudinal (S11), transverse (S22) and vertical (S33) stresses obtained from construction stages and static analyses are 1.60MPa and 2.84MPa; 1.39MPa and 2.43MPa; 0.60MPa and 0.50MPa, respectively. In addition, the minimum S11, S22 and S33 components of stresses obtained from construction stages and static analyses are -1.96MPa and -2.18MPa; -1.54MPa and -1.33MPa; -7.20MPa and -6.32MPa, respectively. The differences between maximum longitudinal, transverse, and vertical stresses obtained from construction stage and static analyses are 78%, 75%, and 17%, respectively. On the other hand, there is averagely 12% difference between minimum stresses for all three directions. However, the stresses obtained from construction stage and static analyses have acceptable values compared to strength of concrete material of the arch dam.

Contour diagrams of S22 and S33 stresses of Type-5 arch dam obtained from the construction stage and static analyses appear in Fig. 12. Fig. 12 shows that the construction stage analysis has important effects on the transverse and vertical stresses of Type-5 arch dam compared to static analysis results.

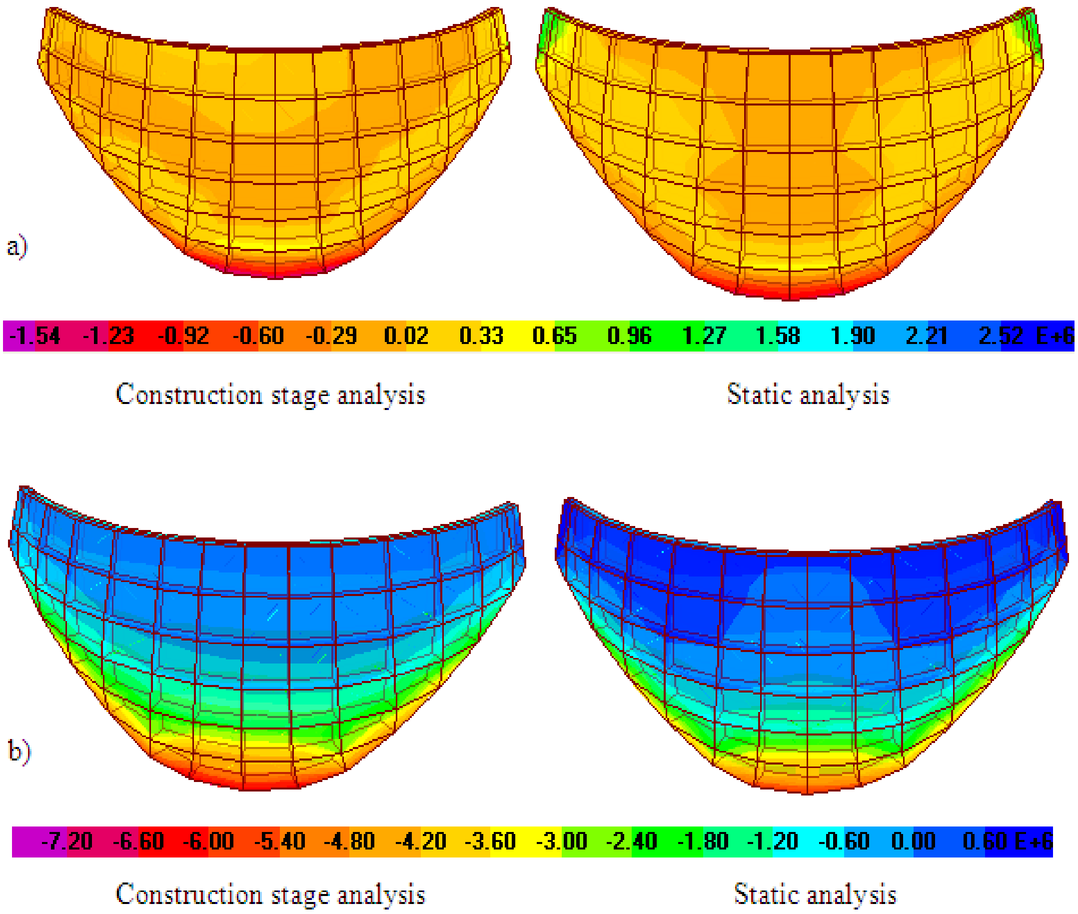


Fig. 12 Contour diagrams of a) S22 and b) S33 stresses of Type-5 arch dam

5. Conclusions

The paper presents an efficient analytical procedure for materially and geometrically nonlinear finite element analysis of arch dams including time dependent effects due to creep, shrinkage and aging of the concrete. A double curvature Type-5 arch dam suggested in ‘‘Arch Dams’’ symposium in England in 1968 is selected for the numerical example. The P-Delta plus large displacement criterion is employed in the geometrical nonlinear analysis. The time dependent material strength variations and geometric variations are included in the analysis. From the results of this study, the following observations can be made:

- The maximum longitudinal, transverse and vertical displacements obtained from construction stages and static analyses are 1.35 mm and 0 mm; -8.44 and 6.68 mm; -4.00 and -9.90 mm, respectively. In addition, vertical displacements increase from the base to crest of the dam for both analyses. However there is not a regular distribution for transverse displacements along the dam height. It is seen that the construction stage analysis has important effects on the displacements of Type-5 arch dam compared to static analysis results.
- The vertical displacements increase towards to middle of the crest both analyses. In addition, vertical displacements distribute symmetrically along to I-I section. Similar variation occurs for transverse displacements obtained from construction stage analysis. However, transverse displacements increase from abutments to 50m and the values decrease towards to middle of the crest.
- The transverse displacements obtained from construction stage analysis are generally bigger than those of static analysis. However, the vertical displacements obtained from static analysis are generally bigger than those of construction stage analysis.
- The maximum longitudinal (S11), transverse (S22) and vertical (S33) stresses obtained from construction stages and static analyses are 1.60MPa and 2.84MPa; 1.39MPa and 2.43MPa; 0.60MPa and 0.50MPa, respectively. In addition, the minimum S11, S22 and S33 components of stresses obtained from construction stages and static analyses are -1.96MPa and -2.18MPa; -1.54MPa and -1.33MPa; -7.20MPa and -6.32MPa, respectively.
- The highest stresses occur near to the abutments of the dam for both analyses. The differences between maximum longitudinal, transverse, and vertical stresses obtained from construction stage and static analyses are 78%, 75%, and %17, respectively. On the other hand, there is averagely 12% difference between minimum stresses for all three directions. However, the stresses obtained from construction stage and static analyses have acceptable values compared to strength of concrete material of the arch dam.
- The results show that construction stage analysis using time dependent material strength variations and geometric variations should be considered in the design phase of arch dams.

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