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Development of engineering software to predict the structural behavior of arch dams

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Abstract. In this study, it is aimed to present engineering software to estimate the structural response of concrete arch dam. Type-1 concrete arch dam constructed in the laboratory is selected as a reference model. Finite element analyses and experimental measurements are conducted to show the accuracy of initial model. Dynamic analyses are carried out by spectrum analysis under empty reservoir case considering soil-structure interaction and fixed foundation condition. The displacements, principal stresses and strains are presented as an analysis results at all nodal points on downstream and upstream faces of dam body. It is seen from the analyses that there is not any specific ratio between prototype and scaled models for each nodal point with different scale values. So, dynamic analyses results cannot be generalized with a single formula. To eliminate this complexity, the regression analysis, which is a statistical method to obtain the real model results according to the prototype model by using fitting curves, is used. The regression analysis results are validated by numerical solutions using ANSYS software and the error percentages are examined. It is seen that 10% error rates are not exceeded.

Keywords: arch dam; engineering software; regression analysis

1. Introduction

With the development of the technology age and the concept of time being so important, there is an increasing trend towards software operations to ensure ease of process. Peng and Law (2002) introduced a software framework, which will serve as the core for collaborative structural analysis program development. Özdemir (2004) analyzed the effects of main and interdependence of data on linear regression and knowledge transfer by aiming to mathematically and structurally define reciprocal dependency structure between two periodic-stochastic hydrological processes. Mittrup and Hartmann (2005) studied on software development for structural control of dams. For this purpose, it is selected Ennepe Dam that gravity dam. The correctness of the software is proved by the tests conducted at the Ennepe Dam and the usage of the application has been recommended. Besiktaş (2010) used the data of some flow observation stations in the Eastern Black Sea Region to estimate flow rates of previously unmeasured points by using the regression analysis method the

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flow continuity curves. Şahin (2009) presented a new algorithm developed to minimize the torsional effects in asymmetric tall buildings. Xiang *et al*. (2011) developed a simply structural damage detection software to identification damage in beams. The presented software in study can be used in actual engineering structures. Qiujing *et al*. (2012) aimed to estimated horizontal displacements, stress and safety of high arch dams during construct and first water storage. Parameters are selected as water level, change of temperature, time, elasticity modulus of rock and concrete. It is aimed to develop formula for obtained dynamic characteristic of historical arch bridges by Bayraktar *et al.* (2014). Within the scope of the Sümerkan (2014) thesis, he developed a formula based on environmental vibration data and finite element analysis to predict the natural frequencies of post-tensioned balanced console bridges. Serhatoğlu (2015) examined the dynamic characteristics and performances of historical minarets. For this purpose, in the scope of the thesis, experimental works and finite element analyses are carried out on 15 historical minarets in Bursa. Within the thesis of Atmaca (2016), software named structGIS is developed in order to complete the earthquake inventory of the existing building stock, which is one of the important stages of earthquake damage estimation and loss reduction studies. Many studies conducted on the subject show that the software is getting more and more important (Chan *et al.* 2010, Şahin and Bayraktar 2010a, Şahin and Bayraktar 2010b, Gu and Özçelik 2011, Cheng 2012, Yılmaz and Şahin 2013).

Dams are engineering constructions with many important tasks such as providing energy, irrigation and drinking water. The difficulty and detail of the design, project and application parts as well as the supervision and control stages are troublesome. Particularly the modeling of the finite elements of dams with arch form is a time consuming and exhausting process. Numerous analytical (Kartal *et al.* 2015), numerical (Ohmachi and Jajali 1999, Oliveira and Faria 2006, Sevim *et al.* 2014) and experimental studies (Nasserzarea *et al*. 2000, Wang 2007, Sevim *et al*. 2011, Sevim *et al*. 2012) have been carried out to obtain the structural behavior of dams. However, with the aid of software developed in the literature, there is few study about estimated the structural behaviors of dams in a short time and easily.

Software is being developed and continuously updated to facilitate the works done in many areas of engineering and to provide save time. It is seen that the need for software is increasing day by day when the researches done are examined. Within the scope of study, it is aimed to obtain the results of the structural behavior of arch dams under dynamic analysis depending on the desired parameters

2. Type-1 arch dam

There are five types of arch dams with different geometries proposed in the symposium "Arch Dams (1968)" held in England in 1968. From this dam types, in order to study in the laboratory were selected model small-scaled Type-1 arch dam. The Type-1 arch dam has geometry that a constant radius, angle and a single curvature.

The geometrical characteristics of the Type-1 arch dam are shown in Fig. 1. The Type-1 arch dam, with a fixed center of 106^o and a fixed radius of 8.65 units, is a symmetrical dam whose downstream face is considegred as a reference. Type-1 arch dam is of 6 units in height, crest and base width of 0.6 units. It is assumed that the cross-section is placed on a valley with a trapezoidal cross-section as shown in Fig. 2 (arch dams 1968). The valley where the Type-1 arch dam is located has of 16 units at the crest level and of 4 units at the base level

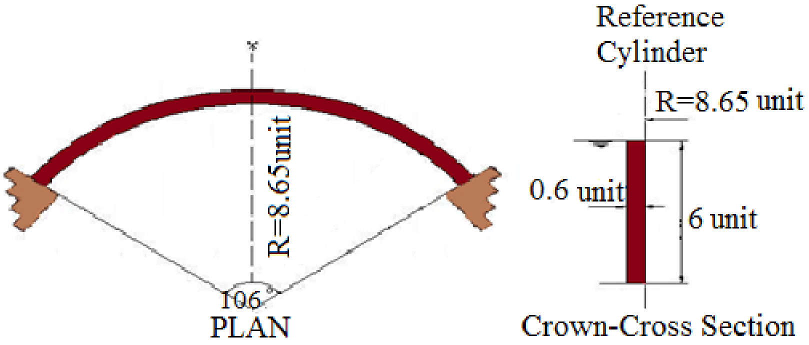


Fig. 1 Geometry properties of Type-1 arch dam (Arch dams 1968)

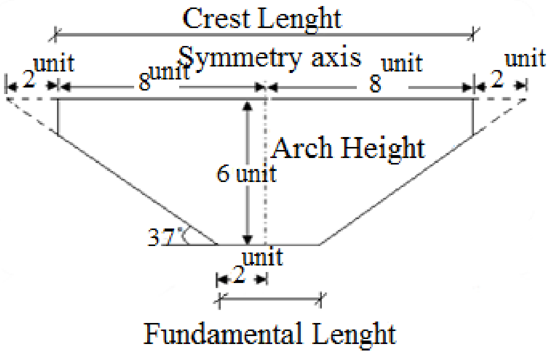


Fig. 2 The cross-section of the valley where the Type-1 arch dam is located (Arch dams 1968)

2.1 Constitution of loboratory model

In the Type-1 arch dam whose dimensions are given in units, 1 unit=10 cm is selected and the laboratory model is created. According to the obtained data, the dam height (H) is 60 cm, the crest and the base width are 6 cm and the crest length of the dam is calculated as 171.13 cm in the upstream face and 160.03 cm in the downstream face. In the studies conducted within the scope of the thesis, the dam model has been developed to include base and reservoir in order to realistically determine the dynamic behavior of the Type-1 arch dam (Sevim 2010). The three-dimensional soil-structure interaction model of the Type-1 arch dam prepared according to these properties and the dimensions of this model are given in Fig. 3. Some photographs of laboratory model of Type-1 Arch DamTip-1 are given in Fig. 4.

2.2 Finite element results

By using the finite element model of the Type-1 arch dam formed in the thesis study done by Sevim (2010), is purposed developing the software to predict the dynamic characteristics and structural characteristics of the dams.

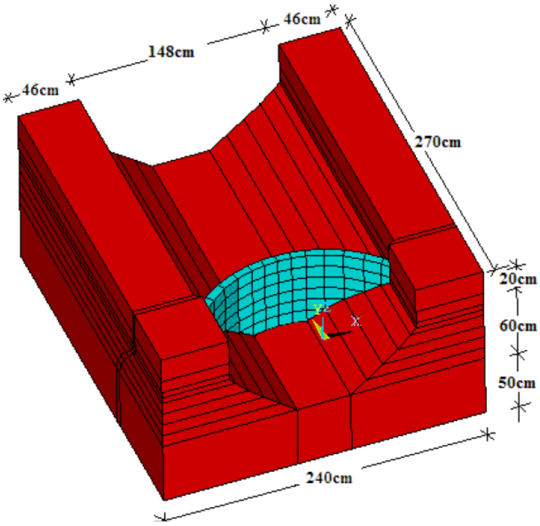


Fig. 3 Three dimension soil-structure interaction model of Type-1 arch dam (Sevim 2010)

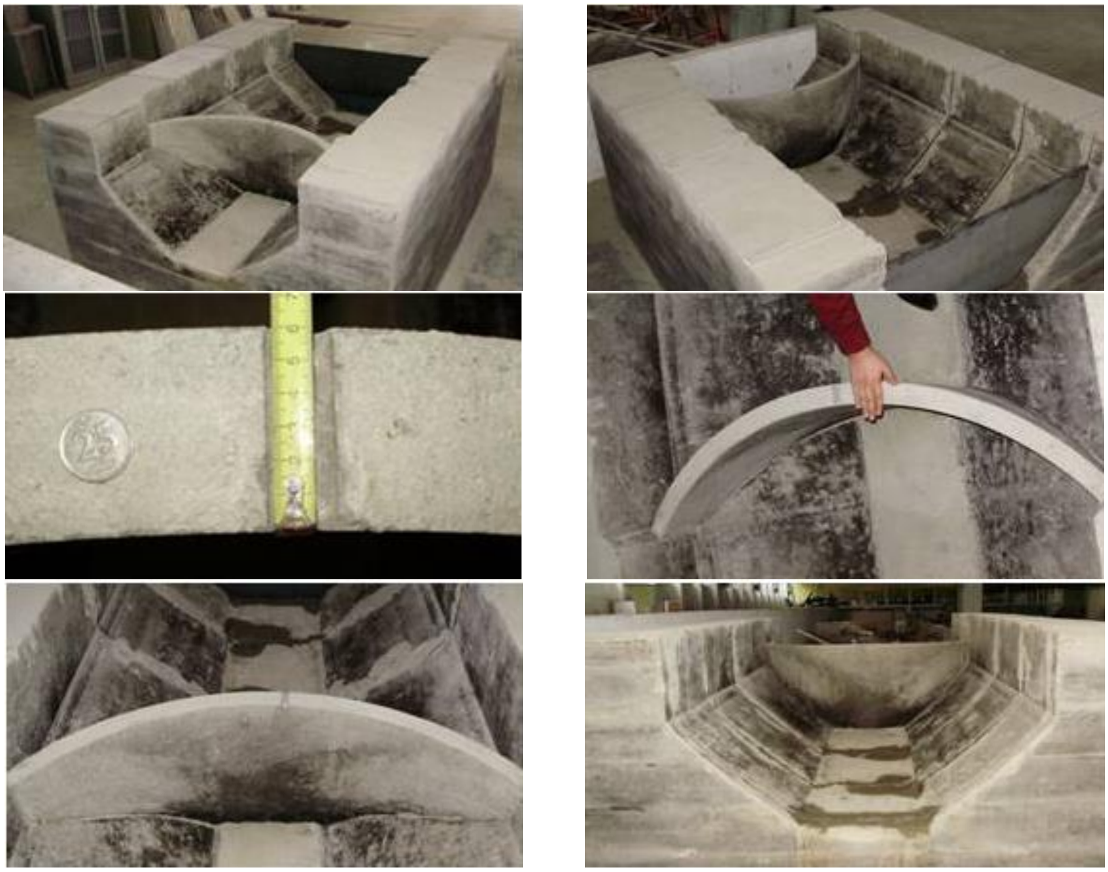


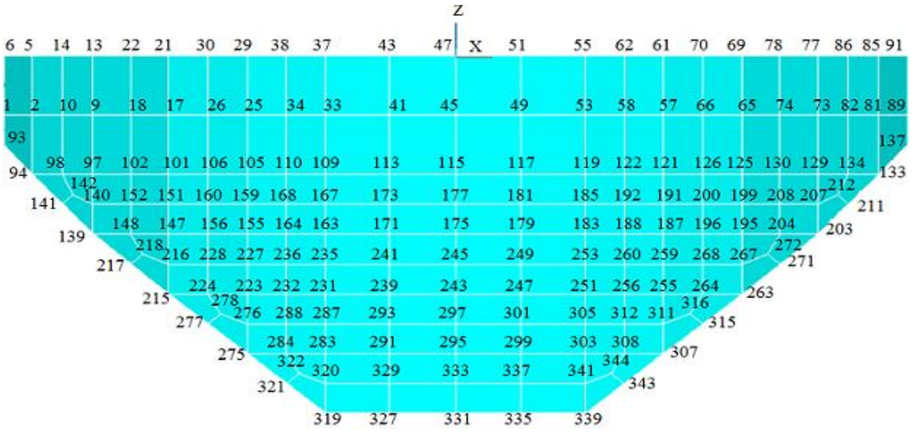
Fig. 4 Some photographs of laboratory model of Type-1 arch damTip-1 (Sevim 2010)

2.2.1 Dynamic analysis results of laboratory model of Type-1 arch dam

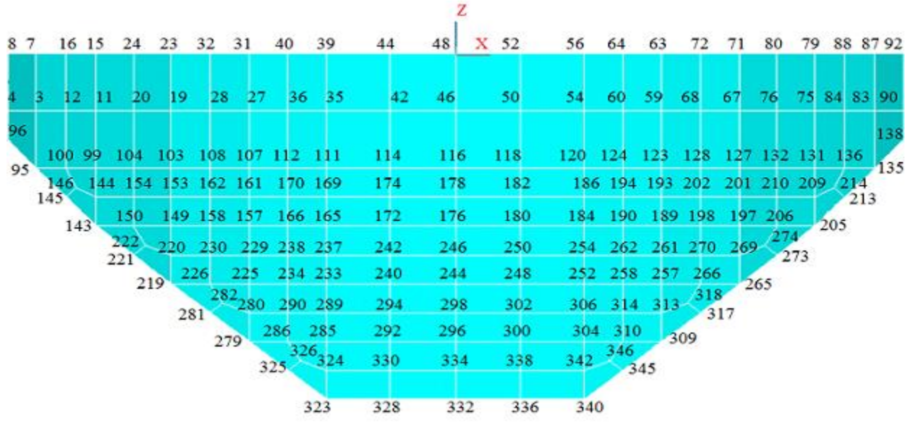
The dynamic analysis of the Type-1 arch dam is carried out by spectrum analysis, taking into account the fact that the reservoir is empty. As a result of dynamic analyses, displacements, principal stresses and principal strains are obtained at all nodal points in the dam body. A total of 346 nodal points are located on the upstream and downstream surfaces of the arch. Fig. 5 shows the number of nodal points on the upstream and downstream surfaces of the arch.

In the scope of the study, 10 nodal points are selected which is give critical values in order to study the changes in displacement, principal stresses and principal strains from nodal points on the arch upstream and downstream surfaces.

The dynamic analysis of the Type-1 arch dam is performed according to Response Spectral Analysis Method. The spectral plots obtained for the 5% damping ratio taken into account during analysis are given in Fig. 6. Relevant graphs are obtained for with a possibility of exceeding of the earthquake within a period of 50 years is 10% and are applied in the upstream-downstream direction by considering the soil-structure interaction and fixed support.



(a) Upstream surface



(b) Downstream surface

Fig. 5 Nodal points numbers of upstream and downstream surface of Type-1 arch dam

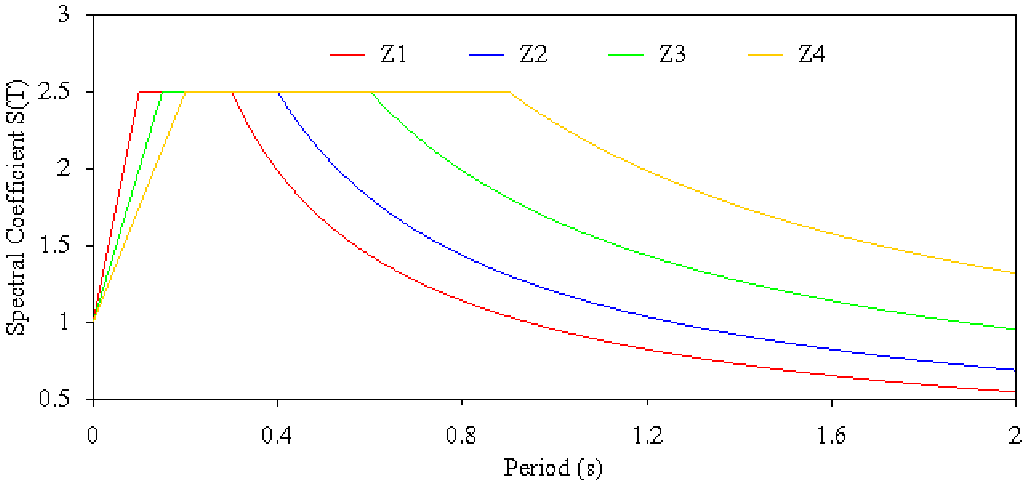


Fig. 6 Spectrum graphic prepared for local site classes

Table 1 Displacement values obtained from Type-1 arch dam that soil-structure interaction

Nodal Points	Displacements (cm)			
	Z1	Z2	Z3	Z4
48	2.2270E-04	2.1301E-04	2.1301E-04	2.0817E-04
103	3.3530E-05	3.2073E-05	3.2073E-05	3.1344E-05
115	1.2778E-04	1.2223E-04	1.2223E-04	1.1945E-04
125	3.1161E-05	2.9806E-05	2.9806E-05	2.9129E-05
169	7.7629E-05	7.4254E-05	7.4254E-05	7.2567E-05
185	7.2703E-05	6.9542E-05	6.9542E-05	6.7962E-05
238	4.0173E-05	3.8426E-05	3.8426E-05	3.7553E-05
246	9.5207E-05	9.1068E-05	9.1068E-05	8.8998E-05
260	3.5417E-05	3.3877E-05	3.3877E-05	3.3107E-05
332	1.9967E-05	1.9099E-05	1.9099E-05	1.8665E-05

Table 2 Displacement values obtained from Type-1 arch dam that fixed support condition

Nodal Points	Displacements (cm)			
	Z1	Z2	Z3	Z4
48	1.5163E-04	1.4503E-04	1.4503E-04	1.4174E-04
103	1.8147E-05	1.7358E-05	1.7358E-05	1.6963E-05
115	9.1853E-05	8.7860E-05	8.7860E-05	8.5863E-05
125	1.6317E-05	1.5608E-05	1.5608E-05	1.5253E-05
169	4.8946E-05	4.6818E-05	4.6818E-05	4.5754E-05
185	4.5475E-05	4.3498E-05	4.3498E-05	4.2509E-05
238	2.0403E-05	1.9516E-05	1.9516E-05	1.9073E-05
246	5.2402E-05	5.0124E-05	5.0124E-05	4.8985E-05
260	1.7415E-05	1.6658E-05	1.6658E-05	1.6279E-05
332	0	0	0	0

The displacement values obtained as a result of the dynamic analysis of the Type-1 arch dam are given in Tables 1 and 2 for the selected nodal points. During the analysis, the empty state of the reservoir is taken into consideration and both soil-structure and fixed support interaction results are examined in order to compare the obtained results.

Table 3 Maximum principal stress values obtained from Type-1 arch dam that soil-structure interaction

Nodal Points	Maximum Principal Stresses (MPa)			
	Z1	Z2	Z3	Z4
48	0.023823	0.022788	0.022788	0.02227
103	0.017686	0.016917	0.016917	0.016532
115	0.020964	0.020052	0.020052	0.019597
125	0.009437	0.009027	0.009027	0.008822
169	0.020436	0.019547	0.019547	0.019103
185	0.020623	0.019726	0.019726	0.019278
238	0.015846	0.015157	0.015157	0.014812
246	0.018644	0.017834	0.017834	0.017428
260	0.011436	0.010938	0.010938	0.01069
332	0.01288	0.01232	0.01232	0.01204

Table 4 Maximum principal stress values obtained from Type-1 arch dam that is fixed support condition

Nodal Points	Maximum Principal Stresses (MPa)			
	Z1	Z2	Z3	Z4
48	0.013445	0.01286	0.01286	0.012568
103	0.012086	0.01156	0.01156	0.011297
115	0.013911	0.013306	0.013306	0.013004
125	0.00445	0.004257	0.004257	0.00416
169	0.009387	0.008979	0.008979	0.008775
185	0.008851	0.008466	0.008466	0.008274
238	0.009563	0.009147	0.009147	0.008939
246	0.006237	0.005966	0.005966	0.00583
260	0.005459	0.005222	0.005222	0.005103
332	0.009888	0.009458	0.009458	0.009243

Table 5 Minimum principal stress values obtained from Type-1 arch dam that soil-structure interaction

Nodal Points	Minimum Principal Stresses (MPa)			
	Z1	Z2	Z3	Z4
48	0.013445	0.01286	0.01286	0.012568
103	0.012086	0.01156	0.01156	0.011297
115	0.013911	0.013306	0.013306	0.013004
125	0.00445	0.004257	0.004257	0.00416
169	0.009387	0.008979	0.008979	0.008775
185	0.008851	0.008466	0.008466	0.008274
238	0.009563	0.009147	0.009147	0.008939
246	0.006237	0.005966	0.005966	0.00583
260	0.005459	0.005222	0.005222	0.005103
332	0.009888	0.009458	0.009458	0.009243

The principal stress (max. and min.) values obtained as a result of the dynamic analysis of the Type-1 arch dam are given in Tables 3-6 for selected nodal points. During the analysis, the empty state of the reservoir is taken into consideration and both soil-structure and fixed support interaction results are examined in order to compare the obtained results.

Table 6 Minimum principal stress values obtained from Type-1 arch dam that is fixed support condition

Nodal Points	Minimum Principal Stresses (MPa)			
	Z1	Z2	Z3	Z4
48	0.00016182	0.00015478	0.00015478	0.00015126
103	0.00015797	0.0001511	0.0001511	0.00014766
115	0.0001835	0.00017552	0.00017552	0.00017153
125	-0.00022422	-0.00021447	-0.00021447	-0.0002096
169	-0.0011011	-0.0010533	-0.0010533	-0.0010293
185	4.2004E-06	4.0177E-06	4.0177E-06	3.9263E-06
238	-0.00092956	-0.00088915	-0.00088915	-0.00086894
246	0.000098718	0.000094426	0.000094426	0.00009228
260	-0.000042164	-0.000040331	-0.000040331	-0.000039414
332	0.00042281	0.00040443	0.00040443	0.00039524

Table 7 Maximum principal strain values obtained from Type-1 arch dam that soil-structure interaction

Nodal Points	Maximum Principal Strains			
	Z1	Z2	Z3	Z4
48	1.5946E-06	1.5253E-06	1.5253E-06	1.4906E-06
103	1.2463E-06	1.1921E-06	1.1921E-06	1.1650E-06
115	1.3194E-06	1.2620E-06	1.2620E-06	1.2333E-06
125	6.8609E-07	6.5626E-07	6.5626E-07	6.4135E-07
169	1.5258E-06	1.4595E-06	1.4595E-06	1.4263E-06
185	1.3413E-06	1.2830E-06	1.2830E-06	1.2539E-06
238	1.2244E-06	1.1711E-06	1.1711E-06	1.1445E-06
246	1.2083E-06	1.1558E-06	1.1558E-06	1.1295E-06
260	7.8553E-07	7.5137E-07	7.5137E-07	7.3430E-07
332	8.4597E-07	8.0919E-07	8.0919E-07	7.9080E-07

Table 8 Maximum principal strain values obtained from Type-1 arch dam that is fixed support condition

Nodal Points	Maximum Principal Strains			
	Z1	Z2	Z3	Z4
48	8.8409E-07	8.4565E-07	8.4565E-07	8.2643E-07
103	8.3497E-07	7.9867E-07	7.9867E-07	7.8052E-07
115	9.0631E-07	8.6691E-07	8.6691E-07	8.4721E-07
125	3.3324E-07	3.1875E-07	3.1875E-07	3.1151E-07
169	7.1448E-07	6.8342E-07	6.8342E-07	6.6788E-07
185	6.1758E-07	5.9072E-07	5.9072E-07	5.7730E-07
238	7.3285E-07	7.0099E-07	7.0099E-07	6.8506E-07
246	4.0388E-07	3.8632E-07	3.8632E-07	3.7754E-07
260	3.9477E-07	3.7761E-07	3.7761E-07	3.6902E-07
332	6.5032E-07	6.2205E-07	6.2205E-07	6.0791E-07

Table 9 Minimum principal strain values obtained from Type-1 arch dam that soil-structure interaction

Nodal Points	Minimum Principal Strains			
	Z1	Z2	Z3	Z4
48	1.9635E-07	1.8781E-07	1.8781E-07	1.8354E-07
103	-1.2774E-07	-1.2218E-07	-1.2218E-07	-1.1940E-07
115	3.6215E-07	3.4641E-07	3.4641E-07	3.3853E-07
125	-8.4921E-08	-8.1229E-08	-8.1229E-08	-7.9383E-08
169	-2.4597E-08	-2.3528E-08	-2.3528E-08	-2.2993E-08
185	1.1772E-07	1.1260E-07	1.1260E-07	1.1004E-07
238	-1.8366E-08	-1.7567E-08	-1.7567E-08	-1.7168E-08
246	2.2962E-07	2.1964E-07	2.1964E-07	2.1465E-07
260	-7.6498E-09	-7.3172E-09	-7.3172E-09	-7.1509E-09
332	5.2318E-08	5.0043E-08	5.0043E-08	4.8906E-08

Table 10 Minimum principal strain values obtained from Type-1 arch dam that is fixed support condition

Nodal Points	Minimum Principal Strains			
	Z1	Z2	Z3	Z4
48	1.0167E-07	9.7254E-08	9.7254E-08	9.5043E-08
103	-1.1209E-07	-1.0722E-07	-1.0722E-07	-1.0478E-07
115	2.0095E-07	1.9221E-07	1.9221E-07	1.8785E-07
125	-4.2187E-08	-4.0353E-08	-4.0353E-08	-3.9435E-08
169	-1.2496E-07	-1.1953E-07	-1.1953E-07	-1.1681E-07
185	3.3176E-08	3.1733E-08	3.1733E-08	3.1012E-08
238	-9.9894E-08	-9.5551E-08	-9.5551E-08	-9.3379E-08
246	8.6839E-08	8.3063E-08	8.3063E-08	8.1176E-08
260	1.3790E-09	1.3190E-09	1.3190E-09	1.2890E-09
332	3.0511E-09	2.9184E-09	2.9184E-09	2.8521E-09

The principal strain (max. and min.) values obtained as a result of the dynamic analysis of the Type-1 arch dam are given in Tables 7-10 for selected nodal points. During the analysis, the empty state of the reservoir is taken into consideration and both soil-structure and fixed support interaction results are examined in order to compare the obtained results.

2.2.2 Investigation of dynamic analysis results of Type-1 arch dams at different heights

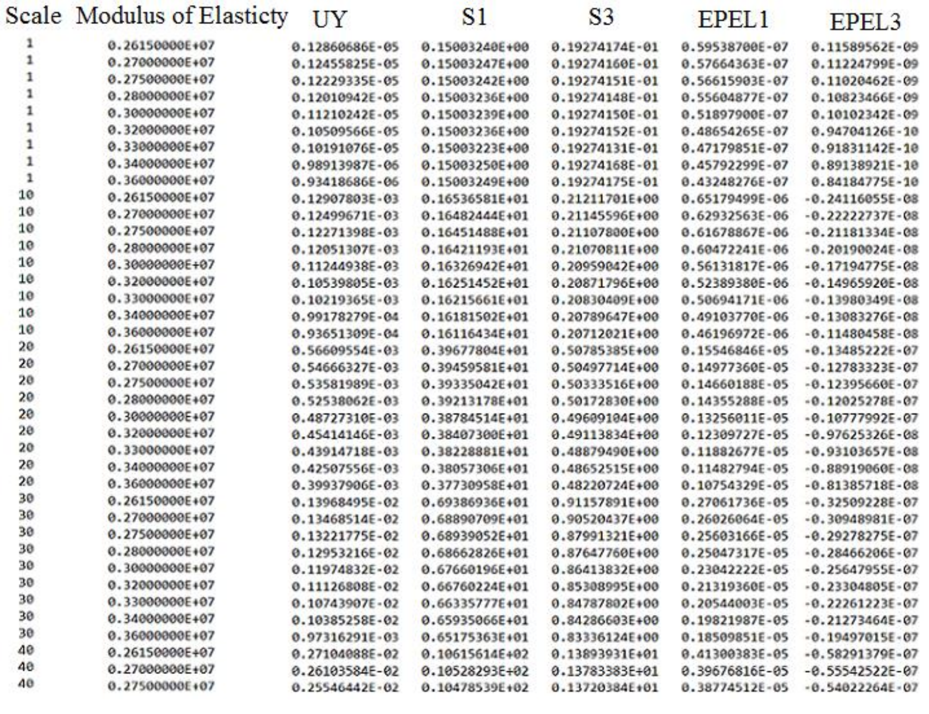
Under the time-dependent changing loads, it seems that there are disproportional between displacements, principal stresses and principal strains values obtained from the prototype and different scale of dam. In other words, the ratio of values obtained at any nodal points on between the dams that enlarged at a certain scale and prototype are not the same as the ratios of values at the between different nodal points on dams. This shows that the values obtained at result of dynamic analysis (displacement, principal stress and strain) can not be generalized with a single formula. For this reason, a regression analysis is used, which is a statistical method for obtaining of the results of large scale real systems according to the prototype results, achieving the desired data by fitting a curve between the results. In regression analysis, which is a parametric study, a curve is obtained by performing a regression analysis with the results of analyzes obtained with different combinations of the desired data in Type-1 arch dam, it is reached the result together with the formula of curve. It has been seen that the expression of the desired values using a single curve at all the nodal points on the dam is not a correct approach. Thus developed different formulas are reflected the results of each nodal point in the dam.

2.3 Selection of analysis parameters

Taking into consideration the fixed support conditions and soil-structure interaction of the Type-1 arch dam, it is obtained a total of 102 unit finite element models as 1, 10, 20, ..., 500 times scale. When the scales are expressed as arch height, they take values ranging between 0.60-300m and these values are also the first parameter for regression analysis. In the Modulus of Elasticity selected as the second parameter, for each model is taken into consideration nine different concrete strength class as C14/16, C16/20, C18/22.5, C20/25, C25/30, C30/37, C35/45, C40/50 and C45/55. Based on these two parameters, 918 different models are created and 3672 response spectrum analysis is applied by considering four different soil classes that is Z1, Z2, Z3 and Z4. All analyses are performed with ANSYS (2010) finite element program.

2.4 Implementation of analysis and arrangement of results

The results obtained in each of the nodal points for 102 different models with respect to nine different concrete strength classes are arranged as in Fig. 7, making them suitable for regression analysis. In Fig. 7, in the arch dam that is be the soil-structure interaction is given a demonstration of a part of the ordering of the results obtained for the 1st nodal point as a result of the spectrum analysis performed according to the soil class Z1. The total data for 1st nodal point consists of 459 observations number.



Scale	Modulus of Elasticty	UY	S1	S3	EPEL1	EPEL3
1	0.26150000E+07	0.12860686E-05	0.15003240E+00	0.19274174E-01	0.59538700E-07	0.11589562E-09
1	0.27000000E+07	0.12455825E-05	0.15003247E+00	0.19274160E-01	0.57664363E-07	0.11224799E-09
1	0.27500000E+07	0.12229335E-05	0.15003242E+00	0.19274151E-01	0.56615903E-07	0.11020462E-09
1	0.28000000E+07	0.12010942E-05	0.15003236E+00	0.19274148E-01	0.55604877E-07	0.10823466E-09
1	0.30000000E+07	0.11210242E-05	0.15003239E+00	0.19274150E-01	0.51897900E-07	0.10102342E-09
1	0.32000000E+07	0.10509566E-05	0.15003236E+00	0.19274152E-01	0.48654265E-07	0.94704126E-10
1	0.33000000E+07	0.10191076E-05	0.15003223E+00	0.19274131E-01	0.47179851E-07	0.91831142E-10
1	0.34000000E+07	0.98913987E-06	0.15003250E+00	0.19274168E-01	0.45792299E-07	0.89138921E-10
1	0.36000000E+07	0.93418686E-06	0.15003249E+00	0.19274175E-01	0.43248276E-07	0.84184775E-10
10	0.26150000E+07	0.12907803E-03	0.16536581E+01	0.21211701E+00	0.65179499E-06	-0.24116055E-08
10	0.27000000E+07	0.12499671E-03	0.16482444E+01	0.21145596E+00	0.62932563E-06	-0.22222737E-08
10	0.27500000E+07	0.12271398E-03	0.16451488E+01	0.21107800E+00	0.61678867E-06	-0.21181334E-08
10	0.28000000E+07	0.12051307E-03	0.16421193E+01	0.21070811E+00	0.60472241E-06	-0.20190024E-08
10	0.30000000E+07	0.11244938E-03	0.16326942E+01	0.20959042E+00	0.56131817E-06	-0.17194775E-08
10	0.32000000E+07	0.10539805E-03	0.16251452E+01	0.20871796E+00	0.52389380E-06	-0.14965920E-08
10	0.33000000E+07	0.10219365E-03	0.16215661E+01	0.20830409E+00	0.50694171E-06	-0.13980349E-08
10	0.34000000E+07	0.99178279E-04	0.16181502E+01	0.20789647E+00	0.49103770E-06	-0.13083276E-08
10	0.36000000E+07	0.93651309E-04	0.16116434E+01	0.20712021E+00	0.46196972E-06	-0.11480458E-08
20	0.26150000E+07	0.56609554E-03	0.39677804E+01	0.50785385E+00	0.15546846E-05	-0.13485222E-07
20	0.27000000E+07	0.54666327E-03	0.39459581E+01	0.50497714E+00	0.14977360E-05	-0.12783323E-07
20	0.27500000E+07	0.53581989E-03	0.39335042E+01	0.50333516E+00	0.14660188E-05	-0.12395660E-07
20	0.28000000E+07	0.52538062E-03	0.39213178E+01	0.50172830E+00	0.14355288E-05	-0.12025278E-07
20	0.30000000E+07	0.48727310E-03	0.38784514E+01	0.49609104E+00	0.13256011E-05	-0.10777992E-07
20	0.32000000E+07	0.45414146E-03	0.38407300E+01	0.49113834E+00	0.12309727E-05	-0.97625326E-08
20	0.33000000E+07	0.43914718E-03	0.38228881E+01	0.48879490E+00	0.11882677E-05	-0.93103657E-08
20	0.34000000E+07	0.42507556E-03	0.38057306E+01	0.48652515E+00	0.11482794E-05	-0.88919060E-08
20	0.36000000E+07	0.39937906E-03	0.37730958E+01	0.48220724E+00	0.10754329E-05	-0.81385718E-08
30	0.26150000E+07	0.13968495E-02	0.69386936E+01	0.91157891E+00	0.27061736E-05	-0.32509228E-07
30	0.27000000E+07	0.13468514E-02	0.68890709E+01	0.90520437E+00	0.26026064E-05	-0.30948981E-07
30	0.27500000E+07	0.13221775E-02	0.68939052E+01	0.87991321E+00	0.25603166E-05	-0.29278275E-07
30	0.28000000E+07	0.12953216E-02	0.68662826E+01	0.87647760E+00	0.25047317E-05	-0.28466206E-07
30	0.30000000E+07	0.11974832E-02	0.67660196E+01	0.86413832E+00	0.23042222E-05	-0.25647955E-07
30	0.32000000E+07	0.11126808E-02	0.66760224E+01	0.85308995E+00	0.21319360E-05	-0.23304805E-07
30	0.33000000E+07	0.10743907E-02	0.66335777E+01	0.84787802E+00	0.20544003E-05	-0.22261223E-07
30	0.34000000E+07	0.10385258E-02	0.65935066E+01	0.84286603E+00	0.19821987E-05	-0.21273464E-07
30	0.36000000E+07	0.97316291E-03	0.65175363E+01	0.83336124E+00	0.18509851E-05	-0.19497015E-07
40	0.26150000E+07	0.27104088E-02	0.10615614E+02	0.13893931E+01	0.41300383E-05	-0.58291379E-07
40	0.27000000E+07	0.26103584E-02	0.10528293E+02	0.13783383E+01	0.39676816E-05	-0.55542522E-07
40	0.27500000E+07	0.25546442E-02	0.10478539E+02	0.13720384E+01	0.38774512E-05	-0.54022264E-07

Fig. 7 A partial image of the ordering of the results obtained for the regression analysis

In the figure above, the data for each nodal point is obtained for all soil classes, fixed support conditions and soil-structure interaction model, and a total of 2768 txt files have been created.

2.5 Investigation of scatterplot of results

The first step is to evaluate whether there is any relationship between the obtained data or a linear or non-linear relationship if there is a relationship. Within the scope of this study, the desired graphics are created with EXCEL software and the relationship between the data is examined in detail. As a result of the review, a linear relationship is generally determined in the scatterplot of the data pertaining to displacement. Nonetheless, nonlinear relationships exist at some nodal points. For this reason, it is evaluated which kind of range is suitable in each nodal points for the displacement results. Scatterplots of some nodal points related to displacement are given in Fig. 8.

Once the trendline of the obtained scatterplot is constructed, the R2 value indicating how the gradient represents the data is readable. It is seen that this values are about 97-98% for the some nodal points shown in Fig. 8. It is seen nonlinear relationship in the scatterplot of data of the principal stress and principal strain as shown in Figs. 9 and 10.

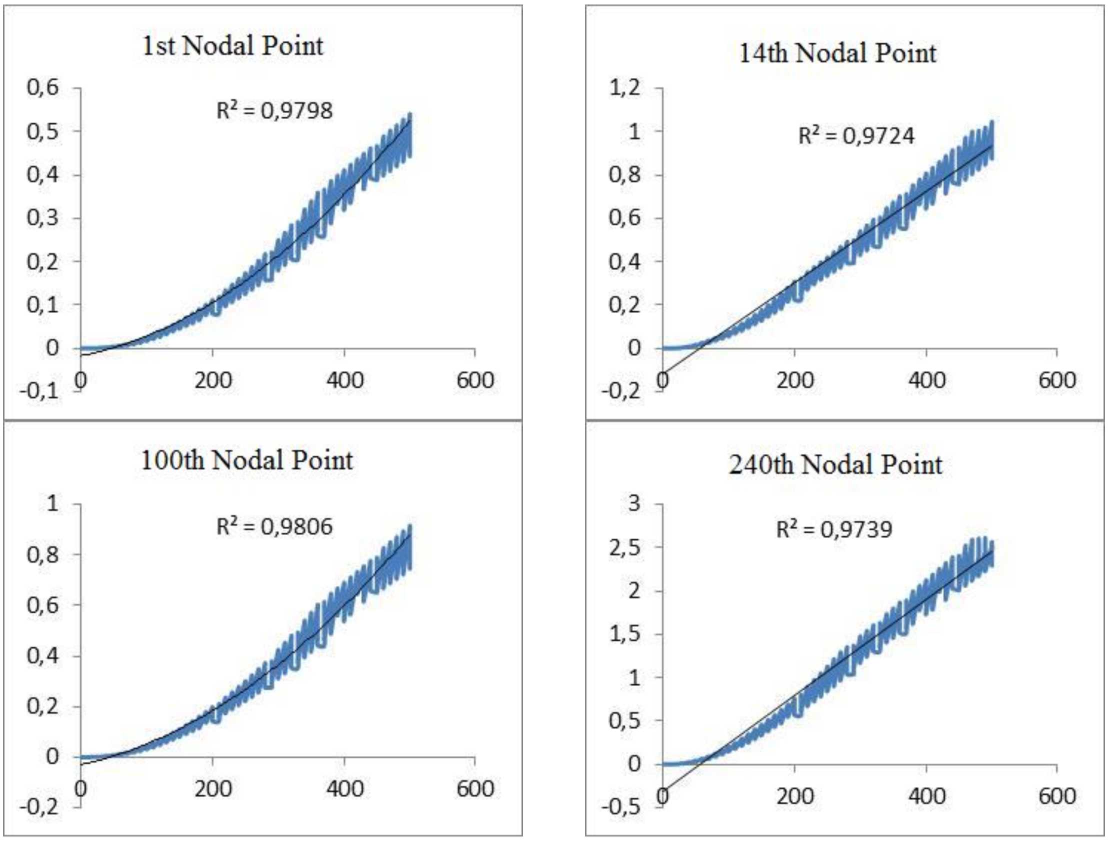


Fig. 8 Scatterplots of the displacement results for some nodal points

2.6 Application of appropriate regression analyzes for results

Two-parameter regression analyses are performed by considering the scale and the modulus of elasticity as parameters. Linear regression analysis is performed at nodal points where the linear relationship is valid for the displacement results. However, for the non-linear relationship, the program code of the 2nd degree regression analysis based on the Least Squares Method given in the thesis study by Başağa (2009) is rearranged according to the two-parameter method. Some of the displacements data of the linear regression analysis at 14th nodal point considering Z1 soil class for soil-structure interaction is shown in Fig. 11. Information obtained with regression analysis and the Anova table is given in Fig. 12.

In the Anova table, the first line is (Multiple R: called as correlation) refers the direction and intensity of the relationship between the parameters constituted with 459 observations. R^2 value is an indicator how much of obtained curve represents of the data. The information in the Anova table is used to calculate R^2 value. Coefficients are the values of the formula created according to the selected parameters. Eq. (1) is formed to the information given in Fig. 11 for the linear regression analysis results.

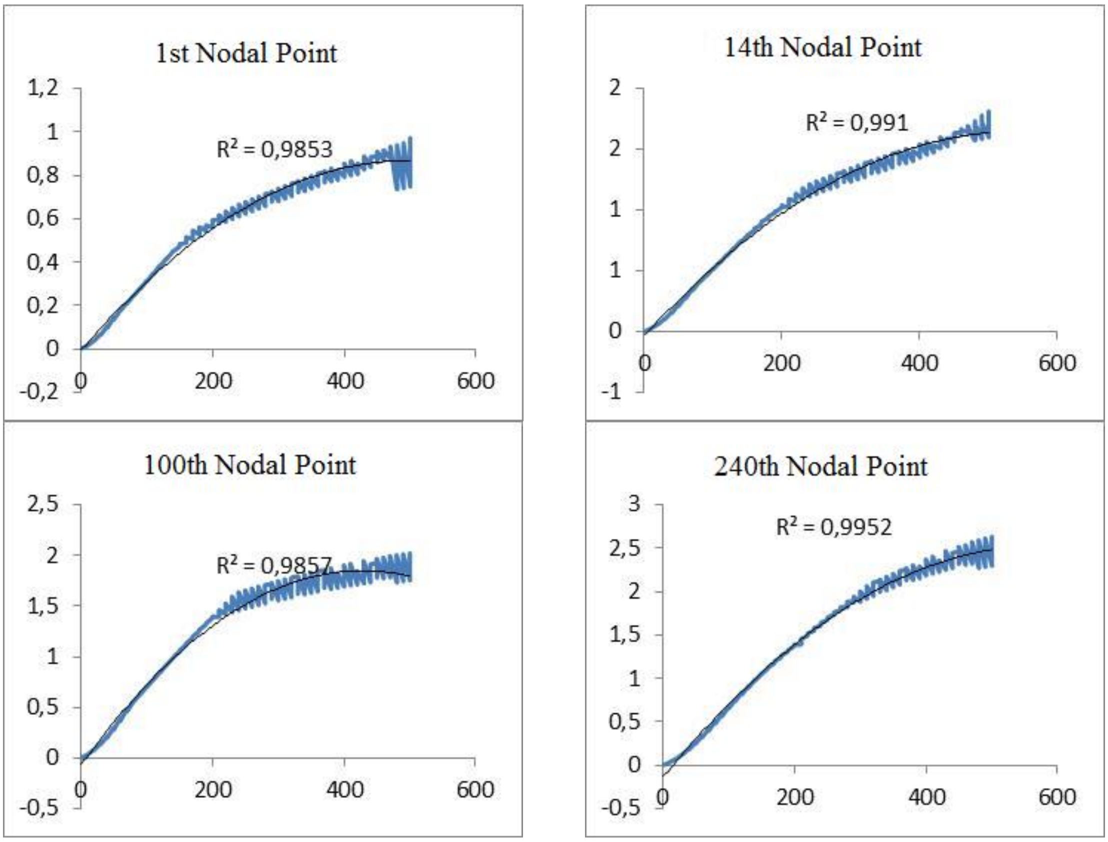


Fig. 9 Scatterplots of the principal stress results for some nodal points

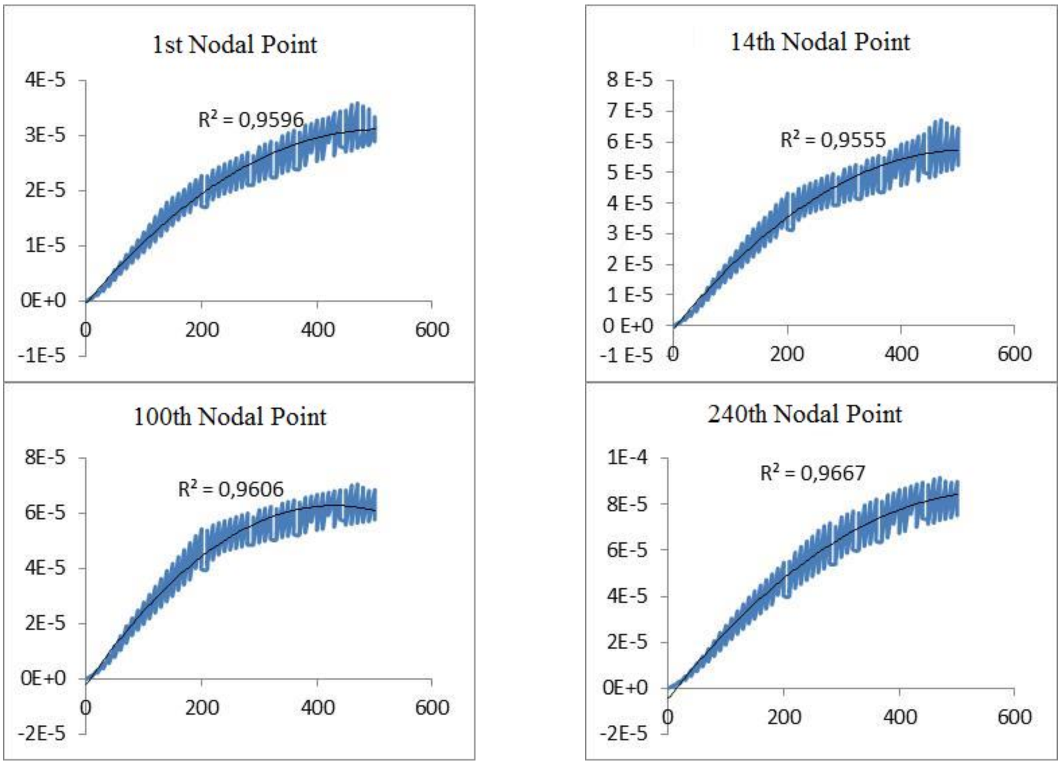
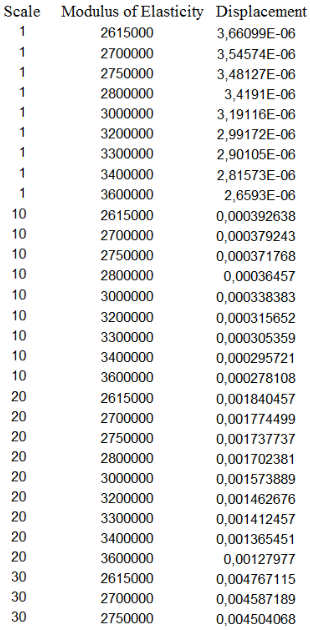
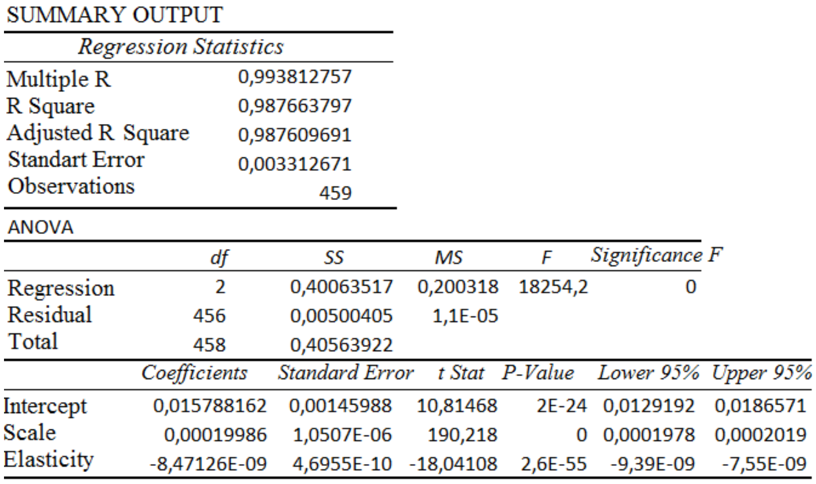


Fig. 10 Scatterplots of the principal strain results for some nodal points



Scale	Modulus of Elasticity	Displacement
1	2615000	3,66099E-06
1	2700000	3,54574E-06
1	2750000	3,48127E-06
1	2800000	3,4191E-06
1	3000000	3,19116E-06
1	3200000	2,99172E-06
1	3300000	2,90105E-06
1	3400000	2,81573E-06
1	3600000	2,6593E-06
10	2615000	0,000392638
10	2700000	0,000379243
10	2750000	0,000371768
10	2800000	0,00036457
10	3000000	0,000338383
10	3200000	0,000315652
10	3300000	0,000305359
10	3400000	0,000295721
10	3600000	0,000278108
20	2615000	0,001840457
20	2700000	0,001774499
20	2750000	0,001737737
20	2800000	0,001702381
20	3000000	0,001573889
20	3200000	0,001462676
20	3300000	0,001412457
20	3400000	0,001365451
20	3600000	0,00127977
30	2615000	0,004767115
30	2700000	0,004587189
30	2750000	0,004504068

Fig. 11 Part of the data from the linear regression analysis of the displacement results of the 14th nodal point



SUMMARY OUTPUT

Regression Statistics	
Multiple R	0,993812757
R Square	0,987663797
Adjusted R Square	0,987609691
Standart Error	0,003312671
Observations	459

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0,40063517	0,200318	18254,2	0
Residual	456	0,00500405	1,1E-05		
Total	458	0,40563922			

	Coefficients	*Standard Error*	*t Stat*	*P-Value*	*Lower 95%*	*Upper 95%*
Intercept	0,015788162	0,00145988	10,81468	2E-24	0,0129192	0,0186571
Scale	0,00019986	1,0507E-06	190,218	0	0,0001978	0,0002019
Elasticity	-8,47126E-09	4,6955E-10	-18,04108	2,6E-55	-9,39E-09	-7,55E-09

Fig. 12 Anova table and information related to linear regression analysis at 14th nodal point for displacement

$$U = 0.015788162 + 0.00019986 \times \text{Scale} - 8.47126\text{E}-09 \times \text{Elasticity} \tag{1}$$

When the selected scale and modulus of elasticity values wrote in formula, it is obtained that the result of the spectrum analysis performed for the Z1 soil class in the 14th nodal point is correct 98%. The coefficients Ao and R are obtained Eq. (2) for the 14th nodal point by adding to the Eq. (1).

$$U = 0.015788162 + 0.00019986 \times S - 8.47126\text{E}-09 \times E \times A_0/R \tag{2}$$

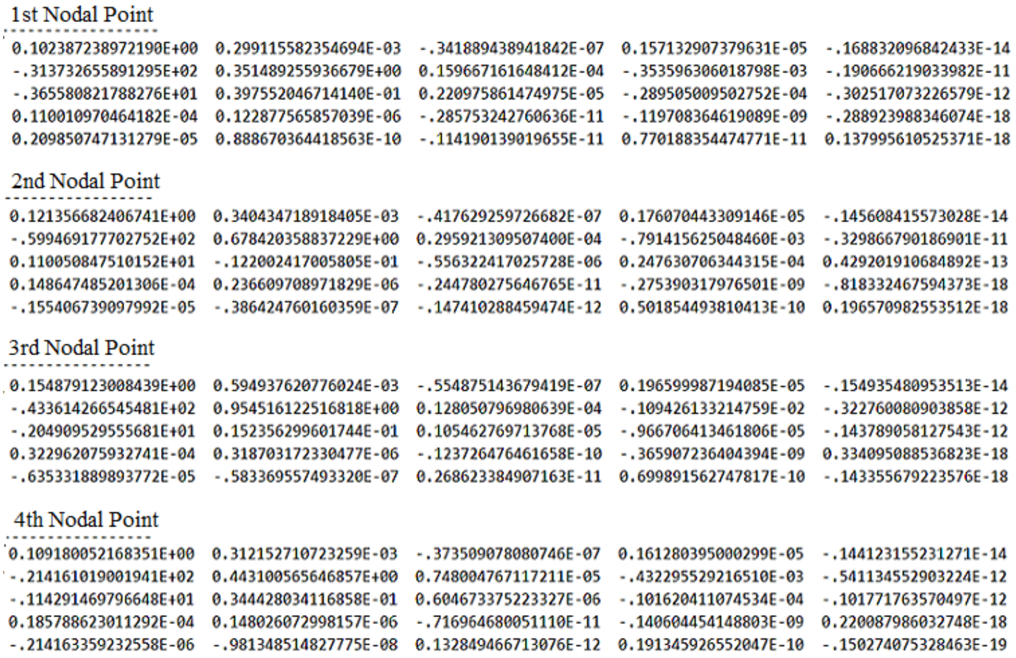
In this equation, S and E denote the scale and modulus of elasticity, respectively.

For nonlinear analysis, coefficients of 2nd degree equations are obtained by using program code generated by Başağa (2009). Fig. 13 shows the regression analysis formula coefficients for the results of the first four nodal points of the soil-structure interaction arch dam as a result of the spectrum analysis for the Z1 soil class. The lines at which the coefficients at the first nodal point are located indicate displacements, maximum principal stress, minimum principal stress, maximum principal strain, and minimum principal strain, respectively.

Displacement formula of 1st nodal point

$$\begin{aligned} U = {} & 0.1023872389219 + 0.299115582354694\text{E}-3 \times S \\ & - 0.341889438941842\text{E}-07 \times E + 0.157132907379631\text{E}-05 \times S^2 \\ & - 0.168832096842433\text{E}-04 \times E^2 \end{aligned} \tag{3}$$

Eq. (3) is obtained. In the equation, S and E are the scale and modulus of elasticity, respectively. Eq. (4) is obtained for the 1st nodal point by adding Ao (effective ground acceleration coefficient) and R (Seismic load reduction factor).



```
1st Nodal Point
-----------------
0.102387238972190E+00  0.299115582354694E-03  -.341889438941842E-07  0.157132907379631E-05  -.168832096842433E-14
-.313732655891295E+02  0.351489255936679E+00  0.159667161648412E-04  -.353596306018798E-03  -.190666219033982E-11
-.365580821788276E+01  0.397552046714140E-01  0.220975861474975E-05  -.289505009502752E-04  -.302517073226579E-12
0.110010970464182E-04  0.122877565857039E-06  -.285753242760636E-11  -.119708364619089E-09  -.288923988346074E-18
0.209850747131279E-05  0.888670364418563E-10  -.114190139019655E-11  0.770188354474771E-11  0.137995610525371E-18

2nd Nodal Point
-----------------
0.121356682406741E+00  0.340434718918405E-03  -.417629259726682E-07  0.176070443309146E-05  -.145608415573028E-14
-.599469177702752E+02  0.678420358837229E+00  0.295921309507400E-04  -.791415625048460E-03  -.329866790186901E-11
0.110050847510152E+01  -.122002417005805E-01  -.556322417025728E-06  0.247630706344315E-04  0.429201910684892E-13
0.148647485201306E-04  0.236609708971829E-06  -.244780275646765E-11  -.275390317976501E-09  -.818332467594373E-18
-.155406739097992E-05  -.386424760160359E-07  -.147410288459474E-12  0.501854493810413E-10  0.196570982553512E-18

3rd Nodal Point
-----------------
0.154879123008439E+00  0.594937620776024E-03  -.554875143679419E-07  0.196599987194085E-05  -.154935480953513E-14
-.433614266545481E+02  0.954516122516818E+00  0.128050796980639E-04  -.109426133214759E-02  -.322760080903858E-12
-.204909529555681E+01  0.152356299601744E-01  0.105462769713768E-05  -.966706413461806E-05  -.143789058127543E-12
0.322962075932741E-04  0.318703172330477E-06  -.123726476461658E-10  -.365907236404394E-09  0.334095088536823E-18
-.635331889893772E-05  -.583369557493320E-07  0.268623384907163E-11  0.699891562747817E-10  -.143355679223576E-18

4th Nodal Point
-----------------
0.109180052168351E+00  0.312152710723259E-03  -.373509078080746E-07  0.161280395000299E-05  -.144123155231271E-14
-.214161019001941E+02  0.443100565646857E+00  0.748004767117211E-05  -.432295529216510E-03  -.541134552903224E-12
-.114291469796648E+01  0.344428034116858E-01  0.604673375223327E-06  -.101620411074534E-04  -.101771763570497E-12
0.185788623011292E-04  0.148026072998157E-06  -.716964680051110E-11  -.140604454148803E-09  0.220087986032748E-18
-.214163359232558E-06  -.981348514827775E-08  0.132849466713076E-12  0.191345926552047E-10  -.150274075328463E-19
```

Fig. 13 Formulation coefficients obtained by second degree regression analysis of some nodal points

$$U = \begin{pmatrix} 0.1023872389219 + 0.299115582354694\mathrm{E}-3 \times S \\ -0.341889438941842\mathrm{E}-07 \times E + 0.15713290737963\mathrm{E}-05 \times S^2 \\ -0.168832096842433\mathrm{E}-04 \times E^2 \end{pmatrix} \times A_0/R \qquad (4)$$

General equation is obtained. In each of the 346 nodal points on the arch body, a total of 13840 formulas are created represented of five different structural behavior, including displacement, maximum and minimum principal stresses, and maximum and minimum principal strains. Formulas of structural properties of some nodal points are given in Table 11.

2.7 Comparison of ANSYS and regression analysis results

The results of the regression analysis are compared with the results obtained from the ANSYS program and the error rates are examined. When the results are analyzed, it is seen that 10% of the error rates are not exceeded. When comparing for the 50-times scaled of Type-1 arch dam, error rates reach 20-40%. This height is considered as the lower limit because the error rate at the scale value corresponding to a dam height of 30 m is high. The upper limit used in the regression analysis is 300 meters arch height which corresponds to 500-times scale. It is decided that the formulas obtained for this reason are suitable for dam heights between 30 m and 300 m. It appears that errors of the predicted results of the formulas of any arch height value in outside these limits will more than 10%. Fig. 14 shows the comparison the error rates of the results obtained according to different selected parameter values in some nodal points.

Table 11 The regression formulas used to obtain the structural properties of 4 different nodal points on Type-1 arch dam that fixed support condition (for Soil class Z1)

48th Nodal Point	$U=\left(0.798013601169917+0.00748168363075604*S-3.2201289043847E-7*E+3.18405183433108E-6*S^2-6.8058752711104-15*E^2\right)*A_0/R$
	$S1=\left(-64.9842893073667+0.957684930792054*S+2.44577840330609E-05*E-0.00116490160132596*S^2-1.94177962855986E-12*E^2\right)*A_0/R$
	$S3=\left(-1.27053083462028+0.0118604040688116*S+5.78317746298122E-07*E-1.96425975643186E-05*S^2-5.93641963397359E-14*E^2\right)*A_0/R$
	$EPEL1=\left(5.18353744059339E-5+3.129283397387E-7*S-2.5862742821022E-11*E-3.7964632554382E-10*S^2+2.5654940341990E-18*E^2\right)*A_0/R$
	$EPEL3=\left(7.59889106195412E-6+3.276728772464E-8*S-3.7850101841224E-17*E-3.276892606877E-11*S^2+3.97701792380212E-19*E^2\right)*A_0/R$
166th Nodal Point	$U=\left(0.258881429567406+0.00138721690860575*S-1.26667606039589E-7*E+9.12449404568445E-07*S^2+8.17775906723147E-12*E^2\right)*A_0/R$
	$S1=\left(-53.8857245629784+0.647326567796881*S+2.54962490738682E-5*E-0.000786195944114529*S^2-2.61670051288379E-12*E^2\right)*A_0/R$
	$S3=\left(0.70281369509689-0.0182139500571884*S-1.3299885020979E-6*E+4.20509115046927E-5*S^2+9.94953823106378E-14*E^2\right)*A_0/R$
	$EPEL1=\left(3.91983674348032E-5+2.4946366144624E-7*S-1.7801667342933E-11*E-3.0396581138754E-10*S^2+1.5559936588862E-18*E^2\right)*A_0/R$
	$EPEL3=\left(-1.8847417541073E-6-1.4834794162454E-8*S+1.8157586470182E-13*E+2.7769525917205E-11*S^2+2.9805719127779E-20*E^2\right)*A_0/R$
200th Nodal Point	$U=\left(0.218557874438529+0.000784690142561596*S-1.18464081477908E-7*E+5.94245115044707E-7*S^2+1.17311206407548E-14*E^2\right)*A_0/R$
	$S1=\left(-17.1891133543784+0.294153040559596*S+6.2117837167177E-06*E-0.000333957292635155*S^2-4.15064627258275E-13*E^2\right)*A_0/R$
	$S3=\left(0.110645089727671+0.00111412542609233*S-2.44345551959163E-8*E-5.80705305849686E-07*S^2+6.5040303607296E-15*E^2\right)*A_0/R$
	$EPEL1=\left(0.000020639545970966+1.1102429769924E-7*S-1.02717421899E-11*E-1.28240404087E-10*S^2+1.0435729675724E-18*E^2\right)*A_0/R$
	$EPEL3=\left(-1.188493383868E-6-6.8332601489181E-9*S+6.07293061655E-13*E+7.767807186298E-12*S^2-6.105811934079E-20*E^2\right)*A_0/R$
331th Nodal Point	$U=\left(0+0*S-0*E+0*S^2-0*E^2\right)*A_0/R$
	$S1=\left(-77.4984657246211+0.969616177719215*S+3.56068669213299E-5*E-0.00113600530528008*S^2-3.58720384206422E-12*E^2\right)*A_0/R$
	$S3=\left(-6.86180267893073+0.0561821697515815*S+3.79034476224199E-6*E-8.3489771433744E-5*S^2-4.4457773381981E-13*E^2\right)*A_0/R$
	$EPEL1=\left(5.2352417272769E-5+3.0739920528939E-7*S-2.4406125858798E-11*E-3.5809935741629E-10*S^2+2.2368152600611E-18*E^2\right)*A_0/R$
	$EPEL3=\left(-2.4188656246621E-7-1.0437898093694E-9*S+1.2459857785480E-13*E+9.771525242626E-13*S^2-1.32347599537046E-20*E^2\right)*A_0/R$

Displacement			
500 Scale, Ao=4, R=1, C30/37, Z1			
Nodal Points	ANSYS	Formula	%Error
1.	1,912806	1,872897	2,086368
10.	3,043458	3,221922	-5,86386
19.	7,591565	7,561946	0,390151
31.	12,77068	12,48698	2,22151
37.	16,31958	16,74372	-2,59896
47.	28,29404	27,3858	3,21
48.	28,33737	27,3858	3,358014
50.	14,99984	14,2395	5,068934
72.	12,42	12,21506	1,65014
81.	2,167173	2,332794	-7,64224
90.	1,977952	1,872897	5,311278
105.	6,075831	6,33973	-4,34342

Displacement			
350 Scale, Ao=4, R=1, C20/25, Z1			
Nodal Points	ANSYS	Formula	%Error
1.	1,265894	1,275612	-0,76764
10.	2,009601	1,888803	6,011048
19.	5,347013	5,271597	1,410442
31.	8,795554	8,682542	1,284874
37.	11,42325	11,6339	-1,84402
47.	19,67354	18,9694	3,579159
48.	19,70543	18,9694	3,735203
50.	10,57422	9,896279	6,411273
72.	8,575083	8,49446	0,940204
81.	1,422197	1,311373	7,792426
90.	1,304489	1,275612	2,213687
105.	4,197693	4,399873	-4,81646

(a) Comparison of displacements

Maximum Principal Strain			
500 Scale, Ao=4, R=1, C30/37, Z1			
Nodal Points	ANSYS	Formula	%Error
1.	0,000128	0,000122	4,771453
10.	0,000203	0,000189	6,678509
19.	0,000371	0,00034	8,494969
31.	0,000587	0,000579	1,459684
37.	0,000584	0,000574	1,698026
47.	0,000712	0,000694	2,575171
48.	0,000518	0,00051	1,530274
50.	0,000483	0,000488	-1,04108
72.	0,000519	0,000492	5,107603
81.	0,000211	0,000192	8,672662
93.	0,000118	0,000118	-0,32144
105.	0,000354	0,000349	1,257514

Maximum Principal Strain			
350 Scale, Ao=4, R=1, C20/25, Z1			
Nodal Points	ANSYS	Formula	%Error
1.	0,000115	0,000116	-0,91788
10.	0,000179	0,000183	-2,2075
19.	0,000349	0,000356	-2,0922
31.	0,000561	0,000552	1,591474
37.	0,000556	0,000551	0,91254
47.	0,000682	0,000676	0,910996
48.	0,000489	0,000491	-0,37904
50.	0,000453	0,000444	1,864185
72.	0,000494	0,000496	-0,23052
81.	0,000197	0,000203	-3,1155
93.	0,000106	0,000103	2,319356
105.	0,000328	0,000327	0,396926

(b) Comparison of maximum principal stresses

Maximum Principal Strain			
500 Scale, Ao=4, R=1, C30/37, Z1			
Nodal Points	ANSYS	Formula	%Error
1.	0,000128	0,000122	4,771453
10.	0,000203	0,000189	6,678509
19.	0,000371	0,00034	8,494969
31.	0,000587	0,000579	1,459684
37.	0,000584	0,000574	1,698026
47.	0,000712	0,000694	2,575171
48.	0,000518	0,00051	1,530274
50.	0,000483	0,000488	-1,04108
72.	0,000519	0,000492	5,107603
81.	0,000211	0,000192	8,672662
93.	0,000118	0,000118	-0,32144
105.	0,000354	0,000349	1,257514

Maximum Principal Strain			
350 Scale, Ao=4, R=1, C20/25, Z1			
Nodal Points	ANSYS	Formula	%Error
1.	0,000115	0,000116	-0,91788
10.	0,000179	0,000183	-2,2075
19.	0,000349	0,000356	-2,0922
31.	0,000561	0,000552	1,591474
37.	0,000556	0,000551	0,91254
47.	0,000682	0,000676	0,910996
48.	0,000489	0,000491	-0,37904
50.	0,000453	0,000444	1,864185
72.	0,000494	0,000496	-0,23052
81.	0,000197	0,000203	-3,1155
93.	0,000106	0,000103	2,319356
105.	0,000328	0,000327	0,396926

(c) Comparison of maximum principal strains

Fig. 14 Comparison of the results obtained for some nodal points

Table 12 Parameters and limits used in software

Using Parameters in Software	
Arch Height	between 0.6 m-300 m
Concrete Strength Classes	C14/16, C16/20, C18/22.5, C20/25, C25/30, C30/37, C35/45, C40/50, C45/55
Site Class	Z1, Z2, Z3, Z4
Effective Ground Acceleration Coefficient	0.1 g, 0.2 g, 0.3 g, 0.4 g
Seismic Load Reduction Factor	It is obtained from DBYBHY-2007 according to structural system behavior factors (R)
Nodal Points	between 1-346

3. Development of software

In the scope of the work done in Type-1 dam, it is not easy to present the desired results due to the reasons such as the excess of the variable parameters and the combination of these parameters, long and specific of the formulas obtained for each nodal point. It is a very difficult process to find and store a desired data from within the plenty data. For this reason, it is aimed to develop a software that will only allow the results of the desired data to be obtained at a selected nodal point and display various graphs and contour diagrams of these results. With the help of the software designed in the EXCEL program, the parameters are asserted the user selection and the static and dynamic analytical results are displayed with the formulas obtained from the regression analysis of the desired nodal point at the arch dam. At the same time, depending on the selected parameters, the change on sectional and the contour diagrams of the results of the arch can be obtained at any nodal point.

3.1 Organization content and appearance of software

In the scope of this study first of all, it is aimed to select the parameters to be presented to the user. Because the results are obtained based on these parameters, the software is established with respect to these parameters. Table 12 submits the parameters and limits presented to the selection of the user.

With the introduction of the parameters mentioned in Table 12, the result which will be calculated at any node in the arch dam body will be automatically calculated by using the formula tables created in EXCEL. In the software, it is planned to present the dynamic characteristic and structural features to be formed under static and dynamic forces. The analysis results, which can be obtained,

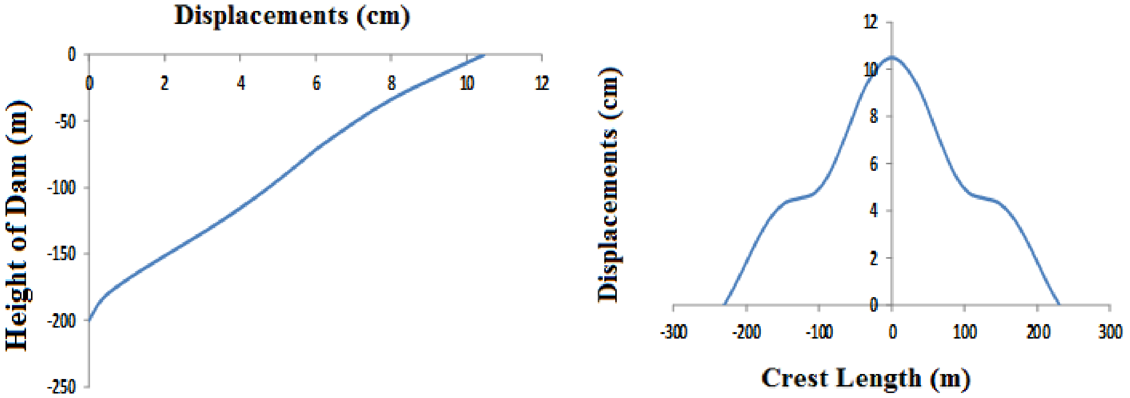
- Modal Analysis Results
- Static Analysis Results
- Dynamic analysis results of Type-1 arch dam that soil-structure interaction
- Dynamic analysis results of Type-1 arch dam for fixed support conditions
- The change on sectional diagrams
    - Static Analysis
    - Dynamic Analysis
- Contour Diagrams

- Static Analysis
- Dynamic Analysis

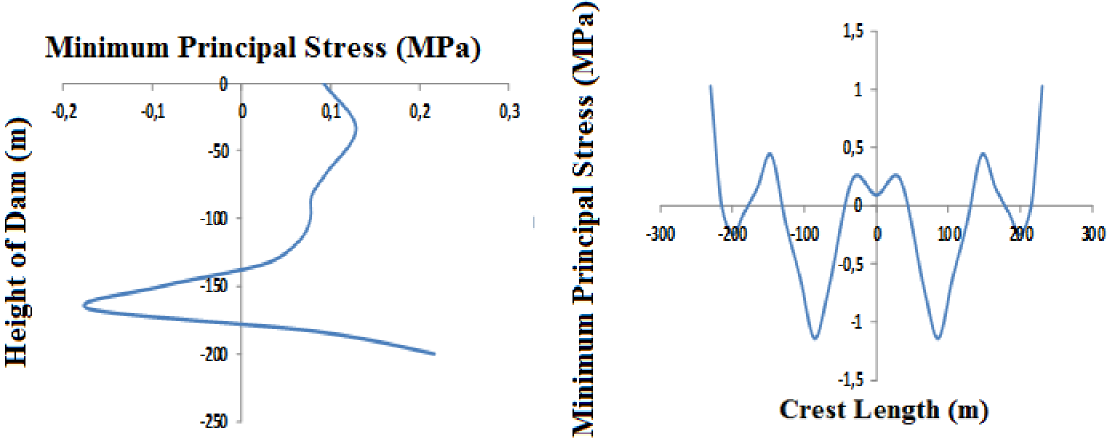
can be listed as.

3.2 Constitution of the change on sectional and the contour diagrams

The change on arch body along the horizontal and vertical sections can also be examined as graphically with the change on sectional and the contour diagrams at that selected nodal point. In the creation of the desired the change on sectional diagrams for the nodal point, the selection of the horizontal and vertical points passing through that node point is made automatically with software developed at Excel. Figs. 15 and 16 shows the change on sectional diagrams and contour along the horizontal and vertical sections of the values selected at the 48th nodal point selected as an example (200 m arch height, C25/30 concrete strength class, 1st degree earthquake zone, Z1 soil class, fixed support conditions) are shown.



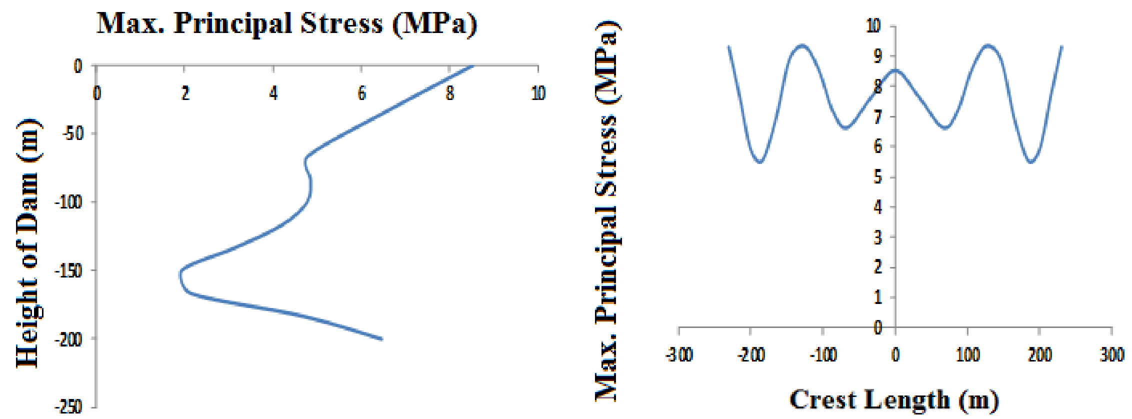
(a) Displacement on vertical sectional diagram (b) Displacement on horizontal sectional diagram



(c) Min. principal stress on vertical sectional diagram

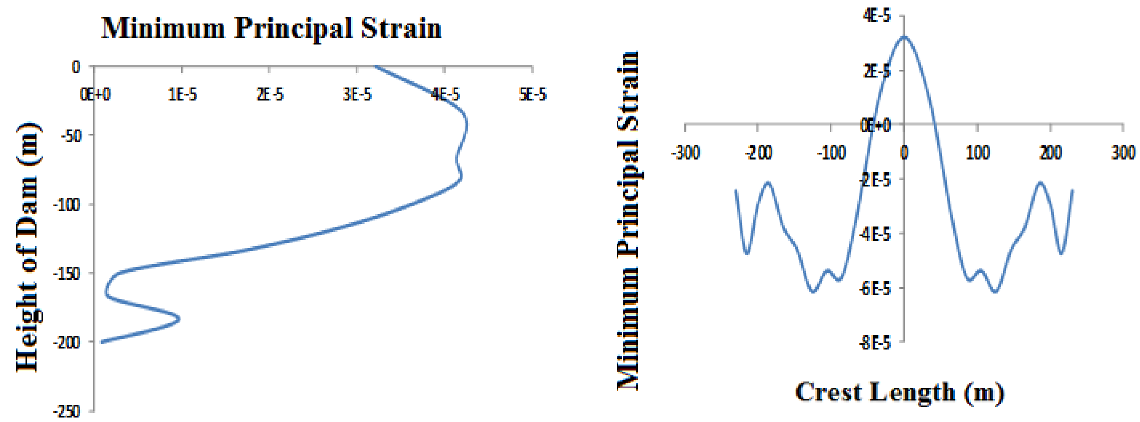
(d) Min. principal stress on horizontal sectional diagram

Continued-



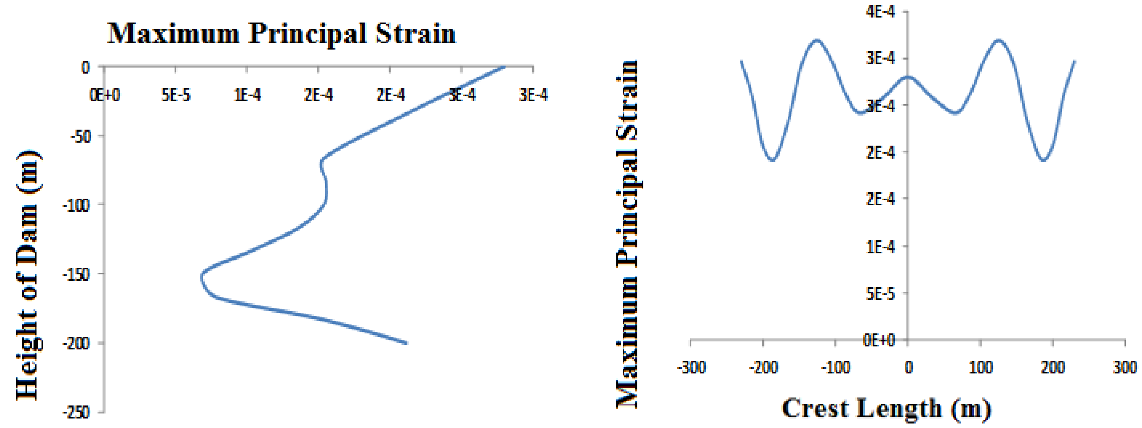
(e) Max. principal stress on vertical sectional diagram

(f) Max. principal stress on horizontal sectional diagram



(g) Min. principal strain on vertical sectional diagram

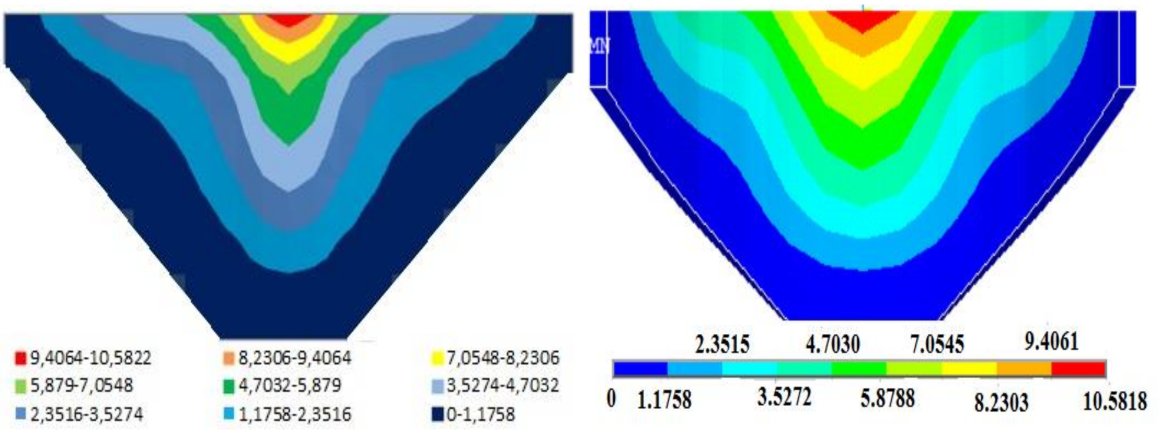
(h) Min. principal strain on horizontal sectional diagram



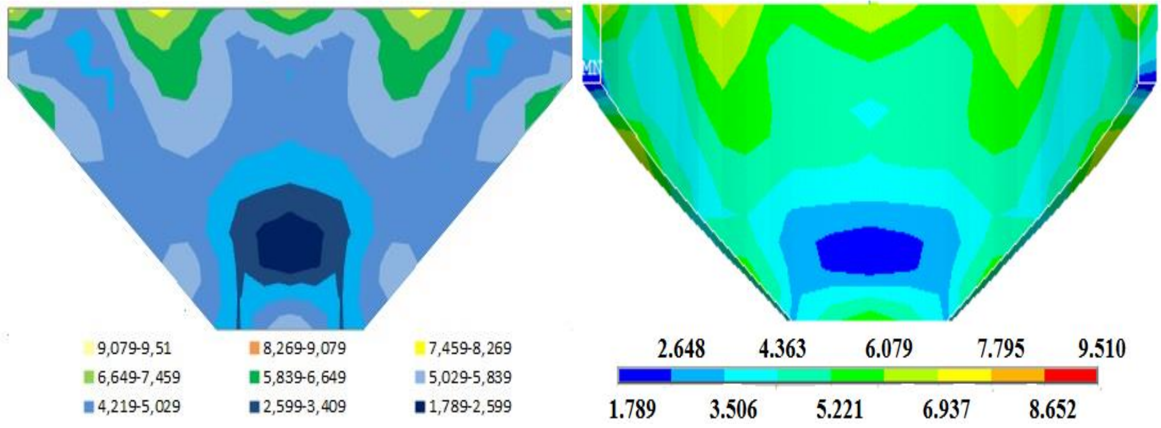
(i) Max. principal strain on vertical sectional diagram

(j) Max. principal strain on horizontal sectional diagram

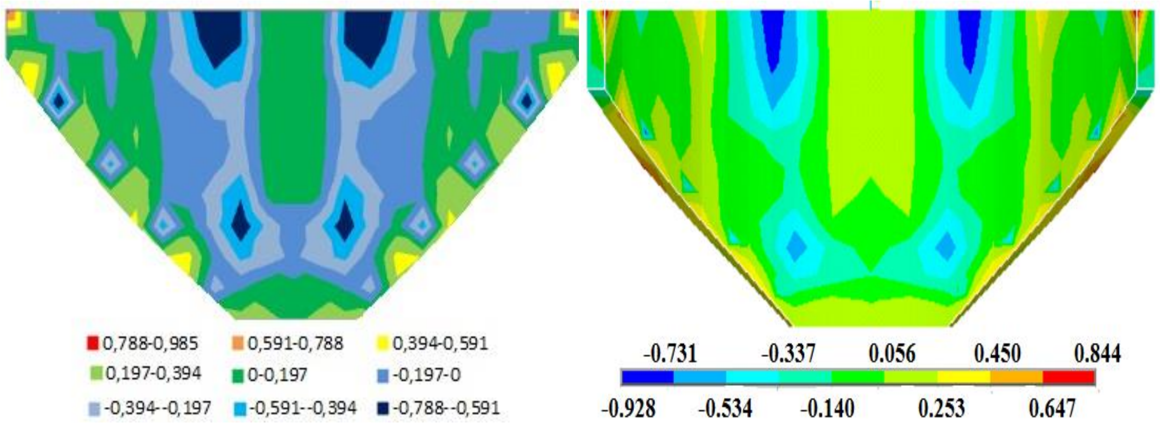
Fig. 15 The change on sectional diagrams for the 48th nodal point



(a) Displacement contour diagram (cm)

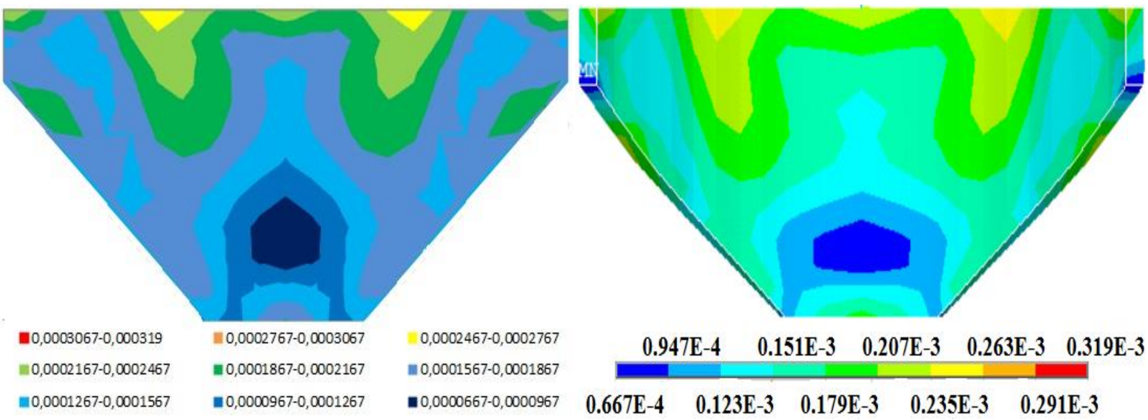


(b) Maximum principal stress contour diagram (MPa)

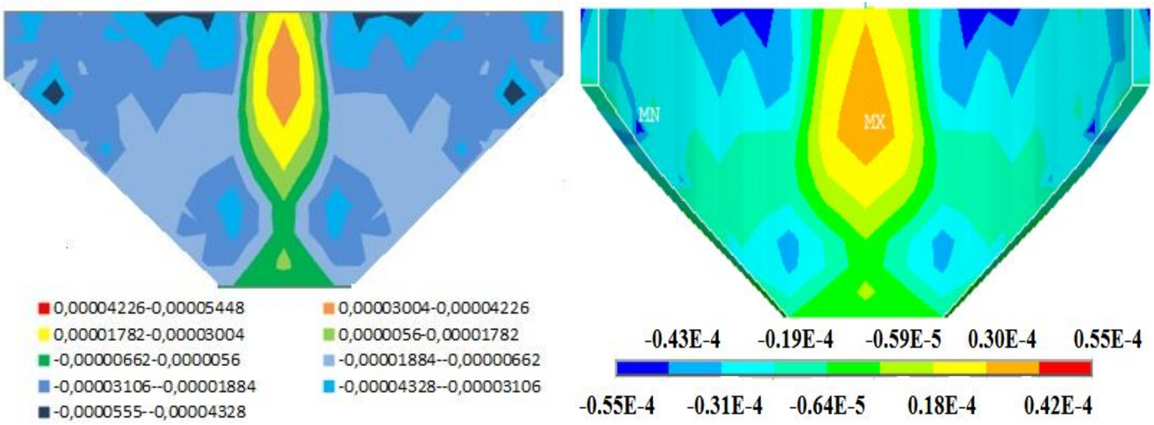


(c) Minimum principal stress contour diagram (MPa)

Continued-

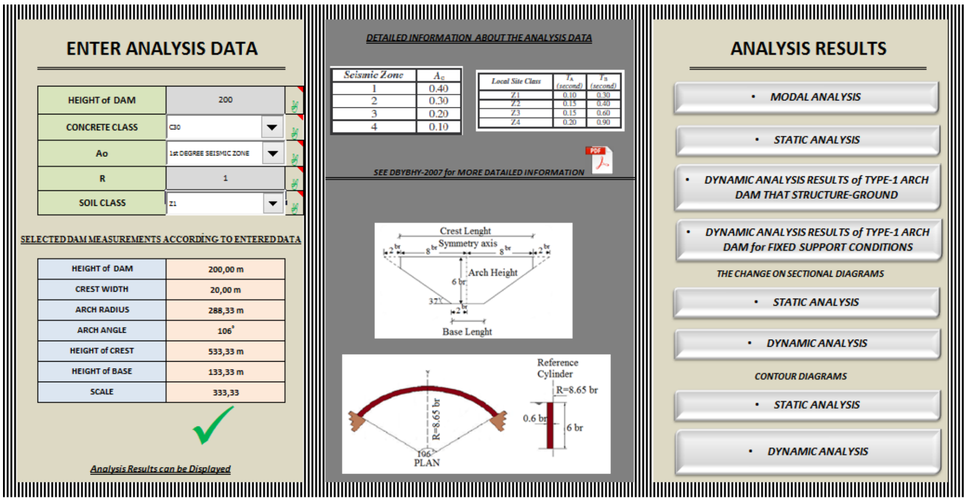


(d) Maximum principal strain contour diagram



e) Minimum principal strain contour diagram

Fig. 16 Example views of the obtained contour diagrams



ENTER ANALYSIS DATA

HEIGHT of DAM	200
CONCRETE CLASS	C30
Ao	1st DEGREE SEISMIC ZONE
R	1
SOIL CLASS	Z1

SELECTED DAM MEASUREMENTS ACCORDING TO ENTERED DATA

HEIGHT of DAM	200,00 m
CREST WIDTH	20,00 m
ARCH RADIUS	288,33 m
ARCH ANGLE	106°
HEIGHT of CREST	533,33 m
HEIGHT of BASE	133,33 m
SCALE	333,33

Analysis Results can be Displayed

DETAILED INFORMATION ABOUT THE ANALYSIS DATA

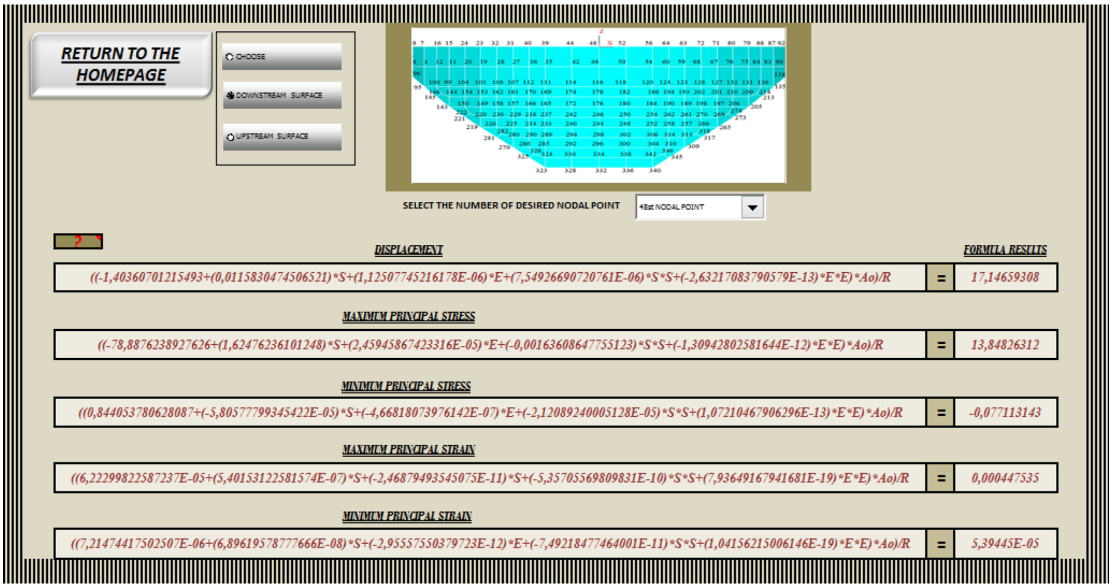
Seismic Zone	A_0
1	0.40
2	0.30
3	0.20
4	0.10

Local Site Class	T_A (second)	T_B (second)
Z1	0.10	0.30
Z2	0.15	0.40
Z3	0.15	0.60
Z4	0.20	0.90

SEE DBYBHY-2007 for MORE DATAILED INFORMATION

Fig. 17 Input of data into home page of the software

The comparison of the graphics of ANSYS and the developed software shows that the results are compatible with each other. The Figurations for the appearance and use of the developed software are shown in detail in Figs. 17-21.



SELECT THE NUMBER OF DESIRED NODAL POINT: 48st NODAL POINT

DISPLACEMENT — FORMULA RESULTS

`((-1,40360701215493+(0,0115830474506521)*S+(1,12507745216178E-06)*E+(7,54926690720761E-06)*S*S+(-2,63217083790579E-13)*E*E)*Ao)/R` = 17,14659308

MAXIMUM PRINCIPAL STRESS

`((-78,8876238927626+(1,62476236101248)*S+(2,45945867423316E-05)*E+(-0,00163608647755123)*S*S+(-1,30942802581644E-12)*E*E)*Ao)/R` = 13,84826312

MINIMUM PRINCIPAL STRESS

`((0,844053780628087+(-5,80577799345422E-05)*S+(-4,66818073976142E-07)*E+(-2,12089240005128E-05)*S*S+(1,07210467906296E-13)*E*E)*Ao)/R` = -0,077113143

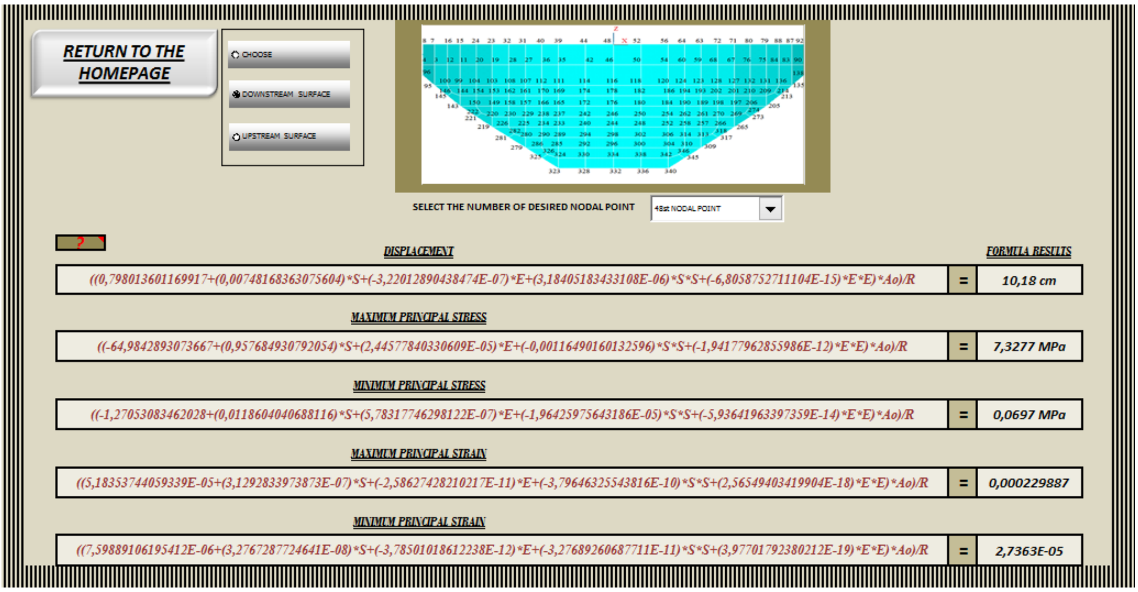
MAXIMUM PRINCIPAL STRAIN

`((6,22299822587237E-05+(5,40153122581574E-07)*S+(-2,46879493545075E-11)*S+(-5,35705569809831E-10)*S*S+(7,93649167941681E-19)*E*E)*Ao)/R` = 0,000447535

MINIMUM PRINCIPAL STRAIN

`((7,21474417502507E-06+(6,89619578777666E-08)*S+(-2,95557550379723E-12)*E+(-7,49218477464001E-11)*S*S+(1,04156215006146E-19)*E*E)*Ao)/R` = 5,39445E-05

Fig. 18 Displaying the related formulas and results of 48 nodal point at dynamic analysis results page of Type-1 arch dam that soil-structure interaction



SELECT THE NUMBER OF DESIRED NODAL POINT: 48st NODAL POINT

DISPLACEMENT — FORMULA RESULTS

`((0,798013601169917+(0,00748168363075604)*S+(-3,22012890438474E-07)*E+(3,18405183433108E-06)*S*S+(-6,8058752711104E-15)*E*E)*Ao)/R` = 10,18 cm

MAXIMUM PRINCIPAL STRESS

`((-64,9842893073667+(0,957684930792054)*S+(2,44577840330609E-05)*E+(-0,00116490160132596)*S*S+(-1,94177962855986E-12)*E*E)*Ao)/R` = 7,3277 MPa

MINIMUM PRINCIPAL STRESS

`((-1,27053083462028+(0,0118604040688116)*S+(5,78317746298122E-07)*E+(-1,96425975643186E-05)*S*S+(-5,93641963397359E-14)*E*E)*Ao)/R` = 0,0697 MPa

MAXIMUM PRINCIPAL STRAIN

`((5,18353744059339E-05+(3,1292833973873E-07)*S+(-2,58627428210217E-11)*E+(-3,79646325543816E-10)*S*S+(2,56549403419904E-18)*E*E)*Ao)/R` = 0,000229887

MINIMUM PRINCIPAL STRAIN

`((7,59889106195412E-06+(3,2767287724641E-08)*S+(-3,78501018612238E-12)*E+(-3,27689260687711E-11)*S*S+(3,97701792380212E-19)*E*E)*Ao)/R` = 2,7363E-05

Fig. 19 Displaying the related formulas and results of 48 nodal point at dynamic analysis results page of Type-1 arch dam for fixed support conditions

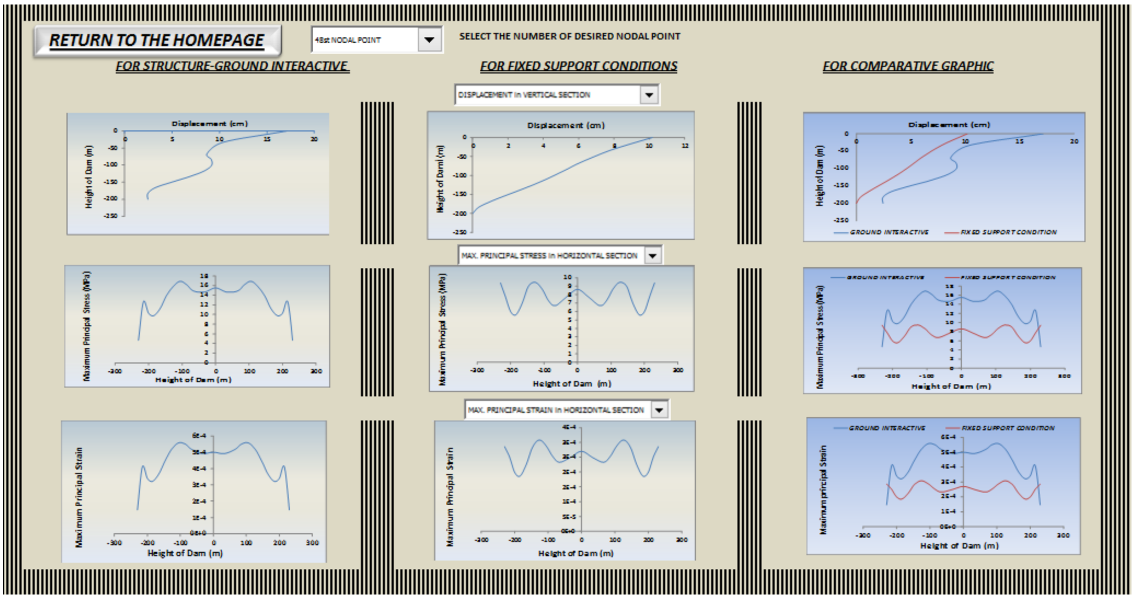


Fig. 20 Displaying the change on sectional diagrams of 48th nodal point at section diagrams page obtained with dynamic analysis

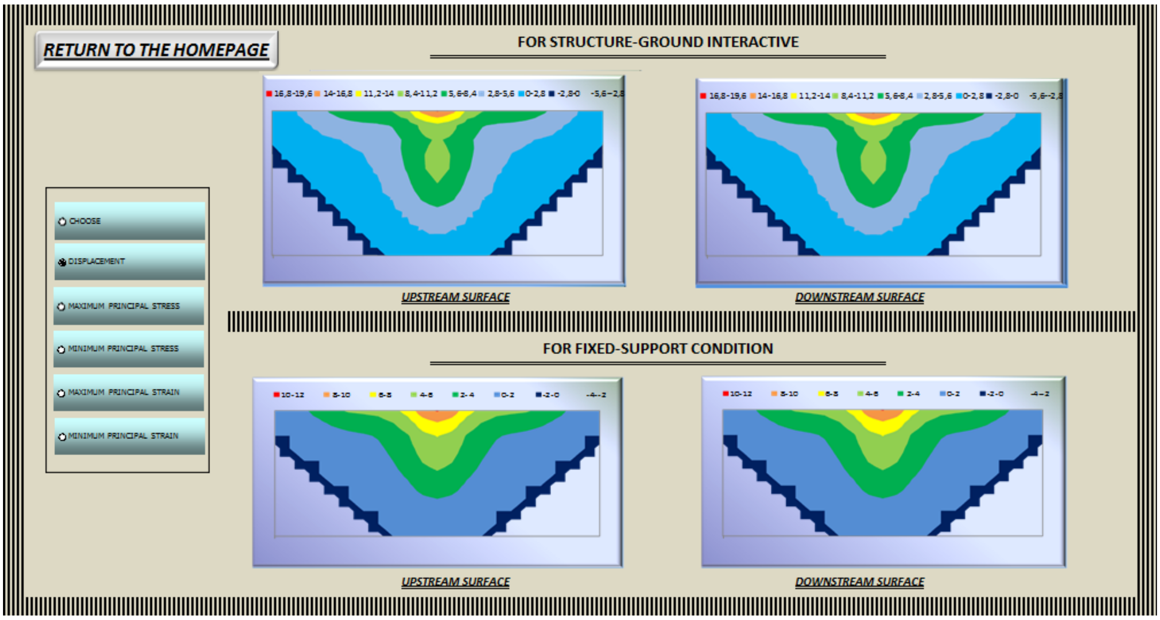


Fig. 21 Display of arch contour diagrams at contour diagrams page generated by dynamic analysis

4. Conclusions

In this study, engineering software is developed to predict the structural behavior of arch dams. By using the finite element model of the Type-1 arch dam modeled in the laboratory, dams are scaled to different heights and dynamic analyses are made. Taking into consideration the fixed support conditions and structure-foundation interaction of the Type-1 arch dam, it is obtained a total of 102 unit finite element models as 1, 10, 20, ..., 500 times scale. When the scales are expressed as arch height, they take values ranging between 0.60-300m and these values are also the first parameter for regression analysis. Modulus of elasticity are selected as second parameter and nine different concrete strength class (C14/16, C16/20, C18/22.5, C20/25, C25/30, C30/37, C35/45, C40/50 and C45/55) are considered for each structural model. Based on these two parameters, 918 different models are created and 3672 response spectrum analyses are applied by considering four different soil classes that is Z1, Z2, Z3 and Z4. All analyses are performed with ANSYS (2010) finite element program. The data for each nodal point on Type-1 arch dam is obtained for all soil classes, fixed support conditions and soil-structure interaction model, and a total of 2768 txt files are created. For regression analysis, the first step is to evaluate whether there is any relationship between the obtained data or a linear or non-linear relationship if there is a relationship. As a result of the review, a linear relationship was generally determined in the scatterplot of the data pertaining to displacement. Nonetheless, nonlinear relationships exist at some nodal points. However, it is seen nonlinear relationship in the scatterplot of data of the principal stress and principal strain. In each of the 346 nodal points on the arch body, a total of 13840 formulas are created represented of five different structural behavior, including displacement, maximum and minimum principal stresses, and maximum and minimum principal strains. The results of the regression analysis are compared with the results obtained from the ANSYS program and the error rates are examined. When the results are analyzed, it is seen that 10% of the error rates are not exceeded. In the scope of the work done in Type-1 dam, it is not easy to present the desired results due to the reasons such as the excess of the variable parameters and the combination of these parameters, long and specific of the formulas obtained for each nodal point. For this reason, it is aimed to develop a software that will only allow the results of the desired data to be obtained at a selected nodal point and display various graphs and contour diagrams of these results.

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