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Dynamic Soil Structure Interaction Study

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ABSTRACT

The effect of the surrounding soil, as depicted by the soil-structure interaction effect, on the dynamic behavior of Brezina concrete gravity arch dam, located in El-Beyadh at the west of Algeria, is investigated in the present study.

Both modal and transient analyses are performed for the dam, presented and discussed as a case study for this work. A three-dimensional finite element model (SOLID185) using ANSYS software is created to model the dam body and the adjacent soil. Three different seismic records having identical peak ground acceleration of 0.2g, assuming three different viscous damping ratios: 2%, 5% and 10%, are used in the analysis.

The results of this analysis constitute a data base for a parametric study investigating the soil-structure interaction effect, that of the mass of soil foundation and that of the damping ratio on the dynamic behavior of Brezina concrete arch dam.

Dynamic analyses for Brezina concrete arch dam for the three studied cases: dam without soil, dam with mass soil foundation and dam with massless soil foundation show that the presence of the soil in the model develops more stresses in the dam body, especially when the soil mass is considered in the model.

KEYWORDS: Concrete dams, Inertial interaction, Kinematic interaction, Dynamic soil-structure interaction.

INTRODUCTION

Gravity dams have fluid-structure-soil interaction problems. It is now generally known that the foundation soil affects the dynamic response of gravity dams during earthquakes (Alemdar Bayraktar et al., 2005). In the literature, there are four different models of the foundation soil: the standard rigid-base model, the massless-foundation model the deconvolved-base-rock model and the free-field dam-foundation interface model (Leger and Boughoufalah, 1989). In the massless foundation model, the absence of mass makes the foundation rock as a spring; i.e., only the flexibility of the foundation rock is taken into account.

The primary energy loss mechanism currently assumed in the analysis of concrete dams is viscous damping. Equivalent viscous damping constants have been experimentally determined. Shaking tests using low-level excitations have been performed on concrete dams throughout the world, and damping ratios of 2 to 5 percent of the critical damping have been frequently reported (Dreher, 1981). However, a damping ratio as

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high as 10 percent of the critical damping has been measured during higher level excitations. Therefore, a damping ratio of 2 to 10 percent appears reasonable for most concrete dams (Dreher, 1981).

OBJECTIVE

In this study, a dynamic analysis is performed for BREZINA concrete arch dam under different generated synthetic earthquake excitations (Armouti, 2004) (with a peak ground acceleration equal to 0.2g). The concrete gravity arch dam of BREZINA is located west of Algeria. The dam is 60 m high; its maximum arch length is 78.5 m. The dam is built on a rock of a modulus of elasticity that is equal to a half of that of concrete.

The material properties for both the concrete arch dam and the foundation are reported in Table 1. These characteristics are provided by a governmental organism in charge of the dam study.

Table 1. Material properties of Brezina dam

Material	Young's Modulus (N/m^2)	Poisson's ratio	Density (kg/m^3)
Concrete dam	28.5e+09	0.2	2500
Foundation	14.5e+09	0.25	2100

To investigate the effects of SSI on the dam, the following types of analysis are performed: linear SSI analysis with mass soil, linear SSI analysis considering massless soil, and for the same structure, analysis is carried out without the consideration of SSI. In the latter case, the dam is considered fixed at its base, which means that the soil is very rigid, and hence its modulus of elasticity is infinite. The effect of damping on the dam response in these three analyses is also taken into account; three damping ratios are used for this investigation: 2%, 5% and 10%.

The responses in the cases of study are then analyzed and compared considering the SSI effect using the "direct method"

It is important to note that the water effect is not taken into account in the present study. This is due to the fact that the target of this work is to study the effect of the presence of soil on the dynamic response of the dam on one hand, and due to limitation of powerful computers to run such analysis on the other.

METHODOLOGY

In this study, for each input motion (each generated record), the following cases are investigated:

- Neglecting the effect of SSI; i.e., assuming the structure as being fixed at its base. The foundation is assumed to be completely rigid (the modulus of elasticity is infinite).
- Linear SSI analysis while allowing for the mass of the foundation (taking into account the inertial effect of the foundation). The foundation modulus of elasticity is taken as a half of the dam concrete modulus of elasticity.
- Linear SSI analysis assuming massless foundation (neglecting the inertial effect of foundation) having a modulus of elasticity equal to a half of the dam modulus of elasticity.
- All the analyses above are repeated for different earthquake records applied in x direction and for different damping ratios.

At first, seismic free field input motion at ground surface is determined. This is achieved by analyzing the unexcavated virgin foundation in the absence of the structure. The free field motion will be calculated using the power spectral density for the foundation. To carry out this step, the computer program GNREQ is utilized (Armouti, 2004). Then, the deconvolution of this motion is carried out using the computer program "Shake". In the second step, the soil-structure behavior is assumed linear. In the third step, by using the analysis of the soil-structure system under the action of ground motion determined in the first step, and by using the linear soil-structure behavior assumed in the second step, by using the analysis is carried out using 3D solid elements in ANSYS (Saeed Moaveni, 1999). The analysis is carried out for different damping ratios, using two assumptions of soil foundation: (mass and massless soil) and two values of foundation modulus of elasticity: infinite value (rigid base) and a half of the modulus of elasticity of the dam.

It is important to note that for each case of analysis named above, modal analysis must be conducted to calculate the fundamental frequency and consequently to calculate the value of structural damping β from the assumed damping ratio using Eq.(1).

The results are tabulated, presented graphically, analyzed and compared.

VISCOUS DAMPING

Viscous damping is the damping of choice in many cases for describing the response of single degree of freedom dynamic systems. One of the main reasons for using viscous damping is associated with the fact that this damping is the most amenable for solving the dynamic equilibrium differential equations. When these concepts are extended to multiple degrees of freedom systems, serious shortcomings come into play, because there is no clear relationship between the physical phenomena and mathematical modeling (Garcia and Sozen, 2003). Using *Rayleigh damping*, the coefficient β is given as:

$$\beta = \frac{2\xi_i}{\omega_i} \qquad \text{Eq. (1)}$$

Dam Damping Ratios

Damping ratio values of 2 to 10 percent presently appear reasonable for most concrete dams (Dreher, 1981). Thus, three damping ratio values are used: 2%, 5% and 10%. The fact that the analysis used is linear elastic, interpolation can be made for other values of damping ratio.

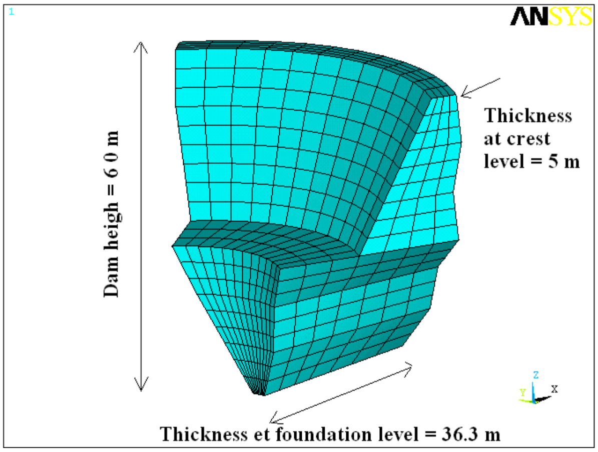

Figure 1: Three-dimensional finite element model for Brezina arch dam without adjacent soil

SSI MODELING USING ANSYS SOFTWARE

The SSI concept will be investigated as presented previously using two finite element models: the first model represents the dam alone neglecting the SSI effect and assuming that the structure is fixed at its support. The second model represents the dam plus the adjacent soil (the soil limits are fixed). A mapped meshing is performed to mesh the two models. The size of this mapped mesh is justified after conducting a sensitivity analysis.

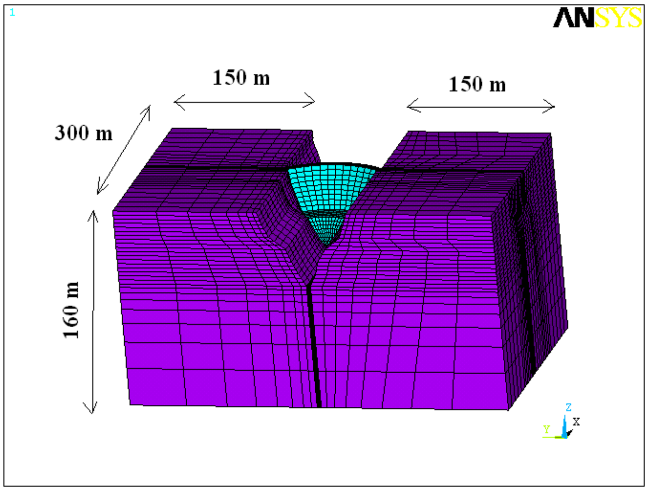

Figure 2: Three-dimensional finite element model for Brezina arch dam with adjacent soil

Table 2. The first ten natural frequencies of the dam without soil

Mode	Frequency (Hz)	Period (second)	Effective mass (kg)	Participation factor
1	12.312	0.08122	0.306853E+08	5539.4
2	18.144	0.05511	132.513	-11.511
3	24.764	0.04038	0.271882E+08	-5214.2
4	26.479	0.03776	0.124626E+08	3530.2
5	27.730	0.03606	54600.5	233.67

Table 3. The first ten natural frequencies of the dam with mass soil

Mode	Frequency (Hz)	Period (second)	Effective mass (kg)	Participation factor
1	6.583	0.15190	0.140694E+08	-3750.9
2	6.998	0.14289	17.5719	- 4.1919
3	7.629	0.13108	130478	-361.22
4	7.829	0.12773	0.532278E+10	72957
5	8.618	0.11604	0.147567E+10	-38414

Finite Element Meshing of Brezina Concrete Arch Dam without Soil and with Adjacent Soil

A three-dimensional (3-D) finite element model with 1378 nodes and 972 cubic elements (SOLID 185) is used to model Brezina dam without surrounding soil (Figure 1).

A three-dimensional (3-D) finite element model with 19035 nodes and 16252 cubic elements is used to model Brezina dam with the surrounding soil (Figure 2). The expansion of the soil is taken equal to 150m at each side in the x and y directions and equal to 100 m in the z direction which is the depth of the soil below the dam. These distances are chosen so that the ground motion is not affected by the presence of the dam.

DYNAMIC ANALYSIS AND PARAMETRIC STUDY

Modal Analysis

The five lowest natural frequencies and the corresponding effective masses and participation factors of Brezina dam without soil, Brezina dam with mass soil and Brezina dam with massless soil are presented in Table 2, Table 3 and Table 4, respectively.

Table 2 shows that frequencies are very important; these vary between 12.312 Hz and 27.730 Hz, which implies that the dam is very rigid. This is obvious as the dam is a fixed end one.

Table 4. The first ten natural frequencies of the dam with massless soil

Mode	Frequency (Hz)	Period (second)	Effective mass (kg)	Participation factor
1	9.275	0.10782	0.599958E+08	7745.7
2	13.439	0.07441	135.168	11.626
3	14.465	0.06913	0.328364E+08	5730.3
4	16.191	0.06176	53664.2	-231.66
5	16.881	0.05924	0.378214E+08	-6149.9

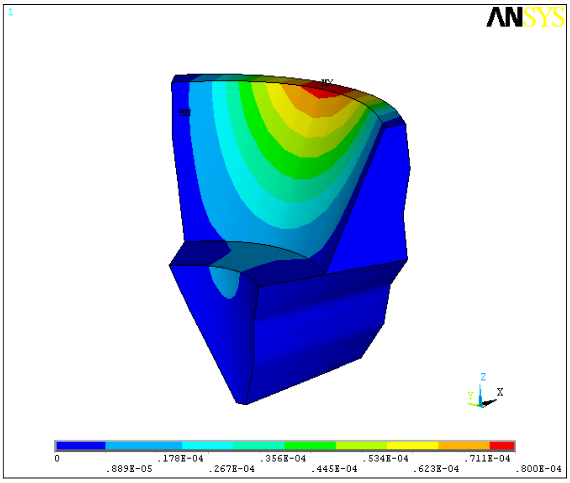

Figure 3: Nodal displacement contours (m) in x direction for dam without soil for $\xi = 0.05$ and random number initializer of 17962

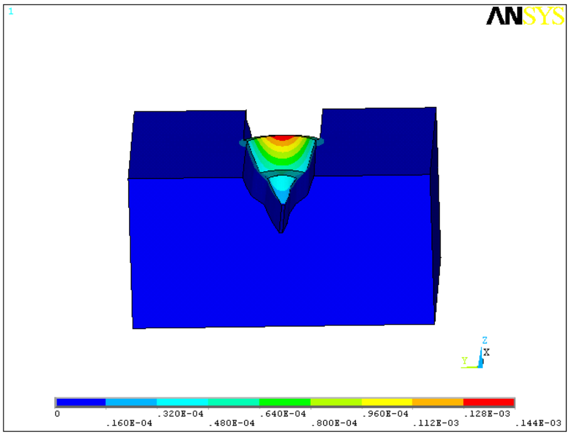

Figure 4: Nodal displacement contours (m) in x direction for dam with massless soil for $\xi = 0.05$ and random number initializer of 17962

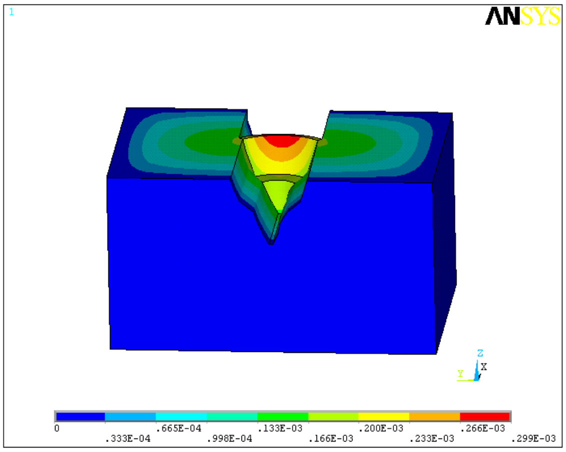

Figure 5: Nodal displacement contours (m) in x direction for dam with mass soil for $\xi = 0.05$ and random number initializer of 17962

From Tables 3 and 4, it is clear that for the case of the dam with massless soil, the frequencies are much greater than those for the case of the dam with mass soil. This is due to the fact that the mass matrix is located at the denominator in the frequency formula. This means that decreasing the mass leads to an increase in the frequency and *vice versa*.

Transient Analysis

A transient analysis using full Newmark method is performed for the three models representing Brezina concrete arch dam. Three generated records are used having the same peak ground acceleration (0.2 g) and different random numbers of initializers and assuming three values of viscous damping (three values of structural damping β).

It is important to mention that the results of the transient analysis are presented below for one synthetic earthquake record having an initializer number of 17962 but these results remain applicable for the three other generated earthquakes having initializer numbers of 16454 and 18124.

Displacement Comparison

Figure 3, Figure 4 and Figure 5 represent the displacement contours in x direction for the dam without soil, dam with massless soil and dam with mass soil, respectively subjected to the first generated record of random number initializer of 17962 with a damping ratio equal to $\xi = 0.05$.

It is important to note that the maximum displacements in the dam structure occur at the same nodes for the case of the dam without soil and the dam with soil. For example, the maximum displacement in x direction occurs at node 123 located at the middle crest of the dam without soil in the downstream face, which is node 339 in the case of dam with soil (the same results are obtained in the y and z directions).

Figure 6, Figure 7 and Figure 8 represent a comparison of the displacements for the crest part of the dam structure in x, y and z directions for the three studied cases (dam without soil, dam with massless soil and dam with mass soil) for viscous damping ratio $\xi = 0.05$ and generated record of random number initializer of 17962.

From these figures, two observations can be made:

The first one is that the case of the dam with soil leads to more displacement amplitude than the case of the dam without soil, where the soil is modeled by fixed end supports. This is due to the presence of the soil which gives more flexibility to the dam body to displace.

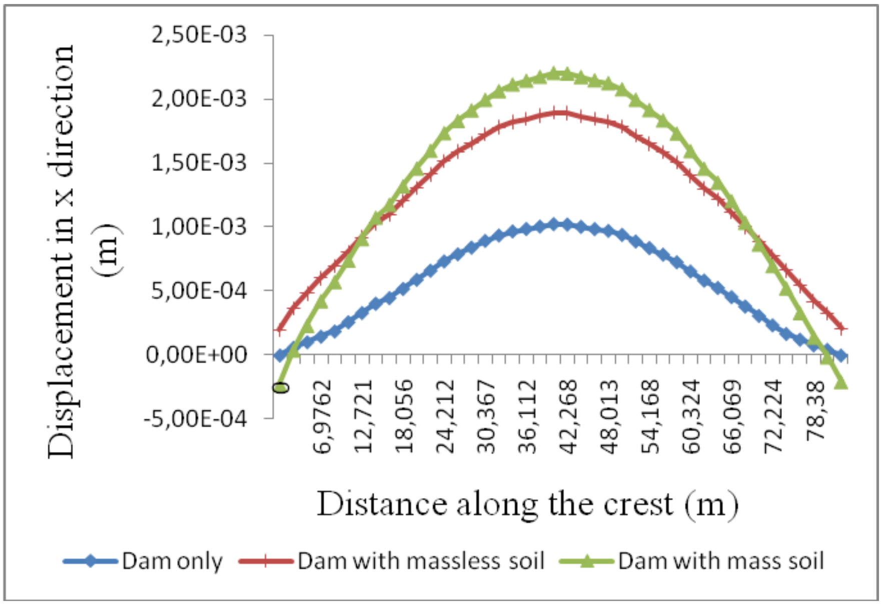

Figure 6: Displacements in x direction along the crest for the three studied cases for $\xi = 0.05$ and random number initializer of 17962

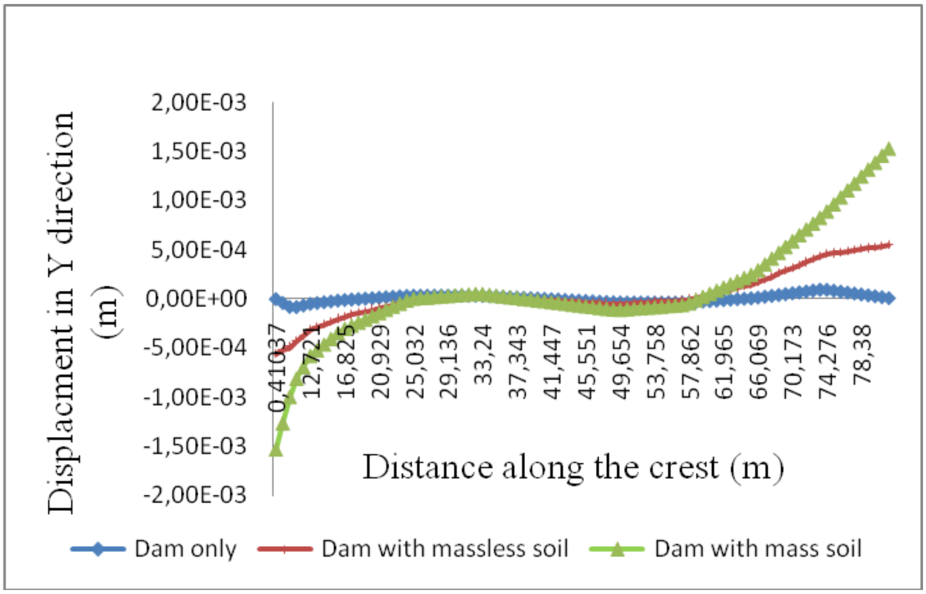

Figure 7: Displacements in y direction along the crest for the three studied cases for $\xi = 0.05$ and random number initializer of 17962

The second observation is that displacements are larger when the soil mass is considered than for the case of massless soil. The results of modal analysis can be used to interpret this observation. Table 3 and Table 4 show that frequencies for the case of dam with mass soil are less than those for the case of dam with massless soil, which means that the periods and, consequently, the displacements of the first case are greater than those for the second case. This is not enough to take conclusions. These, however, are total displacements. For design purposes, relative displacements and stresses are of interest.

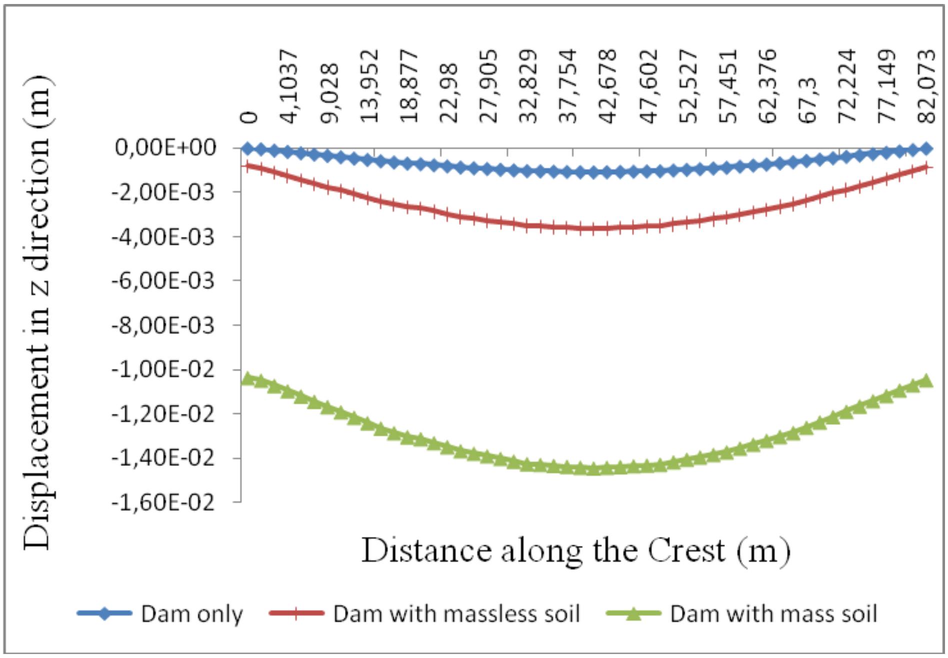

Figure 8: Displacements in z direction along the crest for the three studied cases for $\xi = 0.05$ and random number initializer of 17962

Stress Variation

As for the displacement contours, the maximum stresses in the dam structure occur at the same nodes for the case of the dam without soil and the dam with soil.

Since the response of the dam is complex, the maximal stresses obtained are represented for the two essential parts of the upstream face of the dam: the central zone with its cantilever effect and the crest with its arch effect.

Figure 9, Figure 10, Figure 11 and Figure 12 represent a comparison of the maximal stresses in the x, y and z directions as well as Von Mises stress, respectively, for the three studied cases; dam without soil, dam with massless soil and dam with mass soil.

It can be seen from the figures that the presence of soil develops more stresses in the dam body compared with the case of the dam without soil. Furthermore, when the soil is modeled as mass soil, the same results are obtained along the crest part of the dam for the three cases studied.

Effect of Viscous Damping on Displacement and Stress for the Three Cases Studied

The present study shows that the damping ratio has a very small effect on the dynamic behavior of the dam without soil, the dam with massless soil and the dam with mass soil, where it is obvious that the stresses increase with decreasing the damping ratio.

DISCUSSION OF RESULTS

From this parametric study, the following conclusions can be drawn:

- ✓ The case of the dam with soil is more conservative; it develops more displacement amplitude and more stresses than the case of the dam without soil.
- ✓ The case of the dam with mass soil is more conservative than the case of the dam with massless soil.
- ✓ The damping ratio has a very small effect on the dynamic behavior of the dam without soil, the dam with massless soil and the dam with mass soil, where the stresses increase with decreasing the damping ratio.

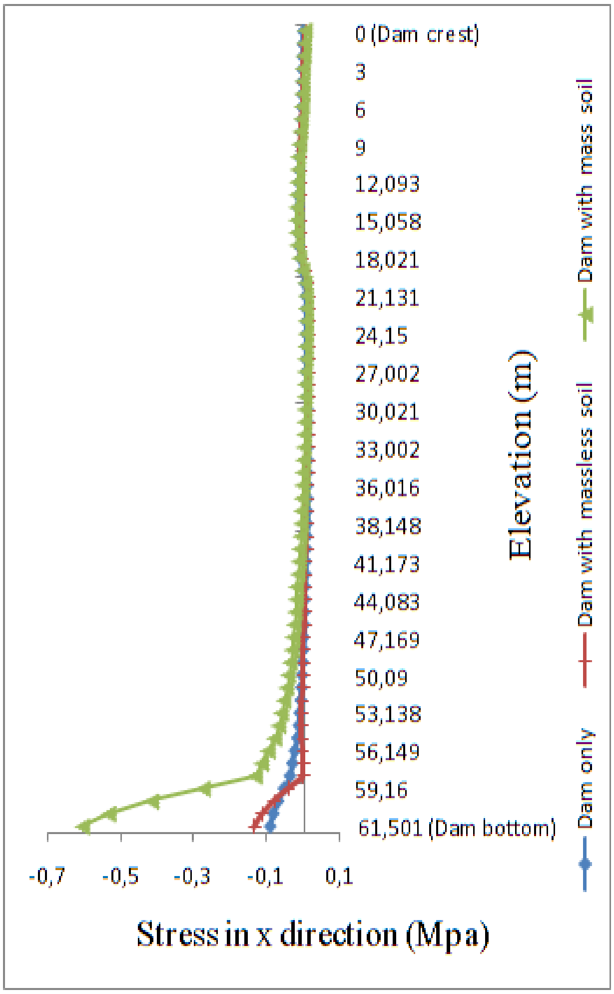

Figure 9: Variation of stresses in x direction in the central part of the dam for the three cases studied for $\xi = 0.05$ and random number initializer of 17962

To interpret the first two results, response spectra (maximum accelerations as function of the natural periods of vibration) which excite the natural periods of the three models need to be compared. In this study, response spectra are constructed using customized program RESSPEC [5]. Figure 13 depicts the response spectra for the first record having an initializer number of 17962 for the three damping ratios (2%, 5% and 10%), which excite the natural periods of the dam (for the three studied cases).

From Figure 13, it is clear that the spectral accelerations that excite the dam without soil are smaller than those for the dam with soil (both mass soil and massless soil), which means that neglecting the soil is not safe in term of design.

The dam with soil is more excited than the dam without soil, which justifies the difference of stresses and displacements for the different cases studied. This is due to the fact that the modulus of elasticity of the soil foundation for the case of the dam with soil is less than the modulus of elasticity of the soil for the case of the dam without soil, where the soil is modeled as a fixed support (which means that the modulus of elasticity is infinite).

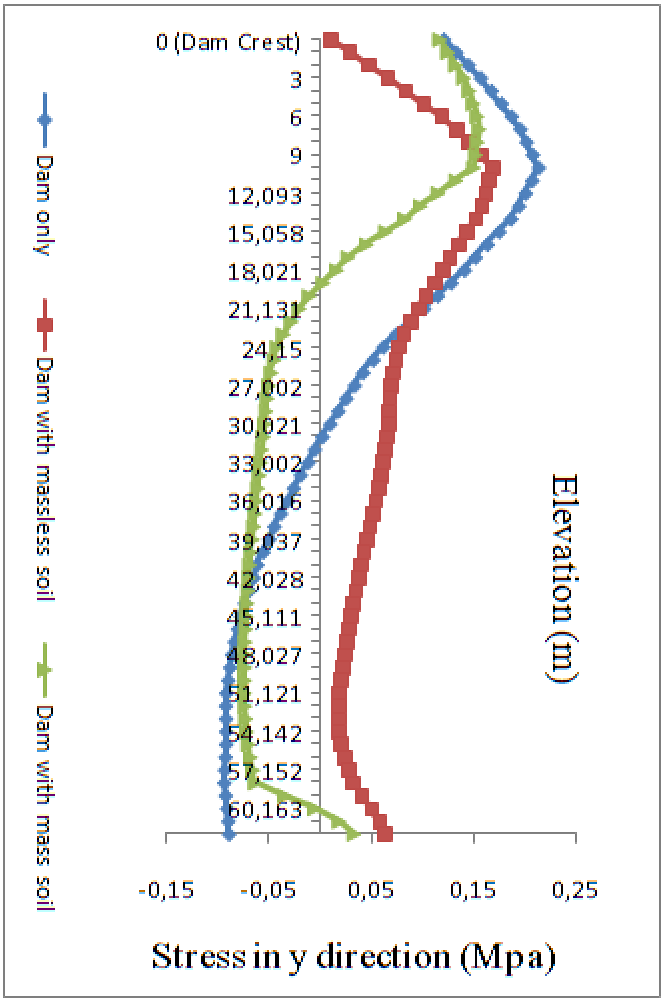

Figure 10: Variation of stresses in y direction in the central part of the dam for the three cases studied for $\xi = 0.05$ and random number initializer of 17962

Adding the soil to the dam leads to a change in the system dynamic properties (natural frequencies) and consequently to a change in its total response. This is known as the soil-structure interaction. The soil with its properties (which are totally different from those of the dam) affects the dam and *vice versa*.

The presence and the behavior of the soil foundation have important effects on the dynamic response of the dam structure. This response depends on the dynamic properties of the dam itself, the soil foundation and the excitation (record).

Taking the mass of the soil foundation into account has proved to be more conservative than ignoring it. Since *Brezina* dam is embedded in soil, the soil mass surrounding the dam will participate in the interaction by its inertial force exerted on the dam, and, consequently, the interaction effect becomes more pronounced than in the case where the soil is considered massless (the soil inertial effect is ignored).

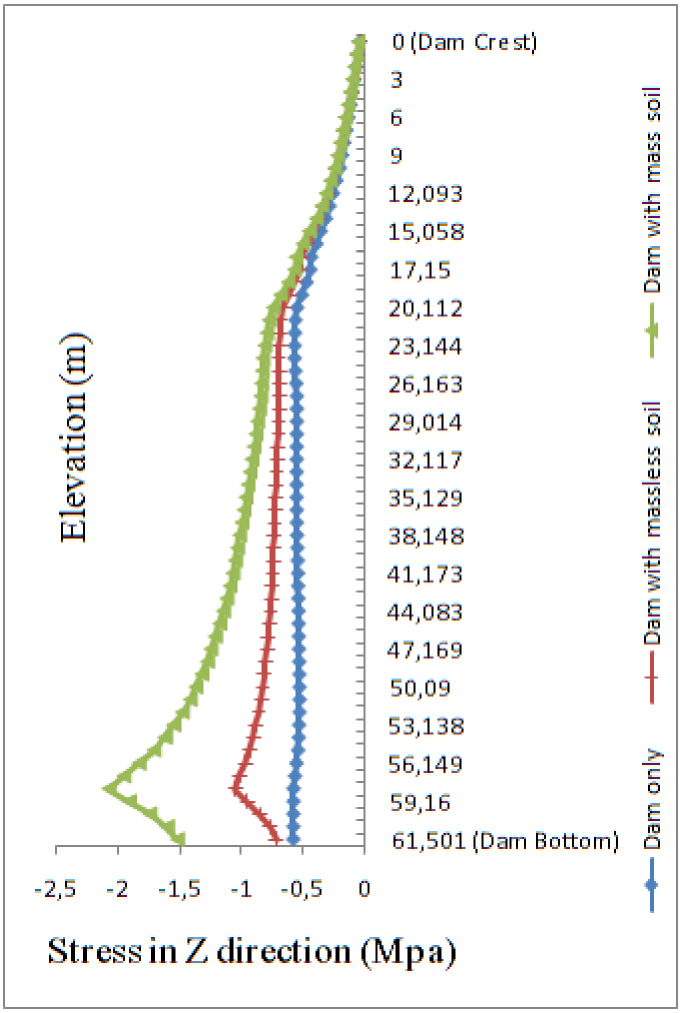

Figure 11: Variation of stresses in z direction in the central part of the dam for the three cases studied for $\xi = 0.05$ and random number initializer of 17962

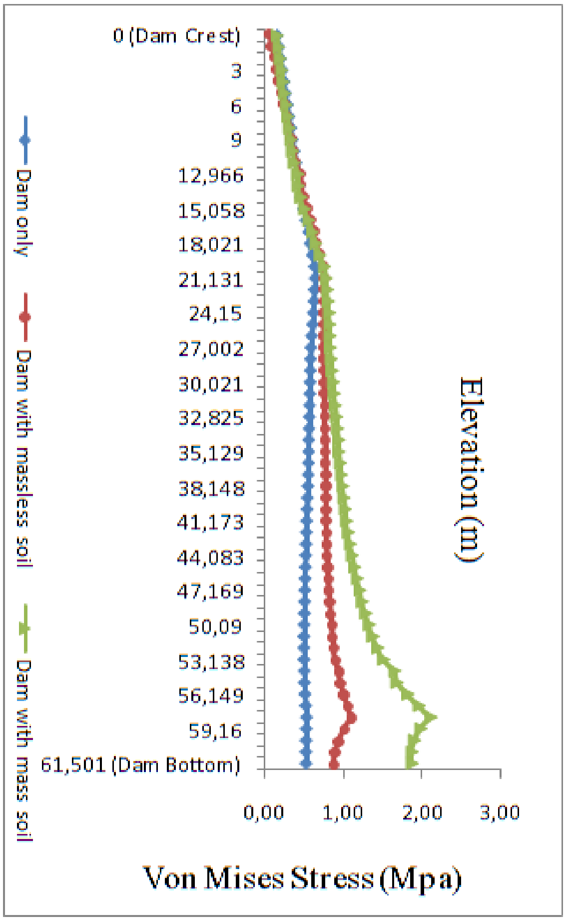

Figure 12: Variation of Von Mises stresses in the central part of the dam for the three cases studied for $\xi = 0.05$ and random number initializer of 17962

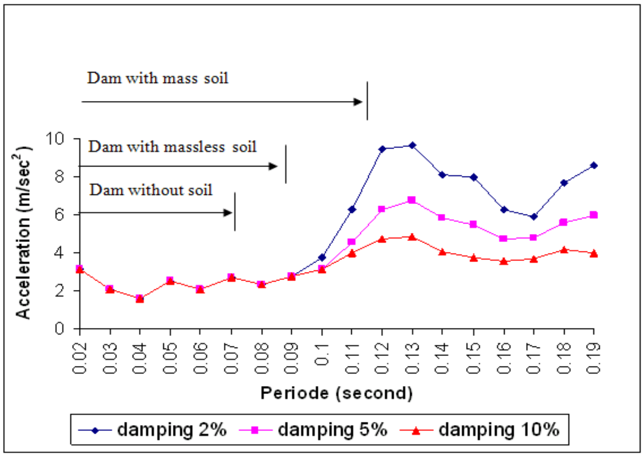

Figure 13: Response spectrum for the record of initializer number of 17962 at different damping ratios

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