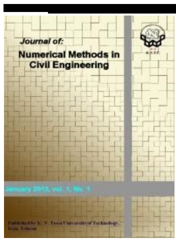

Numerical Methods in Civil Engineering

The effect of earthquake frequency content and soil structure interaction on the seismic behavior of concrete gravity dam-foundation-reservoir system

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***Abstract**:*

The effect of frequency content on the dynamic response of concrete gravity dams is investigated in this paper. Dams are one of the most complex structures to handle when there is dynamic analysis involved. One of the influential parameters on these structures' seismic response is the frequency content of the earthquakes. An index to represent frequency content, which represents frequency content by PGA/PGV ratio(FCI) and sets three ranges including high(FCI>1.2), intermediate(0.8<FCI<1.2) and low-frequency content (FCI<0.8) is used in this paper. To simply study the effect of different frequency contents, a comparative analysis with different earthquake records with different frequency contents is performed on the finite element model of the Pine Flat concrete gravity dam. Results indicate a great influence of frequency content on the dynamic response of the structure. On a side note, to study the effect of soil-structure interaction, the same model has been analyzed under different modular ratios (modular ratio is the ratio of modulus of elasticity of the foundation of the structure(E_f/E_s). This is one of the simplest ways to introduce interaction effects in the analysis. The outcome states that different modular ratios (hence different soil-structure interaction participation) have an immense effect on the dam's dynamic response.

1. Introduction

One of the most glamorous structures of the present time is a dam that might get lost during analyzing procedures. When there is such a complex system like procedure to get the most accurate results with less computational cost, a simplification procedure is where unintended ignorance may occur.

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Most simplifications are made where there is high complexity or high uncertainty. A good example of both these issues is the dynamic analysis of structures, mainly concrete gravity dams, under earthquake excitation. There have been numerous studies on the dynamic analysis of concrete dams in recent years, each covering a unique aspect that might interfere with the analysis results. Studies on the seismic behavior of structural buildings have long been the subject of interest in civil engineering. The particular effect of vibration frequency on the system's response has been studied by many researchers separately. Some real outcomes are presented by Jennings and Kuroiwa [1], Foutch et al. [2], Mcverry [3], and Chopra [4]. One of their significant findings on this subject was that the resonance phenomenon must be dealt with special care since its peak response is expected to happen. Resonance occurs when vibration frequency is very close to the corresponding natural frequency of the system. In 1988 Leger and Boughoufalah. [5] studied the effect of different earthquake input mechanisms for concrete gravity dams. They proposed different mechanisms and performed a comparative study to present the advantages and disadvantages of every proposed model. Although not very accurate, they concluded that assuming a massless foundation and applying earthquake at its boundaries yields fairly acceptable results within the computational cost budget available when dealing with an engineering problem and not a purely academic problem. Later on, Mirzabozorg et al. [6] studied the effect of non-uniform excitation on linear and non-linear responses of arch dams in a dam-reservoir-massed foundation system. They were able to find out that in the case of non-uniform excitation versus uniform excitation, responses obtained from the non-uniform case has completely different frequency content than the uniform case. In 2012, Ghaemian and Sohrabi-Gilani [7,8] investigated the effect of non-uniform ground motion on the seismic response of concrete arch dams. They concluded that multiple support excitation can significantly influence the seismic response of concrete arch dams and even increase the responses in specific cases.

The argument around earthquakes is somewhat extensive, but this paper is dedicated to studying the effect of only one particular property of earthquakes on the seismic behavior of concrete gravity dams, which is their frequency content. The frequency content of earthquakes can have enormous effects on the outcome of concrete gravity dams analysis. One index that can be used as a representative of frequency content is the ratio of PGV (Peak Ground Velocity) to PGA (Peak Ground Acceleration) [9,10]. According to Kramer [11], although this ratio can be interpreted as a meaningful index for frequency content, parameters like predominant period, bandwidth, central frequency, power spectrum intensity, response spectrum intensity, velocity spectrum intensity and acceleration spectrum intensity are also of interest in this category. He states that there are numerous ways to consider frequency content in a problem. Tso et al. [12] and Kermani et al. [13] have shown that although PGV and PGA are useful intensity measures, they can't solely describe frequency content. On the other hand, their ratio is a fine measure to represent frequency content. Livaoglu [14] and Panchal and Jangid [15] investigated the seismic response of elevated steel water storage tanks with the view of considering different characteristics of the earthquakes. Their study analyzed the tank under various earthquake records (and thus different frequency contents) and concluded that frequency content affects the structure responses. Shakib and Omidinasab [16] studied the response of an elevated water storage tank under ground motions with different frequency contents. They found out that earthquakes with low-frequency contents affect the first convective mode more severely and result in large vertical displacements on the free surface of the water. In contrast, earthquakes with high-frequency contents affect the first impulsive mode more and result in high response parameters. Gazetas et al. [17] investigated the effect of different frequency content on the non-linear response of earth dams. They found out that the response of the system is highly sensitive to the predominant period of excitation. Popsecu [18] took the liberty of focusing his research on the seismic behavior of systems when a complex environment like soil is involved. He concluded that earthquake excitation's frequency content and dynamic properties of soil are equally important in the dynamic analysis of any system and can profoundly affect the response of the structure or system. Kianoush and Ghaemmaghami [19] studied the frequency content effects on a particular rectangular liquid tank subject. With some simplifications, they also took soil-structure interaction into account in their study. They concluded that frequency content could have a major influence on the seismic response of the rectangular liquid tanks. The same analysis for a different problem was performed by Cakir [20]. He investigated the effect of earthquake frequency content on the seismic response of cantilever retaining wall with soil-structure interaction. He also found out that frequency content can have profound effects on the dynamic response of the wall.

In this study, frequency content is represented by PGA/PGV ratio. For abbreviation purposes, let's call this ratio (PGA/PGV) the frequency content index or indicator (FCI). This way, an earthquake has high-frequency content if FCI>1.2, intermediate frequency content if 1.2>FCI>0.8, and low-frequency content when FCI<0.8 [19]. The sole purpose of this paper is to investigate the effect of different frequency contents on the seismic behavior of concrete gravity dams. Due to this purpose, a finite element model of the Pine Flat concrete gravity dam is analyzed under different earthquake input motions with varying contents of frequency. As will be seen, results indicate a high dependency on dam response to the frequency content ratio of the earthquake.

Other influential parameters in the analysis, which are up to date and still a dilemma for scientists are fluid-structure and soil-structure interaction. There has been no accurate model that can effectively yet simply take soil-structure interaction into account. Since this paper's aim is mainly focused on frequency content effects in the analysis, no such accurate modeling of interaction is the case here. In order not to completely ignore the existence of this property, one can use a technique like running the analysis for different modular ratios (modular ratio is the ratio of modulus of elasticity of the foundation to the structure $\frac{E_f}{E_s}$) and comparing the results. This is mathematically simple, computationally cheaper than other complicated methods, and yet acceptably accurate. Plus, this leads to the effortless implementation of the soil-structure interaction into the model. The analysis was performed for modular ratios equal to 0.25, 0.5, 1, 2, 4, infinite, which by infinite means a rigid foundation. Results indicate a high dependency of the response to modular ratio as well.

2. Mathematical Basics of the model

As it is clear, the distribution of hydrodynamic pressure in the reservoir is governed by the pressure wave equation. If the fluid (in our case reservoir's water) is assumed incompressible and inviscid, then the wave propagation equation simplifies into the following form known as Laplace equation:

$$\nabla^2 p(x, y, t) = 0 \qquad (1)$$

In which P(x,y,t) is the hydrodynamic pressure only. Note that the above formulation is only valid for small amplitude motions in which convective terms can be neglected.

Since the above equation is a boundary value problem, it needs proper boundary conditions to be solved. There must be no flow across the interface at the fluid-structure interface, which means that there is no relative velocity. This can be represented mathematically in the following form:

$$v_n^s = v_n \qquad (2)$$

In which n is the unit normal vector to the boundary at the dam-reservoir interface and v_n^s and v_n are the velocity of the structure (dam) and fluid along with the n, respectively.

With further manipulations, this leads to the following boundary condition at the dam-reservoir interface:

$$\frac{\partial p}{\partial n} = -\rho a_n^s \qquad (3)$$

In which a_n^s is the normal acceleration of the dam.

With some minor differences, a look-alike equation can be used for the reservoir-foundation boundary condition, which has the following form:

$$\frac{\partial p}{\partial n} - q\frac{\partial p}{\partial t} = \rho a_n^f \qquad (4)$$

Where a_n^f is the normal acceleration of the foundation and q is the admittance or damping coefficient. For a rigid foundation, q becomes zero, and the above equation is virtually the same as the one derived for the dam-reservoir boundary condition.

At the reservoir's surface, the most effective parameter to take into account is the small-amplitude gravity waves. Since it is customary to neglect gravity wave effects at the reservoir's surface, when the system being analyzed is dam-reservoir-foundation, the free-surface boundary condition is appropriately applicable to the problem at hand. This can be interpreted mathematically by the following relationship:

$$P(x, y, H, t) = 0 \qquad (5)$$

In which H is the height of the reservoir.

There remains only one boundary condition, and that is the reservoir's far-end truncated boundary condition. Numerous boundary conditions have been proposed, but for the problem at hand, an appropriate non-reflective boundary condition was applied to prevent any waves reaching the far-end from reflecting back into the system. This is based on the very fact that any wave propagating toward infinity can be accounted as a planar wave and thus, theoretically, can be fully absorbed by appropriate boundary conditions.

3. Properties and modeling

The model at hand is the finite element model of the Pine Flat concrete gravity dam. The properties of the materials used in the modeling are presented in table 1.

The dam is on the Kings River of central California. It is 130 meters high with a total capacity of the reservoir equal to 1.2 cubic kilometers. The whole system is modeled in the analysis, which means a dam-foundation-reservoir system is going to be analyzed. The finite element model of the dam is developed using the existing schematics of the dam. The properties of the dam, reservoir, and foundation were selected according to Table1. Other modeling techniques and assumptions will be illustrated in their respective sections.

Table. 1: Material Properties

	Dam	Reservoir	Foundation
density (kg/cm^2)	2400	1000	0
Elastic modulus (Bulk modulus in case of water) (*10^9 Pa)	27.58	2.07	*---
Poison's ratio	0.33	---	0.2

* *Since one of the subjects of this study is investigating the effect of modular ratio on the response of the structure, foundation modulus will be chosen concerning the intended modular ratio in the analysis.*

It should be noted that the values in Table 1 are selected from the official reports on the subject.

In this paper, the concrete of the dam body is assumed to be elastic. As can be seen in the above table, the density of the foundation is equal to zero. This is purely for modeling purposes. To illustrate this matter a little more, when we have a dam-foundation-reservoir system, modeling all the details in a way that there are consistent with one another is a complex effort. One of the facts that has been a subject of argument for many years now is the foundation's mass. As it is clear, the most realistic model should include a massed foundation along with proper models of reservoir and structure. The Effects of massed foundation on the dynamic results of concrete gravity dams have been studied by many people such as Aghajanzadeh, et al [21], mohammadnezhad et al. [22] and sotoudeh et al. [23]. However the finite element modeling of this very important detail in the analysis is extremely complex, so, an alternative approach should be used. One of the most frequently used approaches is the massless foundation model. Although this model is not a realistic model, it is a suitable approach for modeling foundation for this particular problem. Bear in mind that it is a comparative study meaning where the results will be compared correspondingly; thus, a fairly appropriate approach for all models can be accomplished.

The dam-foundation-reservoir system has been modeled in ABAQUS software [24] and the dam and foundation were modeled using eight-node isoparametric solid elements with the properties given in Table 1. It is worth mentioning that for each analysis, proper value for the foundation modulus of elasticity was chosen with respect to the intended modular ratio. The reservoir was modeled using 8-node acoustic elements. Acoustic elements have only one degree of freedom at each node, and that is pressure.

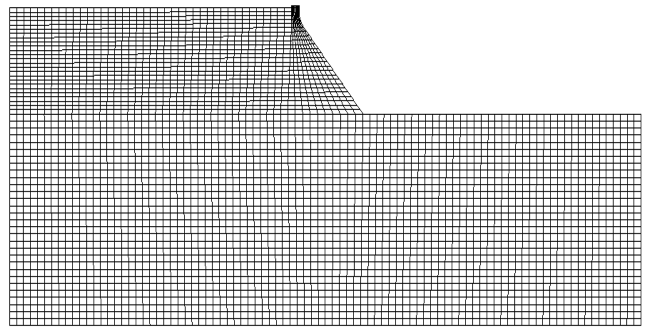
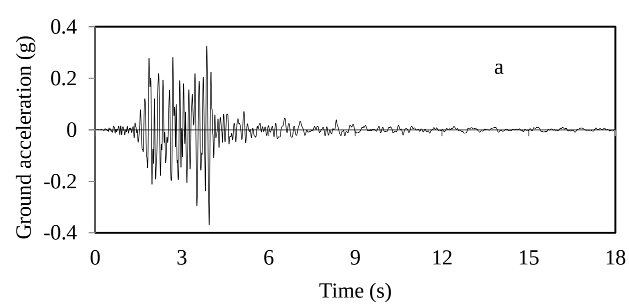
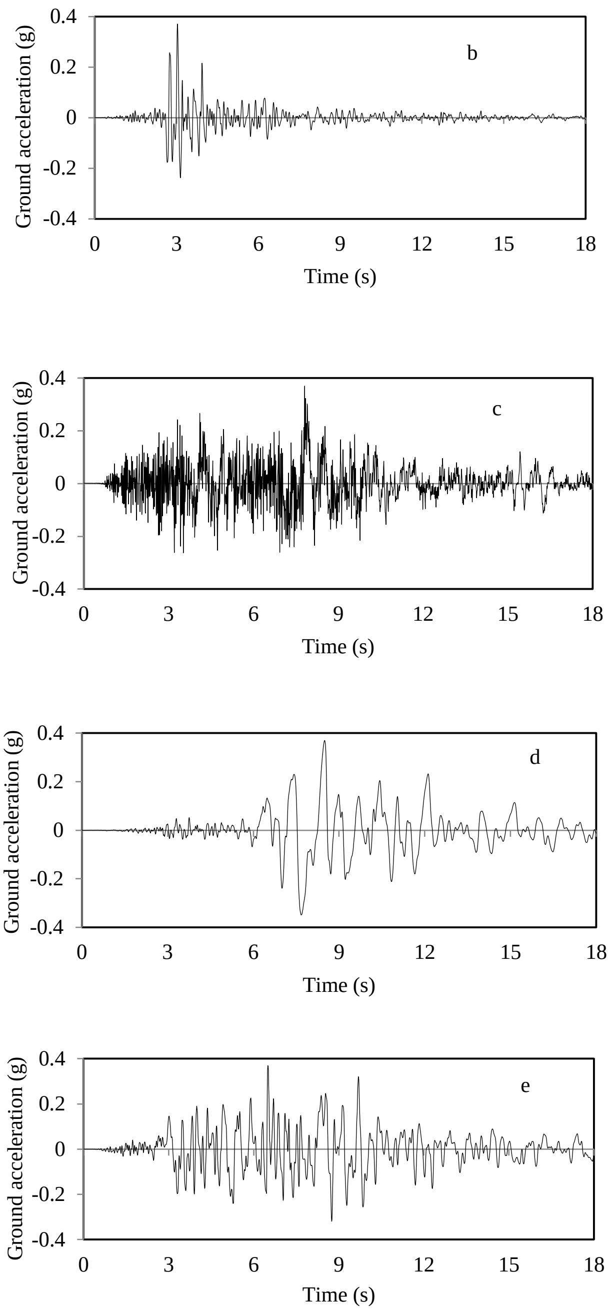


Fig. 1: Finite element model of a dam-foundation-reservoir system

At the reservoir and dam interface, respective nodes of both reservoir and dam were tied together in their translational degrees of freedom. The same condition was applied for the interface of the reservoir and foundation. The finite element model of the dam-foundation-reservoir system is displayed in fig 1.

Earthquake input motion was applied at foundation boundaries. It should be noted that only the horizontal component of the earthquake is applied, and the bottom of the foundation is restrained against vertical movement. To investigate the effect of frequency content on the response of the structure, five different earthquake motions were used, Loma Prieta (1989), Imperial Valley (1983), Northridge (1994), Coalinga 1983), and Whittier Narrows (1987). All these records were scaled to have the same 0.37g PGA. According to the frequency content index or indicator (FCI), Loma Prieta earthquake has low-frequency content, Imperial Valley and Northridge earthquakes have intermediate frequency contents, and Coalinga and Whittier Narrows have high-frequency content. The horizontal components of earthquake records, including (a) Coalinga (b) Whittier Narrows (c) Imperial Valley (d) LomaPrieta (e)Northridge, are displayed in fig 2 respectively, and the PSD function of the records are displayed in fig 3.





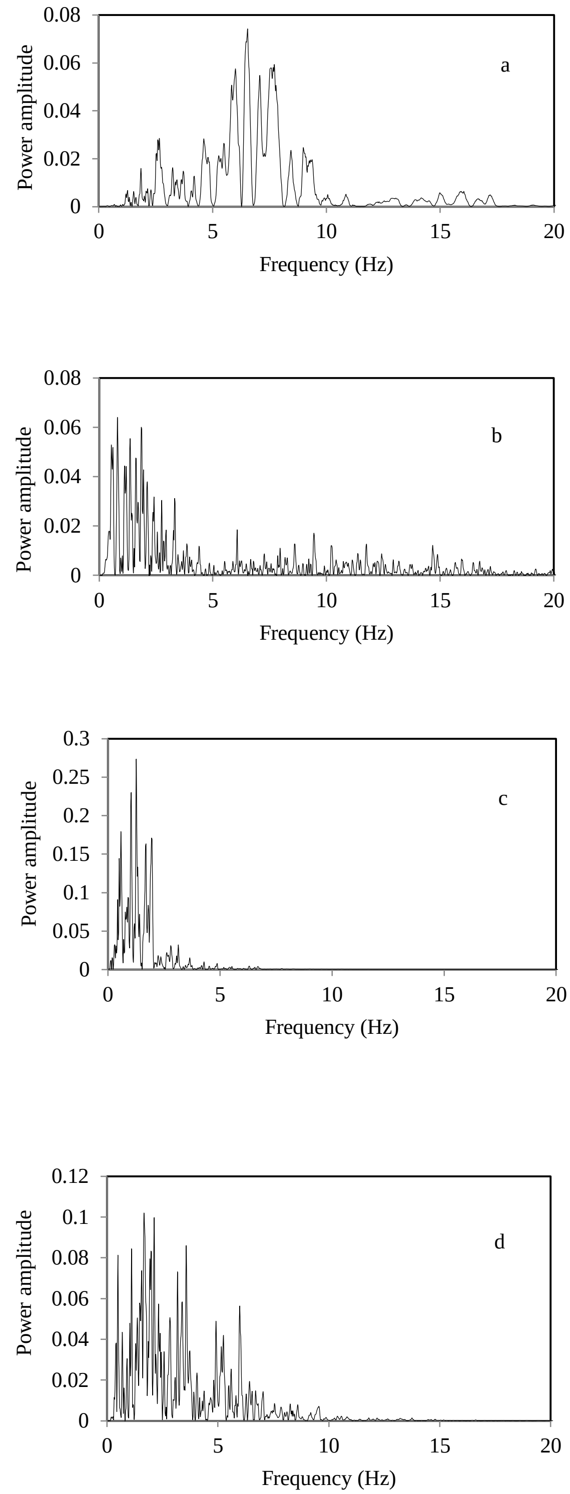


Fig. 2: Horizontal components of earthquake records: (a) Coalinga (b) Whittier Narrows (c) Imperial Valley (d) Loma Prieta (e) Northridge

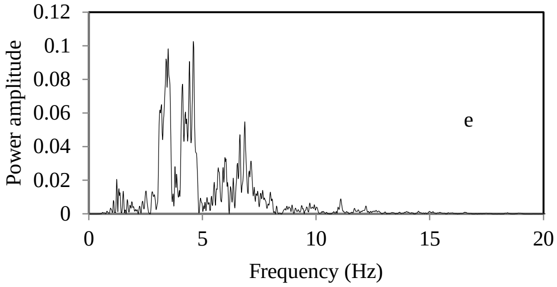


Fig. 3: PSD function of: (a) Coalinga (b) Imperial Valley (c) Loma Prieta (d) Northridge (e) Whittier Narrows

4. Analysis

4.1 Modal analysis

To apply proper damping to the system, a method is needed. Rayleigh's method, by far, is one of the simplest yet fairly accurate methods proposed. Subsequently, Hall [25] proposed a modification that would improve Rayleigh's method in estimating the system's damping. In order to do so, modal analysis was performed for models (a system of dam-reservoir-foundation) with different modular ratios to obtain natural frequencies of the system. According to the following formulation, using Hall's proposed modification, the damping coefficients for different models are presented in Table 2. α and β.

$$[C] = \alpha[M] + \beta[K] \qquad (6)$$

Table. 2: Damping coefficients for different models

modular ratio	**α**	**β**
$\frac{E_f}{S_s} = 0.25$	1.36	0.00085
$\frac{E_f}{S_s} = 0.5$	1.67	0.00077
$\frac{E_f}{S_s} = 1$	1.94	0.00072
$\frac{E_f}{S_s} = 2$	2.14	0.00068
$\frac{E_f}{S_s} = 4$	2.27	0.00066
$\frac{E_f}{S_s} = \infty$	2.45	0.00060

It should be mentioned that the infinite modular ratio in Table 2 means a rigid foundation.

4.2 Dynamic analysis

For the given and calculated properties, a finite element model of the Pine Flat dam was developed for dynamic analysis. Altogether, there are 6 different modular ratios and 5 different earthquakes (which are representatives are different frequency contents). Thus 30 dynamic analyses were performed in this area. The outputs of interest are relative displacement of the crest with respect to the heel of the dam and root mean square of nodal displacements (RMSD). RMSD is the root mean square of nodal displacement for each given time history and is calculated by the following relation proposed by Leger and Boughoufalah [5]:

$$RMSD = \left(\sum_{i=1}^{n} u_j^2(t_i)\right)^{0.5} \qquad (7)$$

t_i is the cumulative time after i^{th} time step, and n is the total number of steps. $U_j(t_i)$ is the jth node's nodal displacement at time step t_i of the time history.

4.3 Results

Modal and dynamic analysis of the dam-foundation-reservoir system was carried out based on the parameters given in table 1.

The maximum relative displacement of the crest to the heel, obtained from the dynamic analysis under the effect of every 5 earthquake records and for different modular ratios is given in table3. RMSD value calculated with formula7 under the effect of 5 earthquake records is exhibited in table4.

Results show maximum relative displacement and RMSD values decrease when modular ratio increases for all records (except Coalinga Earthquake). But this case shows that a clear trend cannot be seen with respect to modular ratio since Coalinga earthquake yields greater displacements when the foundation moves from a highly flexible state to a rigid state.

Table. 3: Max relative displacement of the crest with respect to the heel (cm)

	modular ratio					
Earthquakes	**0.25**	**0.5**	**1**	**2**	**4**	**rigid**
Loma Prieta	18.57	18.96	9.4	7.4	5.8	6.1
Imperial Valley	8.79	8.37	5.8	5.6	3.73	3.8
Northridge	14.5	11	12.6	7.47	6.6	6.9
Coalinga	2.8	3.7	3.9	3.9	5.2	4.8
Whittier Narrows	4.8	3.1	3.5	3.3	3.7	3.4

The time histories of relative displacement of the crest to the heel under the effect of Whittier narrow (high-frequency content) and Northridge (intermediate-frequency content) records in the rigid case are compared in fig4, and under the effect of the imperial valley (intermediate-frequency content) and Lomaprieta (low-frequency content) records are compared in fig5.

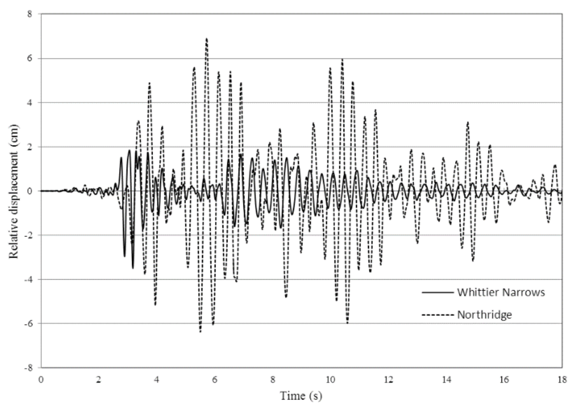


Fig. 4: Time histories of relative displacement of the crest with respect to the heel under the effect of Whittier Narrows and Northridge earthquakes in the rigid case

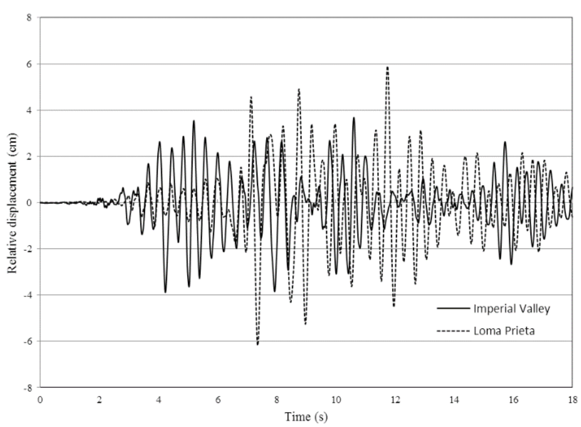


Fig. 5: Time histories of relative displacement of the crest with respect to the heel under the effect of Imperial Valley and Loma Prieta earthquake in the rigid case

As a result, based on fig 4 and 5, it can be seen that by increasing the FCI ratio (which leads to high-frequency content), the maximum relative displacement decreases.

Table. 4: RMSD value (cm)

	modular ratio					
Earthquaks	**0.25**	**0.5**	**1**	**2**	**4**	**rigid**
Loma Prieta	197.1	194.87	104.7	74.27	65.5	67.6
Imperial Valley	109.7	94.9	71.28	61.8	49.17	51.6
Northridge	169.83	152.28	135.12	104.28	83.17	86.5
Coalinga	26.7	35.3	30.15	34.17	44.64	44.3
Whittier Narrows	33.08	27.38	21.98	25.05	25.37	25.7

RMSD values and maximum relative displacements of the crest to the heel under the effect of 5 earthquake records and different Ef/Es ratios are compared in fig 6 and 7, respectively.

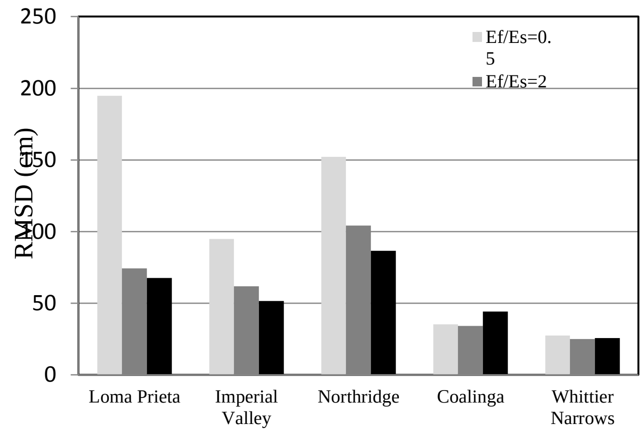


Fig. 6: Comparisons of RMSD for different earthquake records

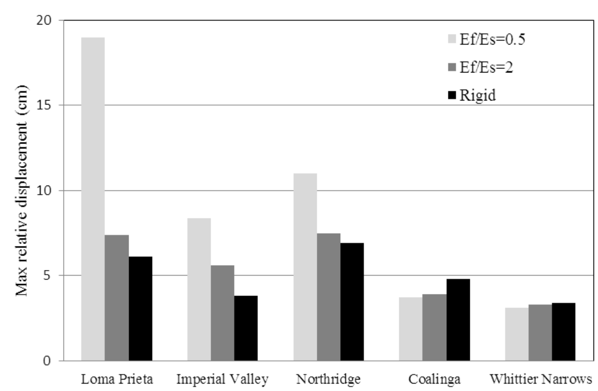


Fig. 7: Comparisons of maximum relative displacement of the crest with respect to the heel for different earthquake records

Figures 6 and 7 show that by decreasing the FCI Ratio (which means reducing of frequency content), the effect of Ef/Es on RMSD value and relative displacement will increase and it is also clear that, as the rigidity of the foundation increases, the maximum relative displacement, and the RMSD value will decrease in low and intermediate frequency content.

Figures 8 and 9 show the time history of relative displacements of the crest for different Ef/Es ratio under the effect of a constant earthquake, including Lomaprieta and Imperial Valley earthquake, respectively. Also, the time histories of relative displacement of the crest for constant Ef/Es ratio under the effect of three earthquake records with different frequency content (low, intermediate and high) are displayed in fig 10 and 11.

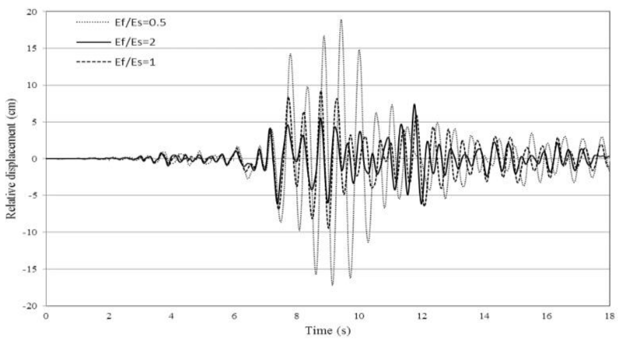


Fig. 8: Time histories of relative displacement of the crest with respect to heel under the effect of Loma Prieta earthquake

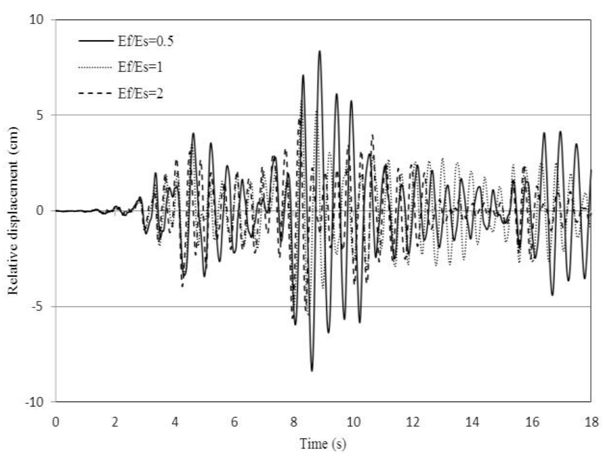


Fig. 9: Time histories of relative displacement of the crest with respect to the heel under the effect of Imperial Valley earthquake

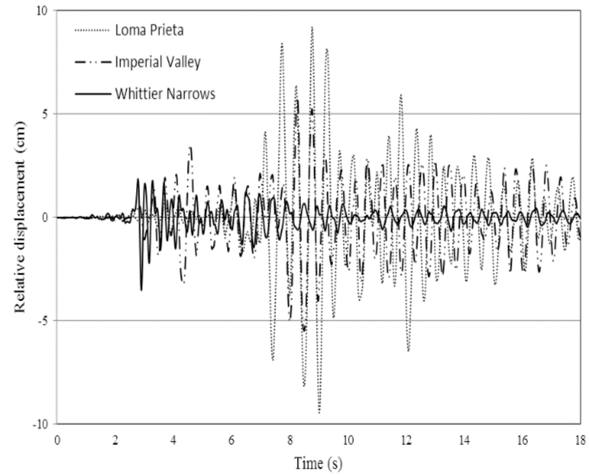


Fig. 10: Time histories of relative displacement of the crest with respect to the heel in Ef/Es=1 case

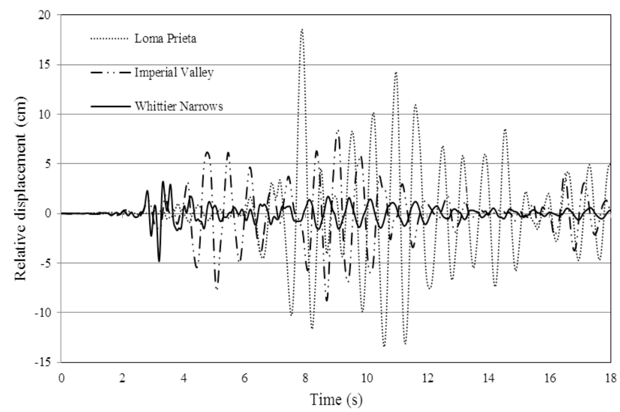


Fig. 11: Time histories of relative displacement of the crest with respect to the heel in Ef/Es=0.25 case

For comparing the tensile and compressive stresses, three elements of the dam, including EL.A, EL.B, and EL.C, have been chosen (shown in fig 12). In a rigid case, the stresses under the effect of 5 earthquake records have been calculated and shown in Figures 13 and 14. Results indicate a dependency of the stresses to frequency content index (FCI) and modular ratio. Nevertheless, stress output in chosen elements has a high discrepancy, and no clear trend is displayed.

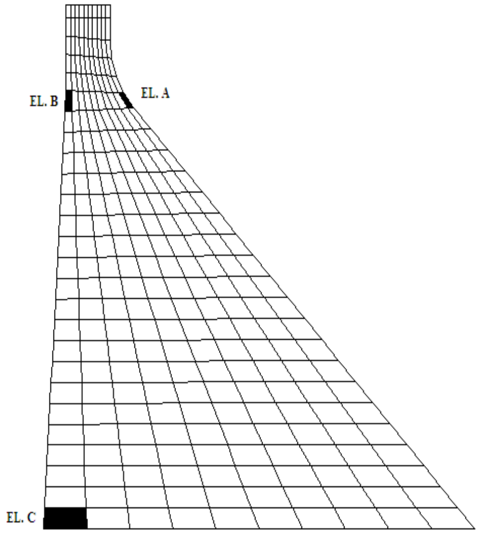


Fig. 12: Elements that used to compare stresses

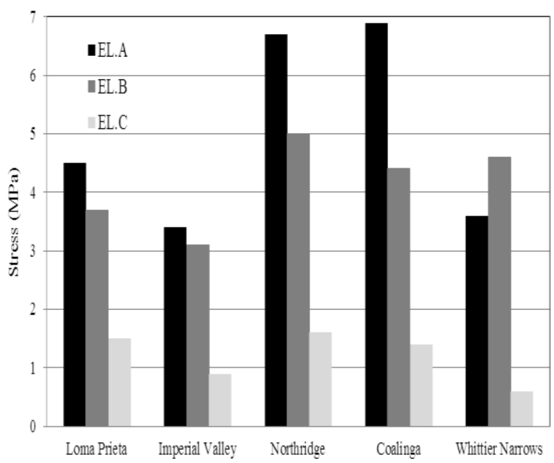


Fig. 13: Comparisons of tensile stress for different earthquake records in the rigid case

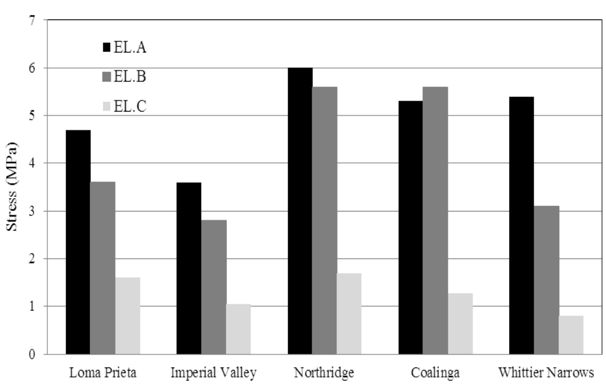


Fig. 14: Comparisons of compressive stress for different earthquake records in the rigid case

5. Conclusion

The effect of earthquake frequency content and soil-structure interaction on seismic response of the Pine Flat concrete gravity dam was investigated in this paper. As it is clear from Tables and Figures, results indicate a high dependency of the structure's response to frequency content index (FCI) and modular Ratio.

Results show that although all records have the same PGA (0.37g), maximum relative displacements and RMSD values differ. This difference is so high that, for example, in the modular ratio equal to 0.25, the maximum relative displacement for Loma Prieta earthquake (which is a low-frequency type of earthquake) is more than six times greater than Coalinga Earthquake (which is a high-frequency type of earthquake). Results indicate that overall, low-frequency earthquakes yield greater response than high-frequency ones.

The Dependency of results on the modular ratio is somehow different. For all records (except Coalinga Earthquake), maximum relative displacement and RMSD values decrease when the modular ratio increases. But this case shows that a clear trend cannot be seen with respect to modular ratio since Coalinga earthquake yields greater displacements when the foundation moves from a highly flexible state to a rigid state. However, stress output in chosen elements has a high discrepancy, and no clear trend is present. Peak values of stress do not differ as much as maximum relative displacement and RMSD value in different cases.

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