# EARTHQUAKE ANALYSIS OF ARCH DAMS: FACTORS TO BE CONSIDERED

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## ABSTRACT:

The factors that influence significantly the three-dimensional analysis of arch dams are identified: the semi-unbounded size of the reservoir and foundation rock domains, dam-water interaction, wave absorption at the reservoir boundary, water compressibility, dam-foundation rock interaction, and spatial variations in ground motion at the dam-rock interface. Linear analysis procedures and implementing computer software, EACD-3D-2008, that include the aforementioned factors are mentioned. Through a series of example analyses of several actual dams, the significance of the aforementioned factors is demonstrated, leading to the conclusion that they should all be included in computing seismic demands on arch dams. Unfortunately, however, most finite element analyses of dams conducted in professional practice are based on commercial software, which ignore these factors.

**KEYWORDS:** Arch dams, dam-water-foundation interaction, spatially-varying ground motion

## 1. INTRODUCTION

Most existing dams in seismic regions were designed by methods that are now considered simplistic and inaccurate. The damage sustained by the few dams that have been subjected to intense ground motions, e.g., Koyna Dam in India, Hsinfengkiang Dam in the People's Republic of China, Sefidrud Dam in Iran, and Pacoima Dam in the United States, together with the growing concern of the seismic safety of critical facilities has led to considerable interest in re-evaluating existing dams using modern analysis and experimental procedures. Over the past twenty years, the seismic safety of many dams has been evaluated, and some of them have been upgraded to improve their seismic resistance.

The dynamic analysis of arch dams is especially complicated because they must be treated as three-dimensional systems that recognize the semi-unbounded size of the reservoir and foundation rock domains, and their dynamic analysis should consider the following factors: dam-water interaction, wave absorption at the reservoir boundary, water compressibility, dam-foundation rock interaction, and spatial variations in ground motion around the canyon. Furthermore, during intense earthquake motions, vertical construction joints may slip or open, and the concrete may crack; thus, nonlinear dynamic analyses may be necessary.

The objective of this paper, restricted to linear analysis, is to discuss analysis procedures that are appropriate and the factors to be included for estimating seismic demands on concrete arch dams.

## 2. LINEAR ANALYSIS PROCEDURES

Based on the substructure method, a linear dynamic analysis procedure has been developed to determine the earthquake response of arch dams and implemented in the computer program EACD-3D-96 (Tan and Chopra, 1995; Tan and Chopra, 1996). This procedure enables three-dimensional analysis of a concrete arch dam supported by flexible foundation rock and impounding a reservoir of water. Utilizing the EACD-3D-96 computer program, extensive parametric studies of the earthquake response of actual dams led to an understanding of how the various factors—dam-water interaction, reservoir boundary absorption, water compressibility, and dam-foundation rock interaction—influence dam response. The practical range of conditions, where each factor is significant, was established, leading to the conclusion that all these factors should be included in the earthquake analysis of dams.

However, most finite element analyses of dams conducted in professional practice are based on commercial software, which ignore these factors. Typically, hydrodynamic effects are represented by an added water mass moving with the dam, implying water compressibility is neglected. Also ignored in these analyses is the partial absorption of hydrodynamic pressure waves by the sediments invariably deposited at the reservoir bottom and sides, or even by rock underlying the reservoir. The foundation rock is usually assumed to be massless, and a portion is included in a finite-element idealization of the system. This extremely simple idealization of the foundation rock, in which only its flexibility is considered but inertial and damping effects are ignored, is popular because the foundation impedance matrix (or frequency-dependent stiffness matrix) is very difficult to determine for three-dimensional unbounded domains.

Although all of these factors known to be significant in the response of concrete dams were included in computer software developed before desktop computers became standard, it remained primarily as a research program. Because it was not especially user friendly, it found only limited application to actual projects.

Starting in 1996, the U. S. Bureau of Reclamation (Reclamation) embarked upon a major program to evaluate the seismic safety of dams. Among the several dams investigated was the famous Hoover Dam, a 221-m (725-ft) high curved gravity dam. Seismological and geological investigations concluded that the Mead Slope Fault, at a distance of about 1 mile, was capable of generating an earthquake strong enough to cause a peak acceleration of about 0.8g at the site. Assuming the foundation rock to be massless and neglecting the water compressibility (i.e., modeling hydrodynamic effects by an added mass due to Westergaard)—assumptions necessitated by the limitations of the computer software available at the time—led to large tensile stresses. At 60 m (200 ft) below the dam crest, the induced stresses on the downstream and upstream faces, respectively, exceeded the tensile strength of the concrete, indicating that the dam would crack through the thickness. These results did not seem credible to Reclamation engineers. Based on engineering judgment, Reclamation engineers believed that this dam, with its cross section similar to gravity dams, should perform much better because it is curved in plan and confined in a narrow canyon.

Subsequent analyses performed by EACD-3D-96 led to stresses that were one-third to one-half compared to those predicted by previous analyses, assuming the foundation rock to be massless, indicating that only minimal cracking of concrete would occur. After this experience with the seismic evaluation of Hoover Dam, Reclamation adopted the philosophy of conducting the most advanced structural analyses—based on realistic material properties and fieldtests—for seismic safety evaluation of their concrete dams. Their analyses of several dams led to the following observations.

## 3. IMPLICATIONS OF NEGLECTING WATER COMPRESSIBILITY

Comparing the earthquake-induced stresses in dams computed under two conditions: water compressibility considered or neglected led to the following observations: the effects of water compressibility, which are generally significant, vary with the location on the dam surface. By neglecting water compressibility, the stresses may be significantly underestimated, as in the case of Monticello Dam, or significantly overestimated as in the case of Morrow Point Dam (Chopra and Nuss, 2009). Thus, water compressibility should be included in the analysis of arch dams; however, most standard finite element analysis software neglects water compressibility.

## 4. IMPLICATIONS OF NEGLECTING FOUNDATION ROCK INERTIA AND DAMPING

Comparing the earthquake-induced stresses in dams, computed under two conditions considering: (1) dam-foundation rock interaction; and (2) foundation rock flexibility only, the largest arch stress on the upstream or downstream face of the dam is 3282 kPa (476 lb/in2) versus 5819 kPa (844 lb/in2) for Deadwood Dam; 5033 kPa (730 lb/in2) versus 9722 kPa (1410 lb/in2) for Monticello Dam; 4585 kPa (665 lb/in2) versus 9211 kPa

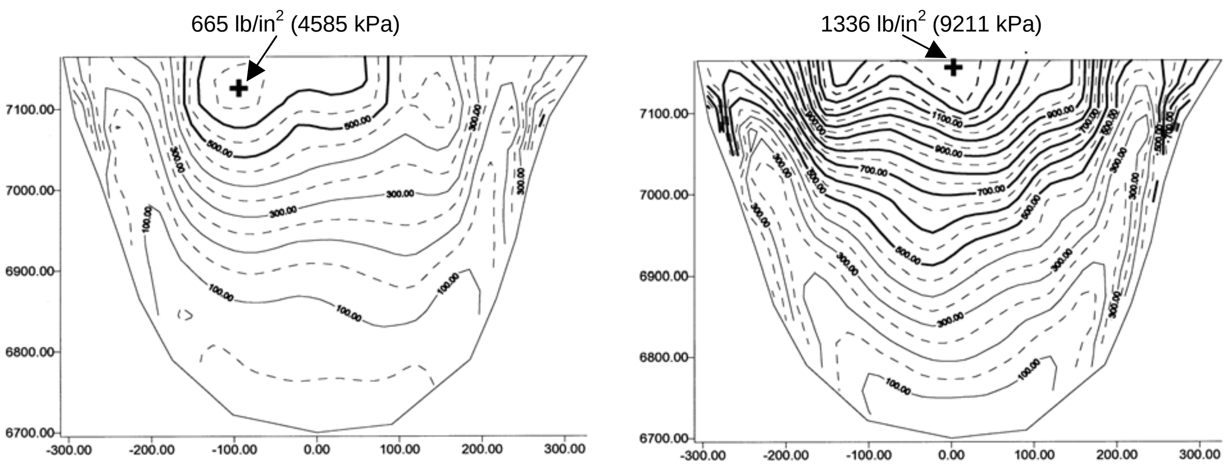
(1336 lb/in2) for Morrow Point Dam; and 5226 kPa (758 lb/in2) versus 15196 kPa (2204 lb/in2) for Hoover Dam. The stress distributions are shown for one dam (Fig. 1); such figures for other dams are available in Chopra and Nuss (2009). If only foundation rock flexibility is considered (i.e., foundation rock is assumed to be massless), the stresses are overestimated by a factor of 2 (approximately) for the first three dams and by a factor of 3 (approximately) for Hoover Dam.

Because such overestimation of stresses may lead to over-conservative designs of new dams and to the erroneous conclusion that an existing dam is unsafe, and, hence, requires upgrading, it is imperative that dam-foundation rock interaction effects should be included in earthquake analysis of concrete dams. However, dynamic analyses for many seismic safety evaluation projects assume massless foundation rock, thus ignoring dam-foundation rock interaction effects, because most commercial and proprietary computer software is based, erroneously, on this unrealistic assumption.

## 5. COMPARISON OF COMPUTED AND MEASURED RESPONSES

Considering the large disparity in results depending on the choice of numerical models, it is important to calibrate numerical models against motions of the dam recorded during forced vibration tests and earthquakes. Data from tests conducted on Morrow Point Dam served as the benchmark for two numerical models of the dam; the first assumed the foundation rock to be massless (Duron and Hall, 1988) and the EACD-3D-96 model avoided this assumption and modeled dam-water-foundation interaction (Nuss et al., 2003). With properties of concrete and foundation rock established from well-known testing procedures, the massless foundation rock model did not represent adequately the measured responses of the dam (Duron and Hall, 1988). With the same material properties, but now including inertia and damping—material and radiation—effects arising from dam-foundation rock interaction, the EACD-3D-96 model agreed reasonably well with the measured responses (Nuss et al., 2003).

Earthquake records from M3.6 to M4.9 earthquakes centered 12-20 km away from three arch dams in Switzerland provided researchers with a rare set of data, although for very low intensity ground motion, to evaluate whether it is reasonable to assume the foundation rock as massless, as is common in practical analysis. Research results [9] utilizing these records are summarized next.


(a)

(b)

Figure 1  Peak values of arch stresses in Morrow Point Dam, considering (a) dam-foundation rock interaction, and (b) foundation rock flexibility only.

Finite element models of the dam-foundation rock system, assuming foundation rock to be massless, were developed and their properties calibrated against ambient tests and forced vibration tests; such calibration led to damping ratios of 2 to 3% for the dams. The response of the Mauvoisin and Punt-dal-Gall Dams due to ground motion recorded in the free field away from the dam base, and of Emosson Dam due to base motion, were computed. Although the models were calibrated against data from ambient or forced vibration tests, the computed motions of the dam crest were much larger than the earthquake records. To achieve reasonable agreement between computed and recorded motions, the damping ratio for dam concrete had to be increased to 15% at Emosson and to 8% at Mauvoisin and Punt-dal-Gall. Because these damping values are unrealistically large, it was concluded that the assumption of massless foundation rock in the preceding analysis was unrealistic. Using the calibrated damping ratio of 2 to 3% for the dam and reasonable damping values for the foundation rock, subsequent analysis included dam-foundation rock interaction effects (considering foundation inertia, material damping, and radiation damping). These analyses, implemented on the EACD-3D-96 computer program, led to computed responses that were closer to the measured responses, but significant discrepancies remained, which were attributed to spatial variations in ground motion that had been ignored in analysis (Proulx et al., 2004) because of limitations of EACD-3D-96 computer program.

## 6. SIGNIFICANCE OF SPATIAL VARIATIONS IN GROUND MOTION

The analysis procedure of Tan and Chopra (1995) and the implementing computer program EACD-3D-06 (Tan and Chopra, 1996) have recently been extended to determine dam response to free-field ground motion that varies spatially along the dam-rock interface (Chopra and Wang, 2008), resulting in the computer program EACD-3D-2008. This extended analysis procedure includes dam-water-foundation interaction effects to the same degree of rigor [as in Tan and Chopra (1995) and Tan and Chopra (1996)]. In contrast, earlier studies of dam response to spatially-varying excitation have excluded foundation inertia and damping, and assumed water to be incompressible (Mojtahedi and Fenves, 2000; Alves, 2004).

Structural response to spatially-varying excitation may be split into two parts: quasi-static and dynamic response (Chopra, 2007). The quasi-static component is the response due to static application of the prescribed displacements of the structural supports at each time instant; in case of a dam, these are the nodal points (in the finite element model) at the dam-rock interface. How significantly the dam response is affected by spatial variations in the excitation is closely tied to the importance of the quasi-static component that depends on the degree to which the ground motion varies spatially along the dam-rock interface. This concept is illustrated next through two examples: Mauvoisin Dam and Pacoima Dam.

The response of Mauvoisin Dam to the spatially-varying ground motions recorded during the Valpelline earthquake (M=4.6) is determined by the EACD-3D-2008 computer program; gravity effects were not included. Figure 2 presents the displacement near the center of the crest, wherein the quasi-static component in the total response is identified. Examining the total displacements, the strongest response occurs in the stream direction; the cross-stream and vertical displacements are 44% and 27%, respectively, of the stream displacement. Although the quasi-static component is dominant in the cross-stream and vertical responses, it is a relatively small part of the displacement in the stream direction, the direction of strongest response. Therefore, the spatial variations in ground motion are expected to only modestly influence stresses in the dam. This expectation is confirmed by the results presented in Fig. 3 where the stresses are presented for two excitations, spatially-uniform and spatially-varying. Although spatial variations in the ground motion cause slightly larger stresses near the dam-rock interface, their overall influence on the stresses in the body of the dam is relatively small.

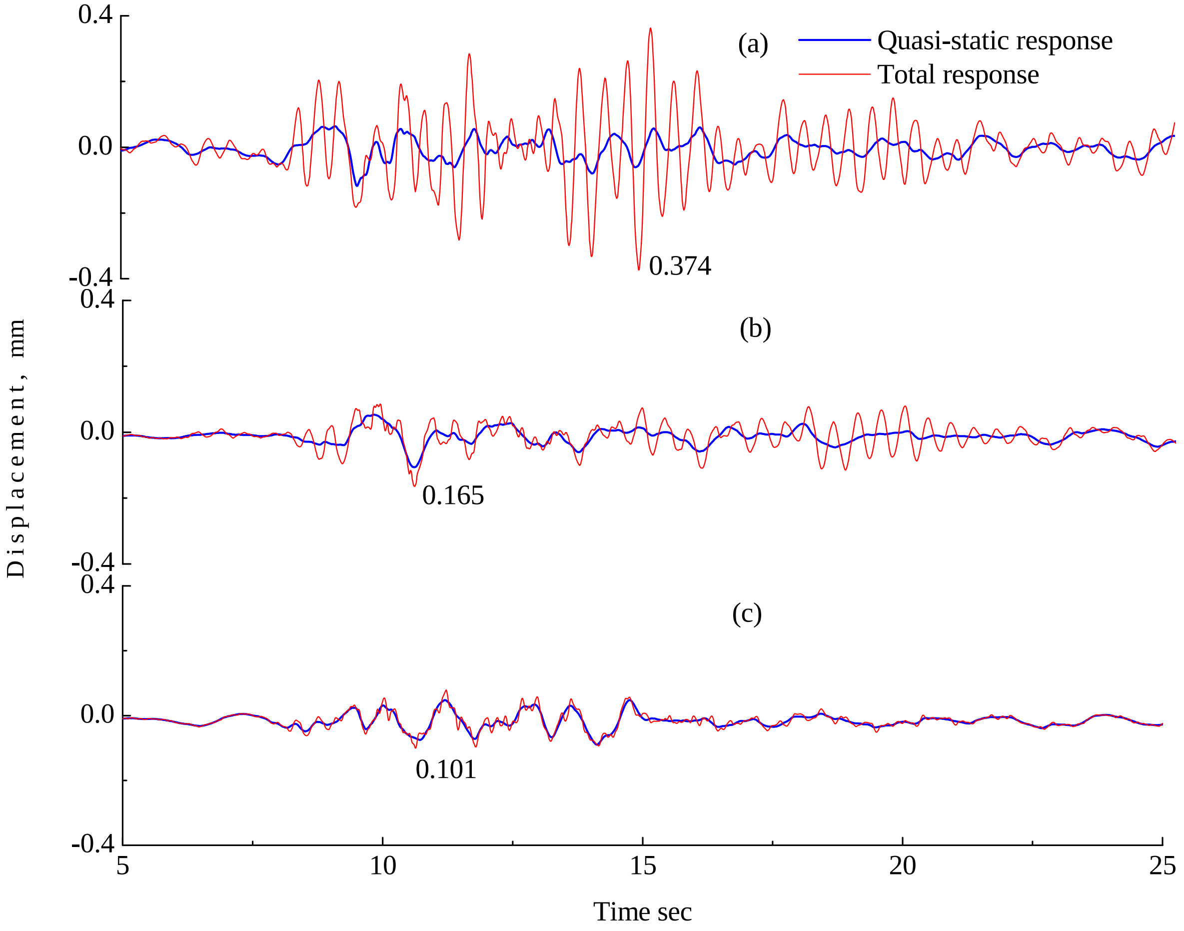


Figure 2 Displacement histories at crest center of Mauvoisin Dam due to spatially-varying ground motion: (a) stream component; (b) cross-stream component; and (c) vertical component

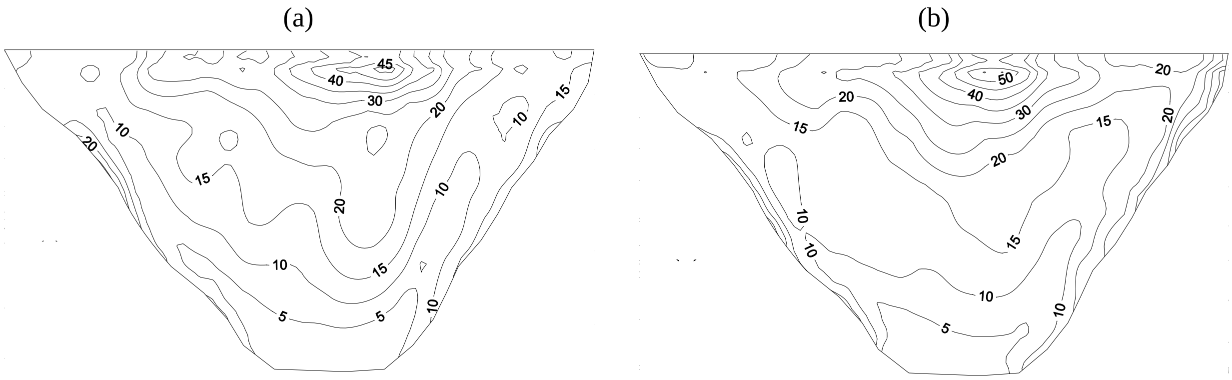


Figure 3 Peak values of tensile arch stresses (KPa) on the upstream face of Mauvoisin dam due to (a) spatially-uniform ground motion; and (b) spatially-varying ground motion

The significance of spatial variations in ground motion on the response of Pacoima Dam has been investigated by Alves (2004) wherein the response of the dam was computed by SCADA, a computer program that permits nonlinear modeling of the dam but assumes the foundation rock to be massless and water to be incompressible. Figure 4 demonstrates that the quasi-static (or pseudo-static) component dominates the total response. As a result, the computed stresses in the dam are very different because of spatial variations in the excitation. This is apparent by comparing Fig. 5a, which presents results for spatially-uniform excitation, with Fig. 5b for spatially-varying excitation. Spatial variations in ground motion have a profound influence on the largest stress as well as on the stress distribution. The dam response to uniform ground motion recorded at the base of the dam is much smaller than due to the spatially-varying excitation, as summarized in Table 1.

Table 1 Maximum responses due to spatially-varying and spatially-uniform ground motions (Alves, 2004)

| Excitation | Arch Compression (MPa) | Cantilever Compression (MPa) | Joint Opening (cm) | No. of Elements Cracked | Crack Opening (cm) |
|---|---|---|---|---|---|
| Spatially-varying | 16.58 | 7.74 | 2.84 | 12 | 0.90 |
| Spatially-uniform | 4.87 | 3.40 | 1.13 | 0 | 0.00 |

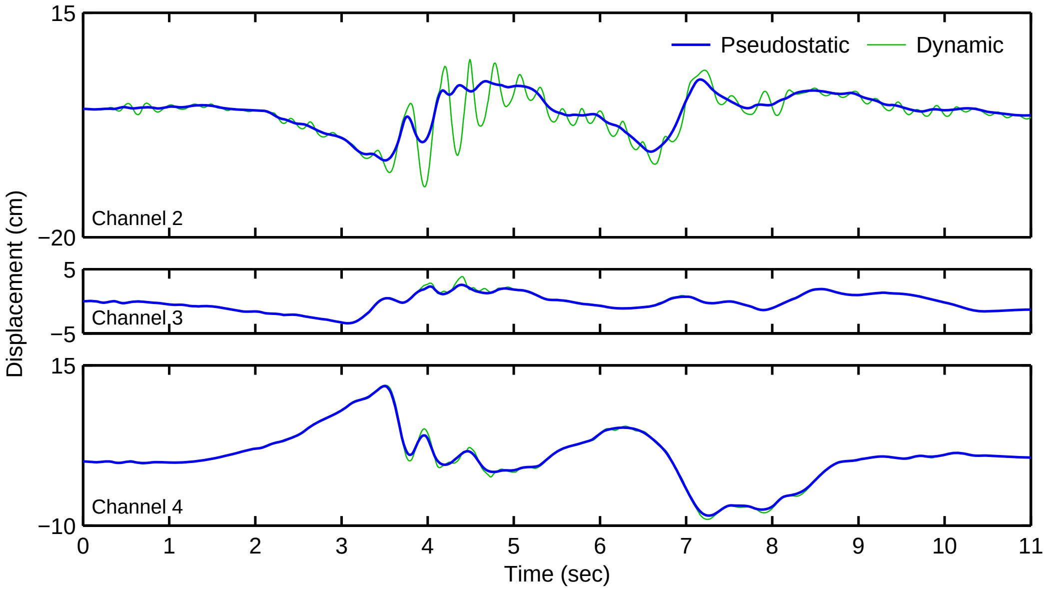
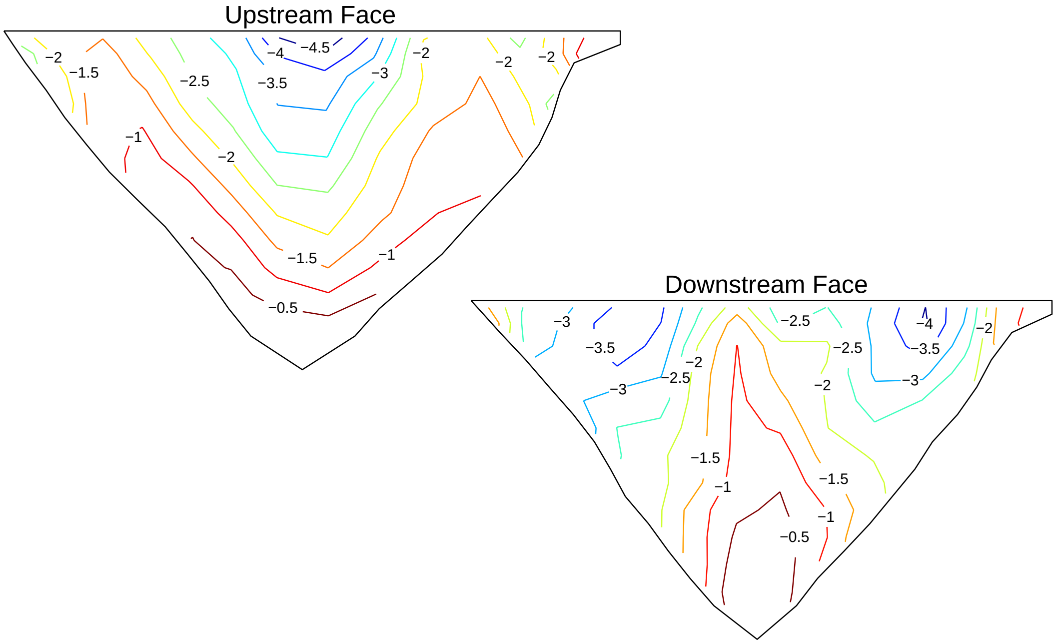


Figure 4 Displacement histories at crest center of Pacoima Dam due to spatially-varying ground motion: (a) stream component; (b) vertical component; and (c) cross-stream component (Alves, 2004).

(a)



(b)

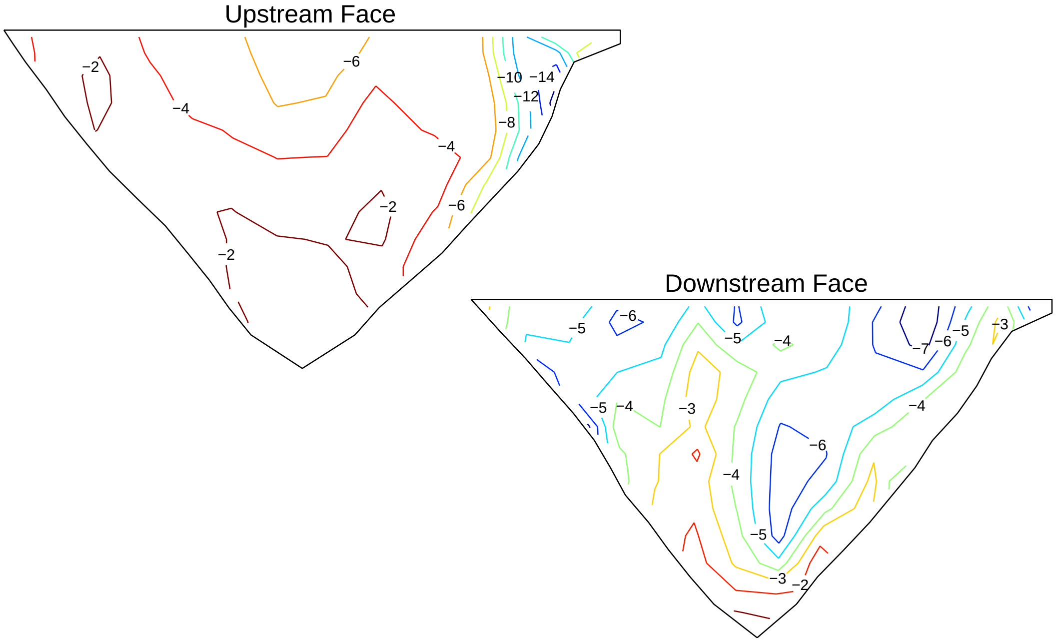


Figure 5  Peak values of compressive arch stresses (MPa) due to: (a) spatially-uniform ground motion; and (b) spatially-varying ground motion (Alves, 2004).

## 7. CONCLUSIONS

Through a series of example analyses of actual dams, it is demonstrated that: (1) By neglecting water compressibility, the stresses may be significantly underestimated for some dams or overestimated for others; (2) By neglecting foundation-rock mass and damping, the stresses may be overestimated by a factor of 2-3; and (3) Spatial variations in ground motion can profoundly influence dam response but these effects may be small in some cases.

Therefore, the earthquake analysis of arch dams should include the following factors: the semi-unbounded size of the reservoir and foundation rock domains, dam-water interaction, hydrodynamic wave absorption at the reservoir boundary, water compressibility, dam-foundation rock interaction, and spatial variations in ground motion at the dam-rock interface; however, most finite element analyses of dams conducted in professional practice are based on commercial software, which ignore these factors.

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