INFLUENCE OF DAM-FOUNDATION INTERACTION IN SEISMIC SAFETY EVALUATION OF TWO ARCH DAMS

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SUMMARY

Based on the extensive research during the past thirty years, it is now generally recognized that, in analyzing the earthquake response of concrete dams the following factors should be considered: dam-water interaction, reservoir boundary absorption, water compressibility, dam-foundation rock interaction [Chopra, 1992], and opening of contraction joints. However, until recently, available analysis procedures and implementing computer programs ignored dam-foundation interaction by assuming the foundation rock to be massless. Development of EACD-3D-96 has enabled full consideration of dam-foundation rock interaction in actual seismic safety evaluation of concrete arch dams, and an assessment of the state-of-practice assuming massless foundation rock. The U.S. Bureau of Reclamation has recently completed the seismic safety evaluation of several existing arch dams. Two of these investigations which showed the most pronounced significance of dam-foundation interaction in dynamic analyses of arch dams, Hoover Dam (726 ft. high) [Bureau of Reclamation, 1998] and Morrow Point Dam (465 ft. high) will be discussed.

INTRODUCTION

The U.S. Bureau of Reclamation has recently completed the seismic safety evaluation of several existing concrete arch dams using program EACD-3D-96 developed at the University of California which incorporates full consideration of dam-foundation interaction. Two of these investigations: Hoover Dam, a 726-foot-high thick arch dam, and Morrow Point Dam, a 465-foot-high thin arch dam, will be discussed in this paper and show the significance of dam-foundation rock interaction in dynamic analyses of some arch dams and the overestimation of seismic response when using the massless foundation approach. Such overestimation of stresses by ignoring the foundation material and radiation damping, typical of most traditional analyses, may lead to overconservative designs of new dams and to the erroneous conclusion that an existing concrete dam may be unsafe. Therefore, it can be important that dam-foundation rock interaction effects be included in seismic safety evaluation of concrete dams.

BACKGROUND

Hoover Dam

Hoover Dam is a 727-foot-high concrete thick-arch dam located on the border between Arizona and Nevada about 36 miles from Las Vegas, Nevada (see figure 1). The dam was completed in 1935, has a crest length of 1244 feet, a crest thickness of 45 feet, and a maximum base width of 660 feet. It is the highest concrete dam in the United States, the eighteenth highest dam in the world, and forms the largest manmade reservoir in the United States [USCOLD, 1995]. Rock exposed in the area adjacent to the dam is volcanic and locally weathered consisting of Miocene lava flows and flow breccia, ash-flow tuffs, sills, dikes, and volcanogenic sedimentary rocks. The lowermost foundation unit at the dam is a Conglomerate. The upper abutments are primarily in welded ash-flow Tuff

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Tuff which was deposited upon an eroded surface of the conglomerate, and was subsequently intruded by two Latite sills.

Morrow Point Dam

Morrow Point Dam is a major feature of the Colorado River Storage Project and is located on the Gunnison River in west-central Colorado about 22 miles east of Montrose (see figure 1). The dam, completed in 1968, is a double-curvature, thin-arch concrete structure with a structural height of 469 feet, and a crest length of 740 feet. The axis is curved in plan to a radius of 375 feet. The maximum section varies in thickness from 12 feet at the crest to 51 feet.

MATERIALS

Hoover Dam

In 1994, 6-inch-diameter concrete core and HQ foundation core (approximately 3-inch diameter) were extracted from the dam and foundation. Tests on concrete cores from Hoover Dam produced average material property values listed in the table 1 [Bureau of Reclamation, 1995]. Reservoir bottom reflection coefficients (alpha) were measured at the dam [Ghanaat, 1995] and used in the analyses.

Table 1: Hoover Dam - Material Properties

Description	Static	Dynamic
Concrete		
Compression (lb/in^2)	7320	8040
Splitting tension (lb/in^2)	600	970
Modulus (Es) (lb/in^2)	6,590,000	4,330,000
Reservoir reflection		0.75
Foundation		
Uniaxial compression		
Conglomerate (lb/in^2)	17,770	
Tuff (lb/in^2)	8,200	
Lattite sills (lb/in^2)	20,550	
Deformation modulus		
Conglomerate (lb/in^2)	3,800,000	
Tuff and Latite (lb/in^2)	2,400,000	
Used in analysis (Ef)	3,100,000	3,100,000
Ratio Ef/Es		0.47
Viscous Damping		5 %

There is one anomaly in these test results. The measured concrete dynamic modulus of elasticity was unusual because normally the dynamic modulus is greater than or equal to the static modulus. This anomaly could be the result of only performing four dynamic modulus tests. A literature search of published dynamic concrete properties showed that the dynamic modulus is typically equal to or greater than the static modulus [Bureau of Reclamation, 1995]. Therefore, the measured static modulus of elasticity was used for the dynamic modulus of elasticity. The elastic modulus chosen for these analyses was 6,590,000 lb/in^2 for concrete and 3,100,000 lb/in^2 for the foundation.

Morrow Point Dam

Laboratory tests on 10-inch-diameter concrete core extracted and tested in 1978 produced average static compressive strengths of 7480 lb/in^2 [Bureau of Reclamation, 1981] and average static direct tension strengths of 230 lb/in^2. Using empirical relationships for splitting tensile strength from compressive strengths led to an apparent static tensile strength of 906 lb/in^2 and apparent dynamic tensile strength of 1340 lb/in^2 [Raphael, 1984]. For the purpose of evaluating the results in these analyses, a static tensile strength of 645 lb/in^2 and a dynamic tensile strength of 1300 lb/in^2 were used. Table 2 summarizes the static and dynamic concrete and foundation rock properties used in the analyses. The low foundation deformation modulus is based on numerous in-situ jacking tests performed during construction and comparing the results to the geologic conditions. It was found that the test values were very consistent and did not vary much with the geologic conditions at the test sites. Reservoir bottom reflection coefficients (alpha) were measured at the dam [Ghanaat, 1995].

Table 2: Morrow Point Dam - Material Properties

Description	Static	Dynamic
Concrete		
Compression (lb/in^2)	7,480	7,400
Direct tension (lb/in^2)	230	-
Modulus (Es) (lb/in^2)	3,250,000	6,500,000
Foundation		
Reservoir reflection		0.55
Deformation modulus (Ef)	920,000	920,000
Density	162.2	162.2
Ratio Ef/Es		0.14
Viscous Damping		5 %

EARTHQUAKE GROUND MOTIONS

Hoover Dam

In 1993, a regional seismotectonic study was conducted for the Hoover Dam area. The postulated maximum credible earthquake (MCE) for Hoover Dam was a magnitude Ms 6.75 on the Mead Slope Fault at 3 km (1.8 miles) closest surface approach to the dam. The fault would exhibit a primarily normal fault rupture mechanism involving rupture from a 15 km (9.3 miles) depth to the surface. In 1995, ground motions were selected to represent the strong shaking at Hoover Dam from the seismogenic sources identified in the regional seismotectonic report. Recommended ground motions representing the Mead Slope Fault were the Convict Creek record of the May 27, 1980, Mammoth Lakes, California, earthquake and the Corralitos record from the 1989 Loma Prieta earthquake. These ground motions were modified based on recommendations by the Consultant Review Board [Bureau of Reclamation, 1996].

Morrow Point Dam

In 1995, site specific seismotectonic studies were conducted for the Morrow Point area [Lettis, 1995]. Based upon these investigations, the nearest active or potentially active fault to Morrow Point Dam is the Busted Boiler Fault north of Ridgway, Colorado. The MCE for this source is M_W6.5 and shortest source to site distance is 29 km. Recurrence relationships developed suggest that for the random earthquake MCE of M_W6.5, a probabilistic epicentral distance of 15.7 km is appropriate for an annual probability of occurrence of $2x10^{-5}$. Recommended ground motions for the analysis of Morrow Point Dam are the three components of Convict Creek record of the May 27, 1980, M_L 6.1 Mammoth Lake, California earthquake.

FINITE ELEMENT MODELS

Computer Program EACD-3D-96

Based on the extensive research during the past thirty years, it is now generally recognized that, in analyzing the earthquake response of concrete dams the following factors should be considered: dam-water interaction, reservoir boundary absorption, water compressibility, dam-foundation rock interaction [Chopra, 1992], and opening of contraction joints. However, until recently, available analysis procedures and implementing computer programs ignored dam-foundation interaction by assuming the foundation rock to be massless. This extremely simple idealization of the foundation rock, which considers only its flexibility but ignores inertial and damping (material and radiation) effects, is popular because the frequency-dependent stiffness matrix is very difficult to determine for three-dimensional foundation rock regions without resorting to this assumption. Computation of this matrix for analysis of arch dams requires solution of a series of mixed boundary value problems governing the steady-state response of the canyon cut in a three-dimensional half-space. Such solutions were achieved only a few years ago and have now been incorporated as a substructure method for analysis of dam-water-foundation rock systems [Tan and Chopra, 1995] and implemented in the computer program EACD-3D-96 [Tan and Chopra, 1996b] developed at the University of California at Berkeley.

Hoover Dam

The earthquake response of Hoover Dam was determined by two computer programs: EACD-3D [Fok et.al, 1986] (assuming massless foundation), and EACD-3D-96 [Tan and Chopra, 1996b] (including dam-foundation rock interaction). Initially, the dam was analyzed using EACD-3D. While the project was still in progress, EACD-3D-96 became available and the analyses were repeated using the new program.

Morrow Point Dam

The earthquake response of Morrow Point Dam was investigated using EACD3D96 including dam-foundation rock interaction and assuming massless foundation.

RESULTS FROM ANALYSIS

Hoover Dam

Maximum tensile arch and cantilever stresses calculated for Hoover Dam using EACD3D and EACD3D96 due to two selected earthquake ground motions are presented in the table 4 and figure 2 (static plus dynamic stresses). The cantilever stresses computed by EACD3D (massless foundation) exceeds the measured concrete strength by 2.25 times (1350 lb/in^2 / 600 lb/in^2), indicating potential cracking of the concrete in the dam or opening of the lift lines on both faces of the dam. Subsequently, EACD-3D-96 (dam-foundation rock interaction) predicted tensile stresses below the concrete strength, leading to the conclusion that the dam should withstand the postulated earthquake without cracking on either face. Observe in table 4 that all the stresses are much smaller when dam-foundation rock interaction is included.

Table 4: Hoover Dam - Maximum Stress (lb/in^2) Comparison Between Structural Analysis With A Massless Foundation (EACD3D) and With Dam-Foundation Interaction (EACD3D96) Ef = 3,100,000 lb/in^2, Ef = 6,590,000 lb/in^2, Ef/Es = 0.45, Alpha = 0.75

Stress Orientation	Convict Creek Ground Motions		Corralitos Ground Motions	
	EACD	EACD3D96	EACD	EACD3D96
Upstream Arch	1940	741	1937	786
Downstream Arch	2004	758	2238	784
Upstream Cantilever	1339	415	1350	440
Downstream Cantilever	1062	440	875	406

Additional EACD3D96 analyses showed the sensitivity of varying the foundation modulus to dam modulus ratio (Ef/Es). The ratio Ef/Es was varied from 0.45 to 1.55 which resulted in the maximum tensile stress increasing from 741 lb/in^2 to 1400 lb/in^2. Notice that the 1,400 lb/in^2 stress with Ef/Es ratio of 1.55 is still less than the 2,004 lb/in^2 stress calculated with the massless foundation. Similar sensitivity of varying foundation modulus to dam modulus ratios were also reported previously, [Munoz, 1999] and [Tan and Chopra, 1996a].

The calculated stresses using EACD3D96 are lower because the unbounded extent of the foundation provides radiation damping. This effect combined with foundation material damping reduces the response of the dam. Because the results are sensitive to the dam and foundation modulus, it is important to determine accurately the dam and foundation modulus.

Morrow Point Dam

Maximum tensile and compressive arch and cantilever stresses calculated in Morrow Point Dam using EACD3D96 with dam-foundation interaction and massless foundation due to the selected earthquake ground motion are presented in the table 5 and figure 3 (static plus dynamic stresses). The cantilever stresses computed with massless foundation exceeded the measured concrete strength by 2.5 times (577 lb/in^2 / 230 lb/in^2), indicating potential cracking of the concrete in the dam or opening of the lift lines. Subsequently, EACD-3D-96 predicted cantilever stresses within or slightly over the concrete strength. Observe in table 5 that the calculated stresses are much smaller when dam-foundation rock interaction is included. As mentioned earlier, EACD-3D-96 gives lower stresses because it accounts for the foundation radiation and material damping and for hydrodynamic wave absorption at the reservoir boundary.

Table 5: Morrow Point Dam - Maximum Stress (lb/in^2) Comparison Between Structural Analysis With A Massless Foundation and With Dam-Foundation Interaction
Ef=920,000 lb/in^2, Es = 6,500,000 lb/in^2, Ef/Es = 0.14, Alpha = 0.55

Stress Orientation	EACD3D96 Massless	EACD3D96 Interaction
Upstream Arch	947	80
Downstream Arch	1440	331
Upstream Cantilever	327	127
Downstream Cantilever	348	111

CONCLUSIONS

1. Dynamic finite element analyses of some arch dams can overestimate earthquake-induced stresses when ignoring the foundation material and radiation damping, typical of most traditional analyses that use a massless foundation approach. This could lead to an erroneous conclusion that an existing dam may be unsafe. Even though the massless approach may be conservative, unnecessary and expensive modifications may result. Limited dam safety funds would be spent on a project that actually has lower risk and these funds could be spent more usefully on other projects. Also, unnecessary rehabilitations only make hydroelectric power more expensive. Therefore, it can be important that structural analysis be performed on concrete dams that incorporate all aspects of the problem, dam-water interaction, reservoir boundary absorption, water compressibility, and dam-foundation rock interaction, to best determine and evaluate the seismic safety of concrete dams.

2. Results from dynamic finite element analysis that incorporates dam-foundation rock interaction are dependent on the dam and foundation modulus used in the analysis. Therefore, the modulus values used in the analysis are very important. For existing dams, U.S. Bureau of Reclamation is extracting concrete and foundation cores and determining the modulus values in the laboratory. The foundation modulus is determined by empirical methods based on jointing to determine a deformation modulus used in analysis. Natural frequencies of the dam are then calculated and compared with actual field measured natural frequencies of the dam. Most recently, the natural frequencies of a dam were determined by instrumenting with microseismic instruments, measuring ambient vibrations of the dam, and extracting frequencies from a spectral analysis of the motions.

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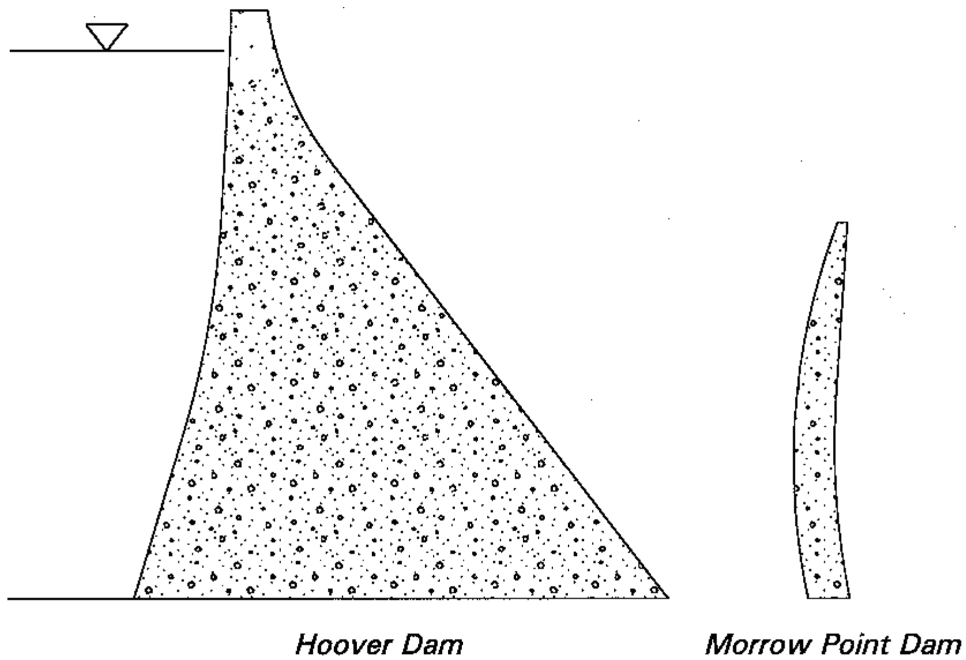
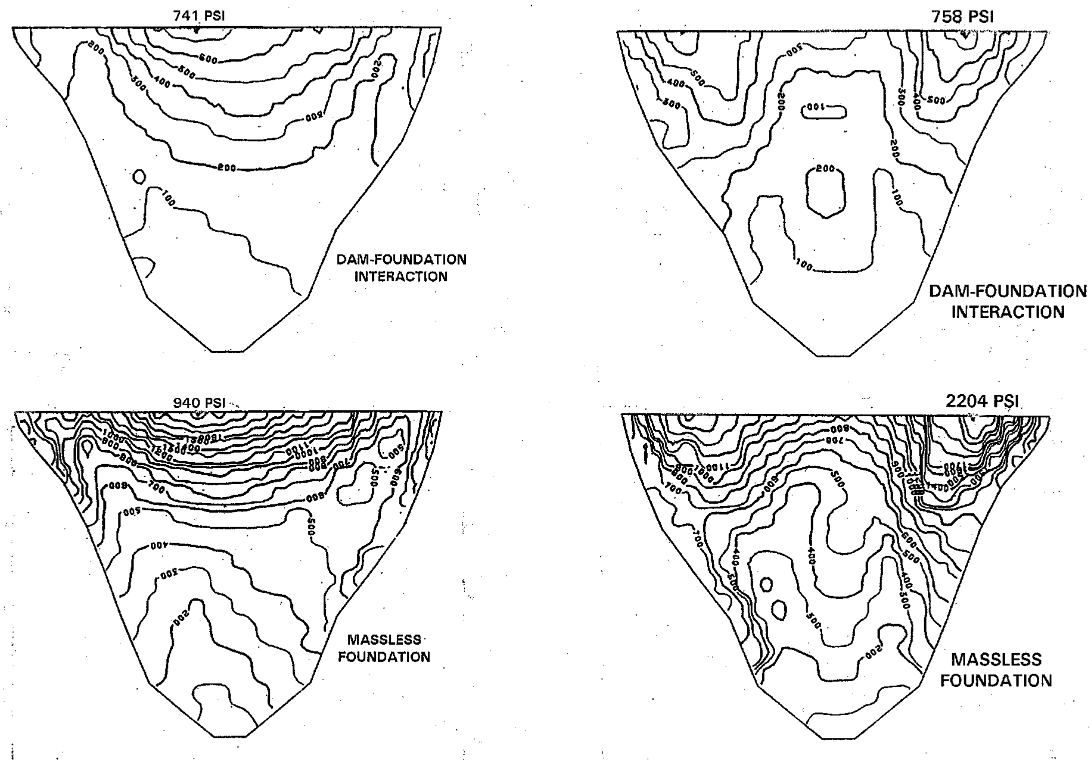
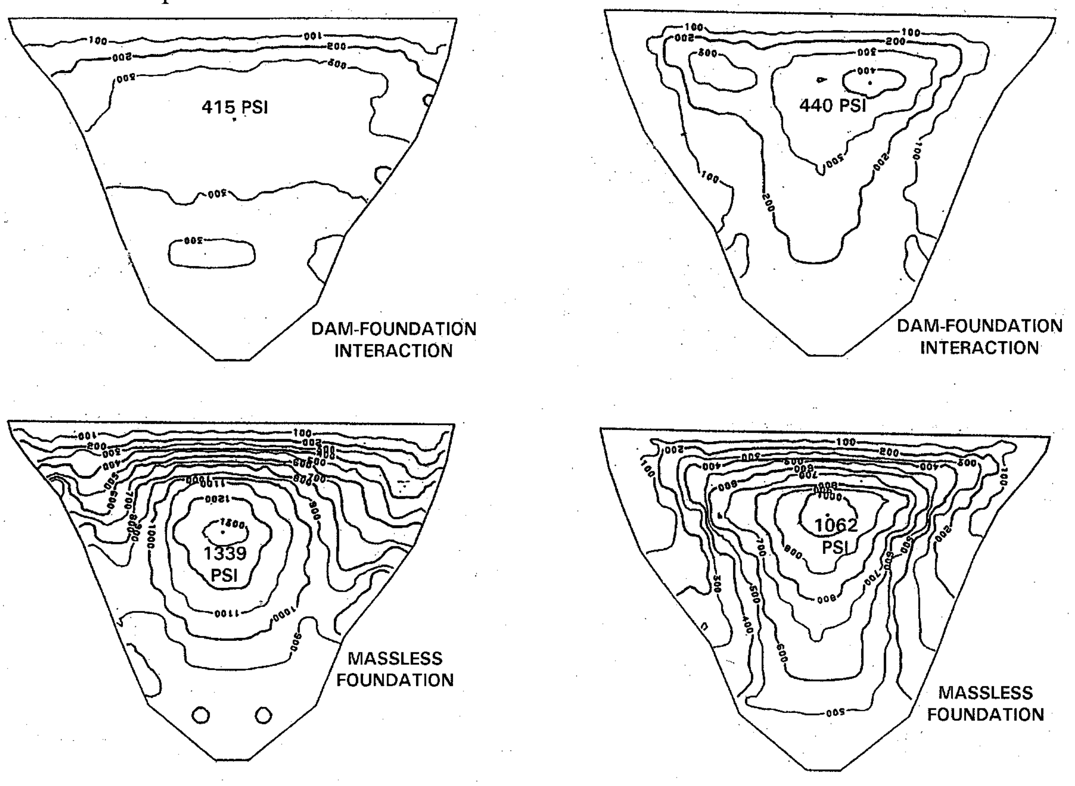
Figure 1: Maximum Vertical Sections (at the same scale)





A - Upstream Arch Stress

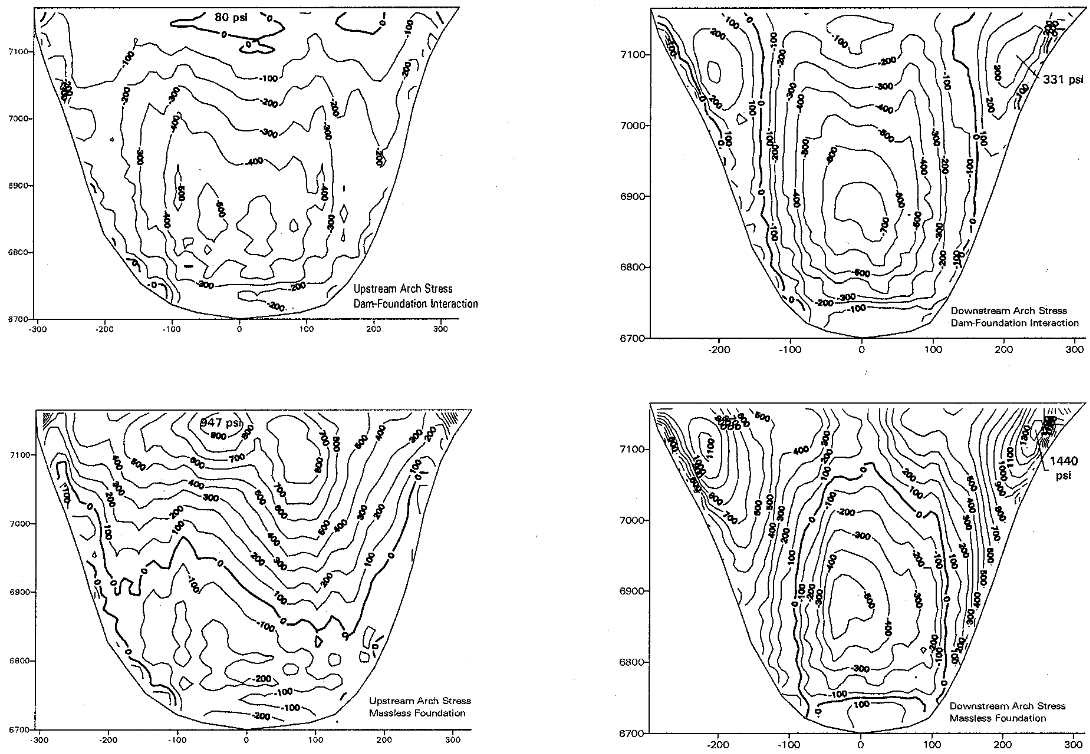
B - Downstream Arch Stress



C - Upstream Cantilever Stress

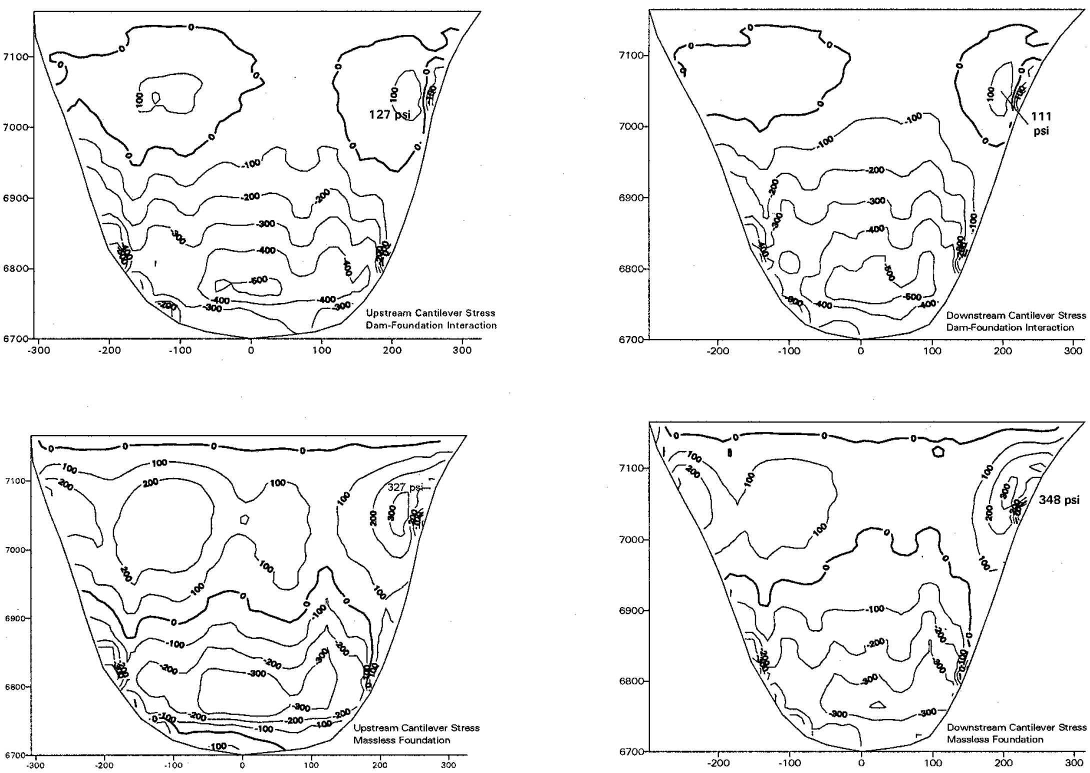
D - Downstream Cantilever Stress

Figure 2: Comparison of Maximum Arch and Cantilever Stress (lb/in^2) Results for Hoover Dam Using Massless Foundation and Dam-Foundation Rock Interaction Approaches



A – Upstream Arch Stress

B – Downstream Arch Stress



C – Upstream Cantilever Stress

D – Downstream Cantilever Stress

Figure 3: Comparison of Maximum Arch and Cantilever Stress (lb/in^2) Results for Morrow Point Dam Using Massless Foundation and Dam-Foundation Rock Interaction Approaches