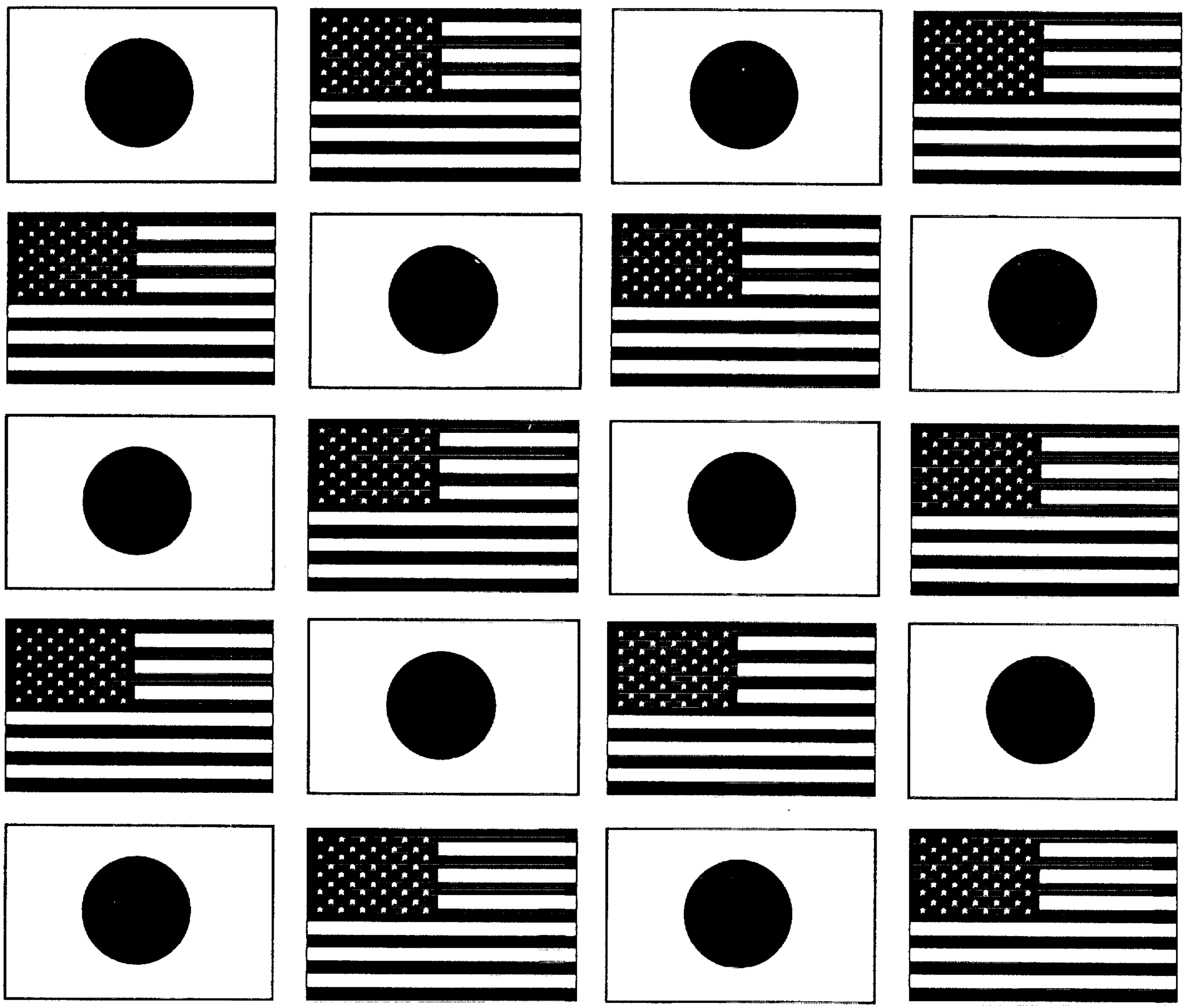
# Wind and Seismic Effects

## Proceedings of the 30th Joint Meeting

NIST SP 931



**U.S. DEPARTMENT OF COMMERCE**
**Technology Administration**
**National Institute of Standards and Technology**

# Wind and Seismic Effects

## NIST SP 931

PROCEEDINGS OF THE 30TH JOINT MEETING OF THE U.S.-JAPAN COOPERATIVE PROGRAM IN NATURAL RESOURCES PANEL ON WIND AND SEISMIC EFFECTS

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# EARTHQUAKE ENGINEERING

# Seismic Analysis of Hoover Dam [1)]

by

By Larry K. Nuss [2)]

ABSTRACT

Hoover Dam is a 221-m (727-foot) high concrete thick-arch dam located on the border between Arizona and Nevada about 58 km (36 miles) from Las Vegas, Nevada. The postulated maximum credible earthquake (MCE) for Hoover Dam is a magnitude Ms 6.75 on the Mead Slope Fault. Initial structural finite element analysis calculated stresses larger than the tensile strength on the upper portions of the dam. More sophisticated analysis followed when additional data was obtained for material properties and seismic loading. The first approach was a linear-elastic analysis incorporating foundation-structure interaction with mass in the foundation. The second approach was a non-linear analysis incorporating concrete cracking and contraction joint interaction using smeared crack techniques and kinematic stability analysis of the top of the dam.

KEYWORDS: Hoover Dam; concrete arch dam; nonlinear and linear dynamic structural analysis; foundation impedance; hydrodynamic interaction, reservoir bottom reflection coefficient; EACD3D96; ANACAP.

## 1. INTRODUCTION

Hoover Dam is a 221-m (727-foot) high concrete thick-arch dam located on the border between Arizona and Nevada about 58 km (36 miles) from Las Vegas, Nevada. The dam was completed in 1935, has a crest length of 380 m (1244 feet), a crest thickness of 14 m (45 feet), and a maximum base width of 201 m (660 feet) (see figure 1). 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]. The postulated maximum credible earthquake (MCE) for Hoover Dam is a magnitude Ms 6.75 on the Mead Slope Fault, with primarily normal fault rupture mechanism involving rupture from 15 km (9.3 miles) depth to the surface and 3 km (1.8 miles) closest surface approach to the dam [O'Connell, 1996]. The probability of the MCE is postulated to be as frequent as 1:10,000 years or as infrequent as 1:100,000 years. Initial structural analysis using conventional linear-elastic three-dimensional dynamic finite element methods, assuming material properties and a massless foundation, calculated stresses larger than the tensile strength on the upper portions of the dam. These results indicate concrete cracking occurs in the upper 61 m (200 feet) of the dam. If the top 61 m (200 feet) of the dam failed during a seismic event, the downstream consequences would be massive. An estimated loss-of-life of 400 people and damages not including losses from project benefits totaling $17 billion (US) could occur.

More sophisticated analysis followed when additional data was obtained for material properties and seismic loading. Currently, there is no software code available that incorporates all the important aspects (hydrodynamic interaction, impedance of dam-foundation interaction, contraction joint action, or rigid block kinematic movements) associated with a concrete dam for a complete structural analysis. For this reason, various software programs were run using the Hoover finite element model and knowledge of the influence of each aspect

1) Submitted for presentation at the 30th joint meeting of the U.S-Japan Panel on Wind and Seismic Effects, May 12-15, 1998, Gaithersburg, Maryland.
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affecting the dam was gleamed. This way the relative impact of each aspect on the stability of Hoover Dam was determined. These analyses took two different approaches. The first approach was a three-dimensional linear-elastic analyses (EACD3D96) incorporating foundation-structure interaction with mass in the foundation, impedance contrast between the dam and foundation, and hydrodynamic interaction using compressible fluid [Chopra 1996; Payne 1998]. The second approach was a non-linear three-dimensional dynamic finite element analysis incorporating concrete cracking and contraction joint interaction using smeared crack techniques [ANATECH 1997, Koltuniuk 1997] and kinematic stability analysis of the top of the dam [Scott 1982; Mills 1997].

## 2. GROUND MOTIONS

In 1993, a regional seismotectonic study was conducted for the Hoover Dam area [O'Connell 1993]. In 1994, estimates for strong ground motions that seismogenic sources, identified in the regional seismotectonic report, could be produced at Hoover Dam. Recommended ground motions representing the Mead Slope Fault are the Convict Creek record of the May 27, 1980 Mammoth Lakes, California earthquake and the Corralitos recording from the Loma Prieta 1989 earthquake (see figures 2 and 3). These ground motions were modified and accepted based on recommendations by the consultant review board [Bolt 1995, O'Connell 1995].

## 3. CONCRETE CORE AND LABORATORY TESTING

Laboratory tests [Reclamation 1995] on extracted 15-cm (6-inch) diameter concrete core from the dam showed the concrete was very strong and had average properties as shown in the table.

The 29,854 MPa (4,330,000-lb/in$^2$) dynamic modulus of elasticity was suspect. A literature search of published dynamic concrete properties showed that the dynamic modulus is typically equal to or greater than the static modulus [Harris 1997]. Therefore, the measured static modulus was used for the dynamic modulus.

Tested Material Properties

| Description MPa (lb/in$^2$) | Static | Dynamic |
|---|---|---|
| Compressive | 50 | 55 |
| | (7230) | (8040) |
| Splitting tensile | 4 | 7 |
| | (600) | (970) |
| Concrete Modulus | 45,436 | 29,854 |
| | (6,590,000) | (4,330,000) |
| Foundation Modulus | | |
| Lower elevations | 26,200 | 26,200 |
| | (3,800,000) | (3,800,000) |
| Upper elevations | 16,547 | 16,547 |
| | (2,400,000) | (2,400,000) |
| Apparent cohesion | 0.63 | 0.63 |
| (see figure 4) | (91) | (91) |
| Friction angle | 48° | 48° |

## 4. RESERVOIR BOTTOM REFLECTION COEFFICIENT

Dr. Yusof Ghanaat measured the reservoir-bottom reflection coefficient (alpha coefficient) at Hoover Dam in 1995 [Ghanaat 1995]. The silt elevation at the dam heel is at elevation 216 m (708.8 ft) (depth of 54 m (176.8 ft)). Reflection surveys measured alpha coefficients of -0.09 for the bottom surficial material, 0.68 for the dam concrete, and 0.77 for the canyon rock walls. Refraction surveys measured alpha coefficients of -0.02 and -0.05 for the bottom surficial material.

## 5. HYDRODYNAMIC INTERACTION

The effect of hydrodynamic interaction on Hoover Dam was studied and included in all the various dynamic studies [Payne 1997, 1995]. Sensitivity studies included the affects of incompressible fluid, compressible fluid, and various reservoir bottom reflection coefficients. The findings were that hydrodynamic interaction had a relatively small affect on the stress of state in the dam during an earthquake because of the massive size and inertia of the dam body compared to the inertia force of the water. There was no single correction factor to convert stress values when incompressible fluid or compressible fluid is used. Stress magnitudes and areas of high stresses and the time they occur vary with each earthquake. Use of compressible fluid instead of incompressible fluid did not always produce smaller stresses.

## 6. STRUCTURAL ANALYSIS

Currently, there is no software codes available that incorporate all the important aspects (hydrodynamic interaction, impedance of dam-foundation interaction, contraction joint action, or rigid block kinematic movements) associated with a concrete dam for a complete structural analysis. For this reason, various software programs were run using the Hoover finite element model and knowledge of the influence of each aspect affecting the dam was gleamed. This way the relative impact of each aspect on the stability of Hoover Dam was determined. The same finite element model was used in all the studies (see figure 5).

### 6.1 TRADITIONAL STRUCTURAL ANALYSIS

Traditional structural analyses were made using the SAPIV linear-elastic three-dimensional dynamic finite element code with a massless foundation, 10 percent viscous damping, and hydrodynamic interaction using incompressible fluid added masses [Nuss 1996, Dollar 1994]. Maximum calculated arch tensile stresses, with superimposed static stresses, were 12.2 MPa (1772 lb/in$^2$) on the upstream face and 12.7 MPa (1840 lb/in$^2$) in the downstream face. Maximum calculated cantilever tensile stresses were 10.0 MPa (1445 lb/in$^2$) on the upstream face and 11.6 MPa (1684 lb/in$^2$) on the downstream face. This is well over the dynamic tensile strength of the concrete and would indicate cracking of the structure.

### 6.2 INCORPORATING STRUCTURE - FOUNDATION INTERACTION

The influence of including mass in the foundation during a structural finite element analysis is investigated using a relatively new program EACD3D96 [Chopra 1996]. This program was tested and evaluated for consistency with the previous EACD3D version and for reasonability of the results when foundation and dam moduli were varied [Payne 1998]. The impedance between the dam and foundation and radiation damping is included in the analysis. This is believed to be the most realistic linear-elastic structural analysis to date.

Analysis, incorporating mass in foundation, shows great reduction of stress in the dam to the point that cracking of the dam is not expected from the MCE (thus, lack of nonlinear capability in this program is no longer a concern). For example, calculated stress levels are reduced from 11.6 MPa (1684 lb/in$^2$) not including the foundation mass to 4.1 MPa (600 lb/in$^2$) by including foundation mass and interaction (see figure 6). Lower stresses are attributed to the following: First, the stiffness of the concrete compared to the stiffness of the foundation material inhibits seismic energy from entering the structure and thus reduces the seismic affect. Second, the infinite boundary of the foundation provides a radiation damping affect that allows earthquake energy to dissipate from the structure.

### 6.3 NONLINEAR DYNAMIC ANALYSIS

Despite the above finding, a non-linear analysis with a "traditional" massless studies were continued as a back up and also because of the paucity of testing and experience with the new program incorporating foundation mass.

The influence of including contraction joints and concrete cracking in structural finite element analyses is investigated using smeared crack techniques in program ANACAP [Anatech 1997]. However, this analysis does not include the dam-foundation and produces higher dynamic inertia forces, which shake the dam enough to open and close contraction joints and crack the concrete in the finite element analysis. Since these analyses were nonlinear, various verification studies are performed to determine the appropriate solution time step, damping, convergence tests, and modeling. Four finite element models evolved during these studies: a 5-joint element model, a 24-pre-directed joint model, a 16-pre-directed joint model, and an 8-pre-directed joint model [Koltuniuk 1997].

Using the Convict Creek ground motion, the ANACAP analysis predicted horizontal cracking 46 m (150 feet) below the dam crest on the upstream face, continuing through the dam in the downstream direction, sloping upward toward the downstream face (see figure 7). ANACAP indicated stability and 3-cm (1.1-inch) movement of the dam upstream. This cracking pattern forms concrete blocks capable of sliding independently from the dam body along the cracked basal plane and bounded on the sides by vertical contraction joints.

Using the Corralitos ground motion, the calculated cracking, which is significantly less, is located 82 m (270 feet) below the dam crest on the downstream face, and does not progress through to the upstream face. Therefore, further stability analysis using this earthquake record is not needed.

The capability of extracting an XYZ time history of hydrodynamic pressures at nodes on the upstream face from EACD3D was developed which made it possible to apply hydrodynamic forces to other finite element codes. This allowed for the ability to apply full compressible hydrodynamic forces including reservoir bottom reflection effects to the nonlinear ANACAP model of Hoover Dam. Incorporating full hydrodynamic compressible fluid effects in the nonlinear ANACAP model of Hoover Dam showed cracking developed sooner, cracking advanced at a slower rate, but the final cracking pattern was very similar compared to the incompressible fluid effect. Thus, use of full hydrodynamic would not have changed results in terms of preventing formation of a potential sliding mass in the upper part of the dam.

### 6.4 KINEMATIC STABILITY OF THE TOP OF DAM

Kinematic studies were performed to investigate the sliding stability of an independent concrete block formed separate from the dam body bounded by horizontal cracking and vertical contraction joints. The computer program RIGID uses a Newmark procedure to determine movements of a rigid body [Scott 1982]. Loads applied to the block were the accelerations calculated in the concrete dam at 46 m (150 feet) from the crest, static reservoir loads, and forces representing full hydrodynamic and reservoir boundary effects [Mills 1997] (see figure 8). The maximum "expected" displacement if a "cracked block" were to form in upper part of dam during the earthquake is about 9 cm (3.5 inches) in the upstream direction. Such small displacement would not impair stability of the dam or result in reservoir release because the dam is 30 m (100 feet) thick at this depth arch action and the wedging provides side restraint.

## 7. CONCLUSIONS

Based on structural analysis incorporating foundation mass, Hoover Dam is predicted to withstand shaking from the maximum credible earthquake without significant cracking. This improved performance over previous traditional analyses is attributed to the impedance contrast between the dam and foundation, which inhibits earthquake energy from entering the structure. Calculated stress levels during the maximum credible earthquake are below the tensile strength of the concrete when incorporating the impedance between the dam and foundation.

Based on nonlinear structural analysis with a massless foundation (performed in the event that the impedance between the dam and foundation proves to be inaccurate) concrete cracking at 46 m (150 feet) below the dam crest is indicated. However, even if this cracking extends through the upstream to downstream thickness of the dam, forming independent blocks separate from the dam body, the calculated block movements are on the order of a few inches, which would not cause instabilities nor an uncontrolled release of the reservoir.

The top of dam is considered stable for the post-earthquake condition because of many positive factors. The dam has 20-cm (8-inch) diameter formed drains at 3-m (10-foot) centers cross-canyon in the dam body to reduce uplift pressures from infiltration of water along any upstream cracking. Arch action is maintained during and after an earthquake, which inhibits any downstream movements. The top 46 m (150 feet) of the dam resembles a gravity dam section with a downstream slope of 0.7:1. This size gravity section is stable for static loads without arch action. Calculated earthquake induced cracking is radial so arch action is maintained. The horizontal basal plane formed by cracking during an earthquake slope upward toward the downstream face, which produces a stable slide plane.

## 8. ACKNOWLEDGEMENTS

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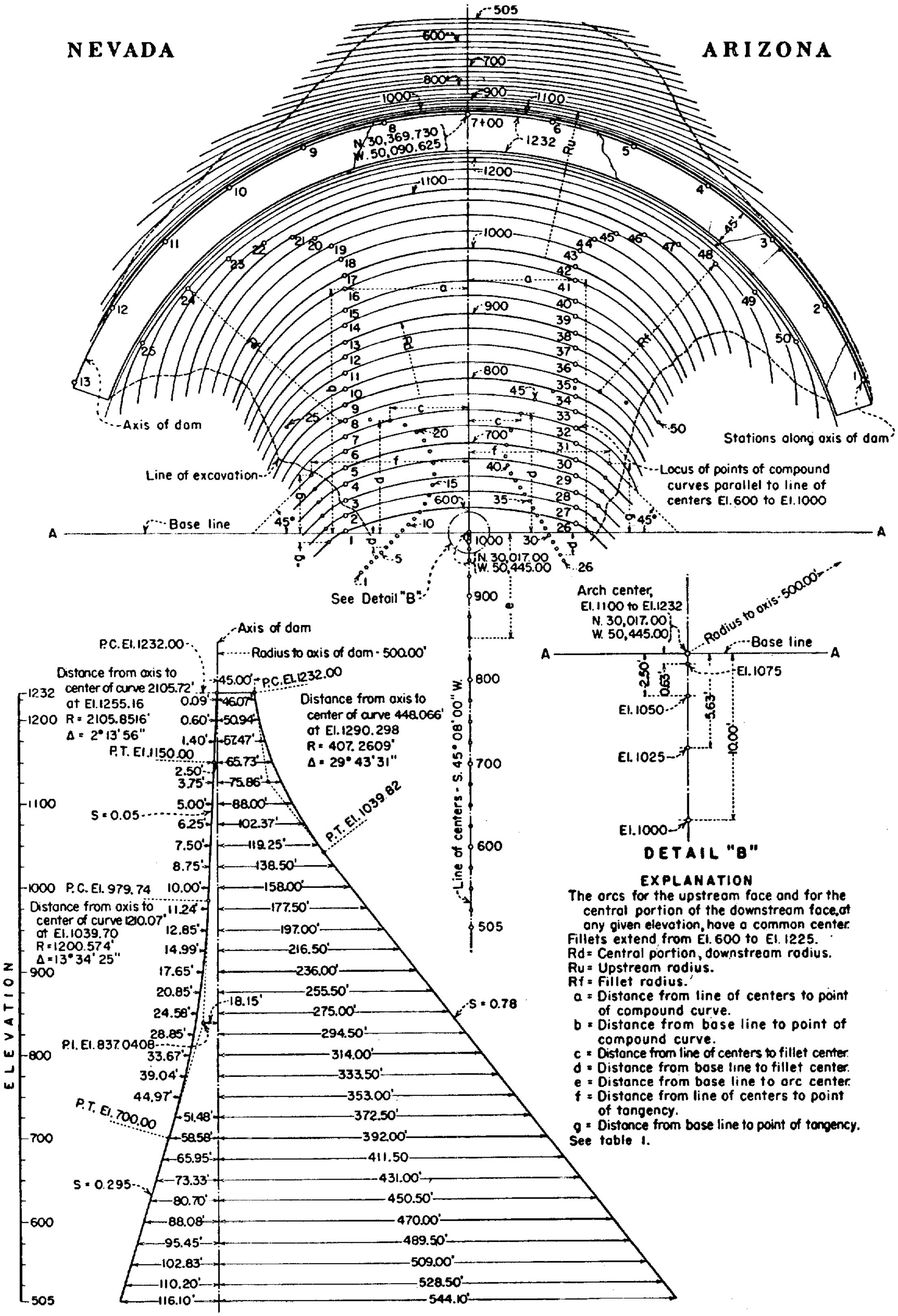



Figure 1 - Plan and Section of Hoover Dam
(reprint from Boulder Canyon Project – Final Reports – 1941)

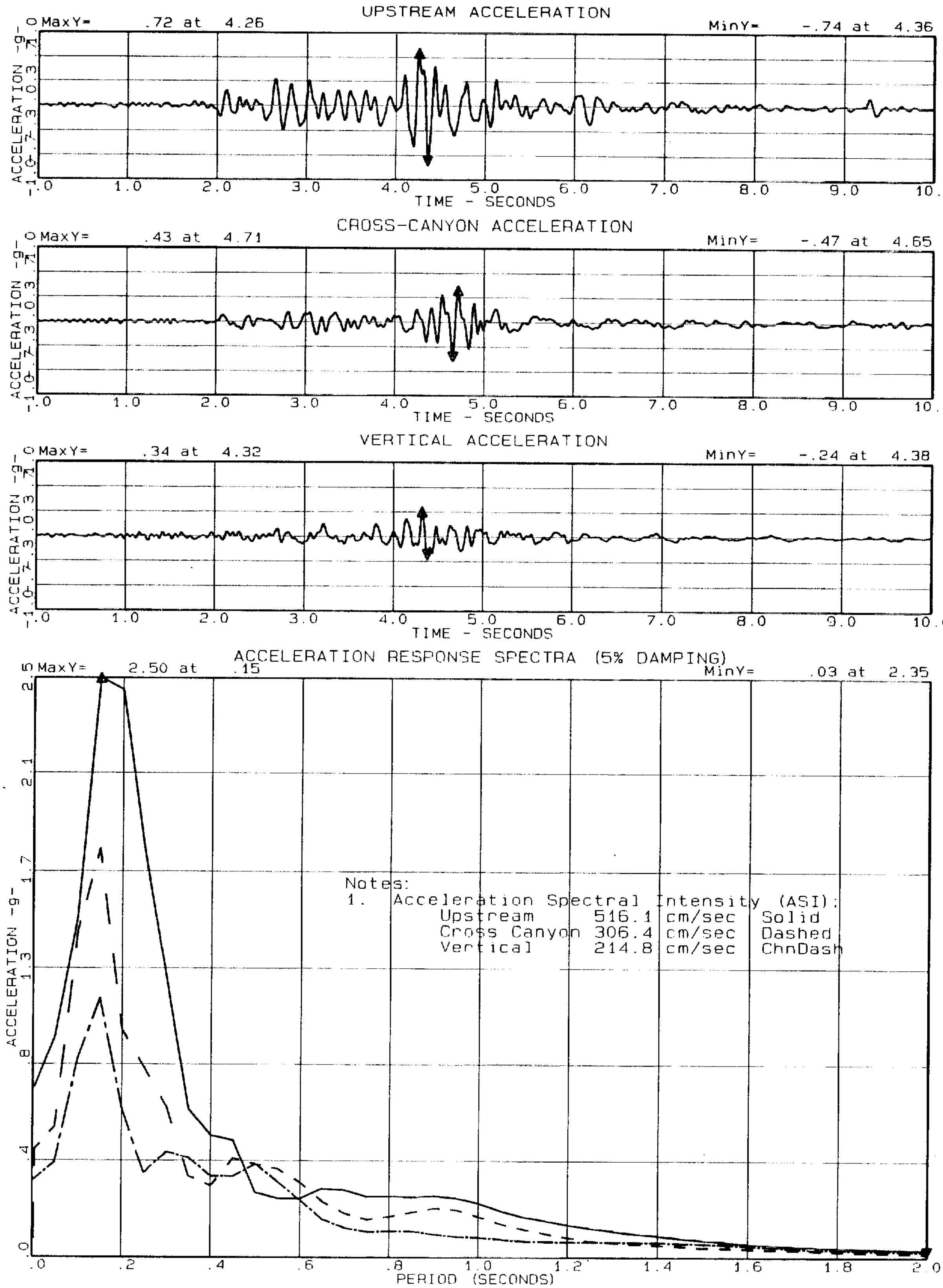



**Figure 2 - Convict Creek Accelerograms And Acceleration Response Spectra**

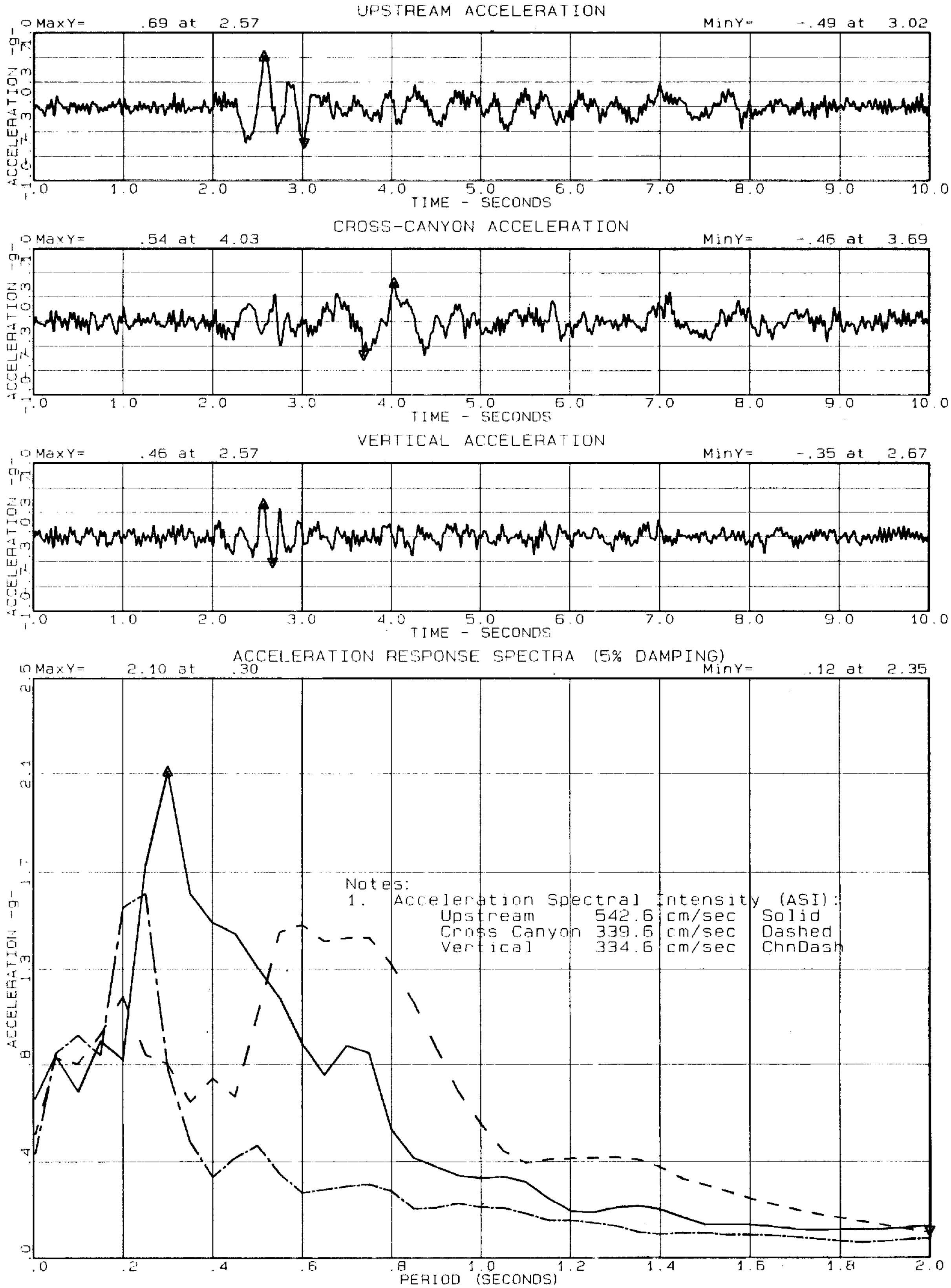
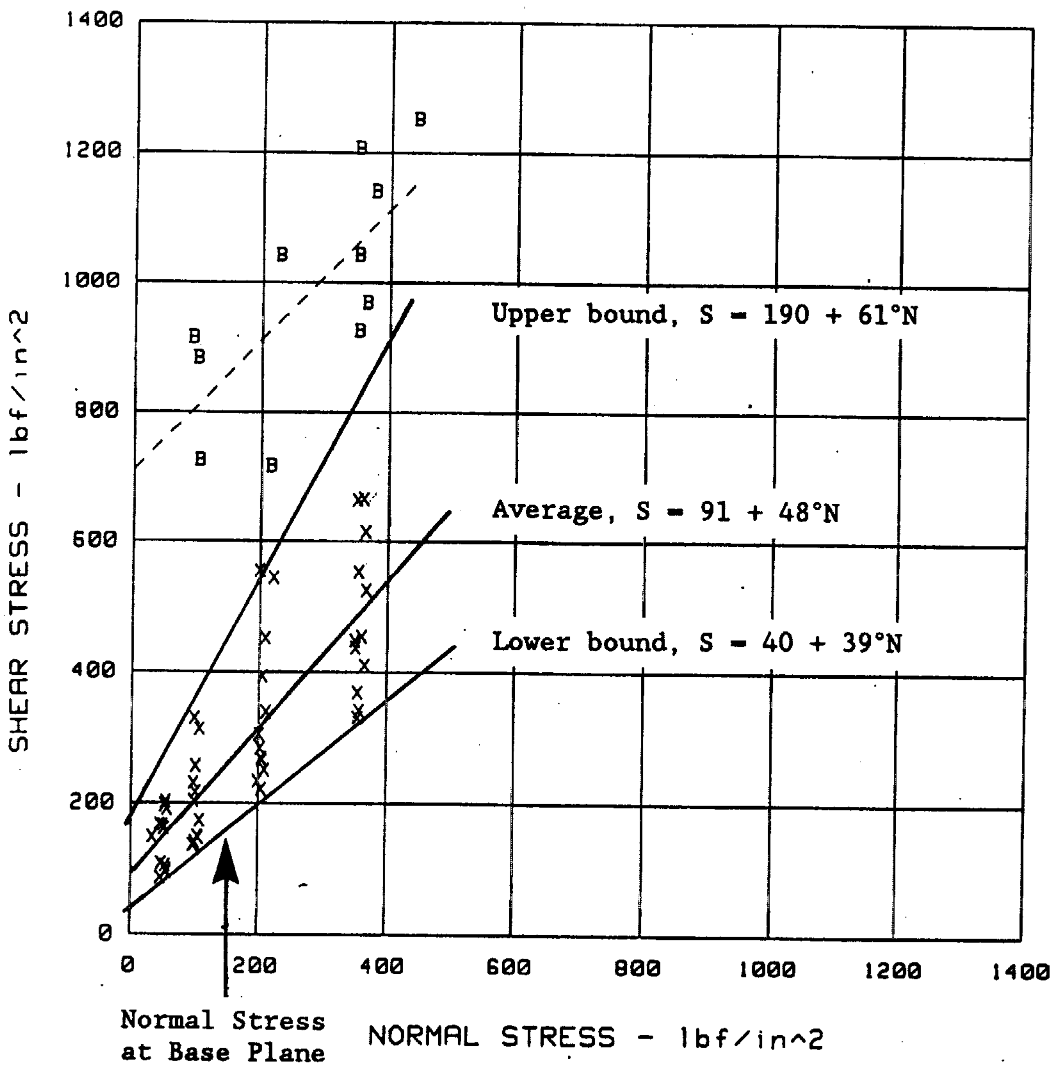



Figure 3 - Corralitos Accelerograms And Acceleration Response Spectra

## DIRECT SHEAR TEST
ALL LIFT LINE SPECIMENS




Project: BOULDER CANYON
Feature: HOOVER DAM
Combined:

INTACT SHEAR STRENGTH
S= 710.7 + 1.004 (N)
Cohesion = 711 lbf/in^2
Phi= 45 deg Corr Coef= .7319

SLIDING FRICTION RESULTS
S= 91.3 + 1.122 (N)
Cohesion = 91 lbf/in^2
Phi= 48 deg Corr Coef= .8308

| SPECIMEN NO. | | Normal Stress lbf/in^2 | Shear Stress lbf/in^2 |
|---|---|---|---|
| LL-HD1-7.6 | (B) | 103 | 725 |
| LL-HD1-8.1 | (B) | 365 | 969 |
| LL-HD2-2.1 | (B) | 352 | 1043 |
| LL-HD2-4.0 | (B) | 353 | 925 |
| LL-HD2-8.7 | (B) | 229 | 1042 |
| LL-HD3-2.9 | (B) | 378 | 1140 |
| LL-HD3-2.9 | (S) | | |
| LL-HD3-6.4 | (B) | 444 | 1251 |
| VHPHD1-2.4 | (B) | 100 | 883 |
| VHPHD1-4.4 | (B) | 92 | 914 |
| VHPHD2-7.2 | (B) | 216 | 716 |
| VHPHD212.3 | (B) | 352 | 1206 |

LEGEND
(S) - No Intact Value
(B) - Intact Shear Determined

Sliding Frict. Values(X) ———
B = Intact Shear Strength - - - -

Figure 4 - Tested Shear Properties On Extracted Concrete Core

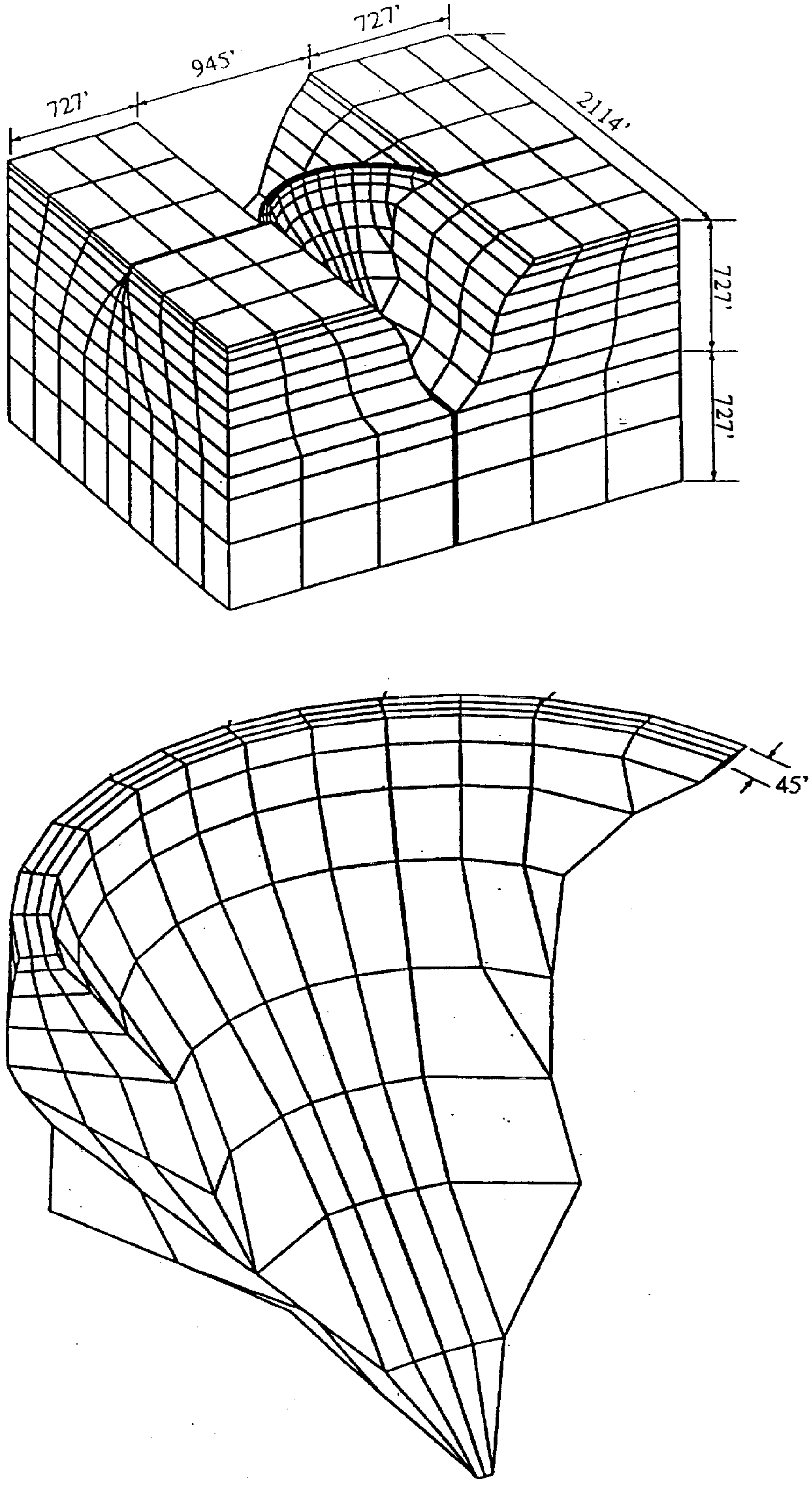



Figure 5 – Finite Element Model Of Hoover Dam And Foundation

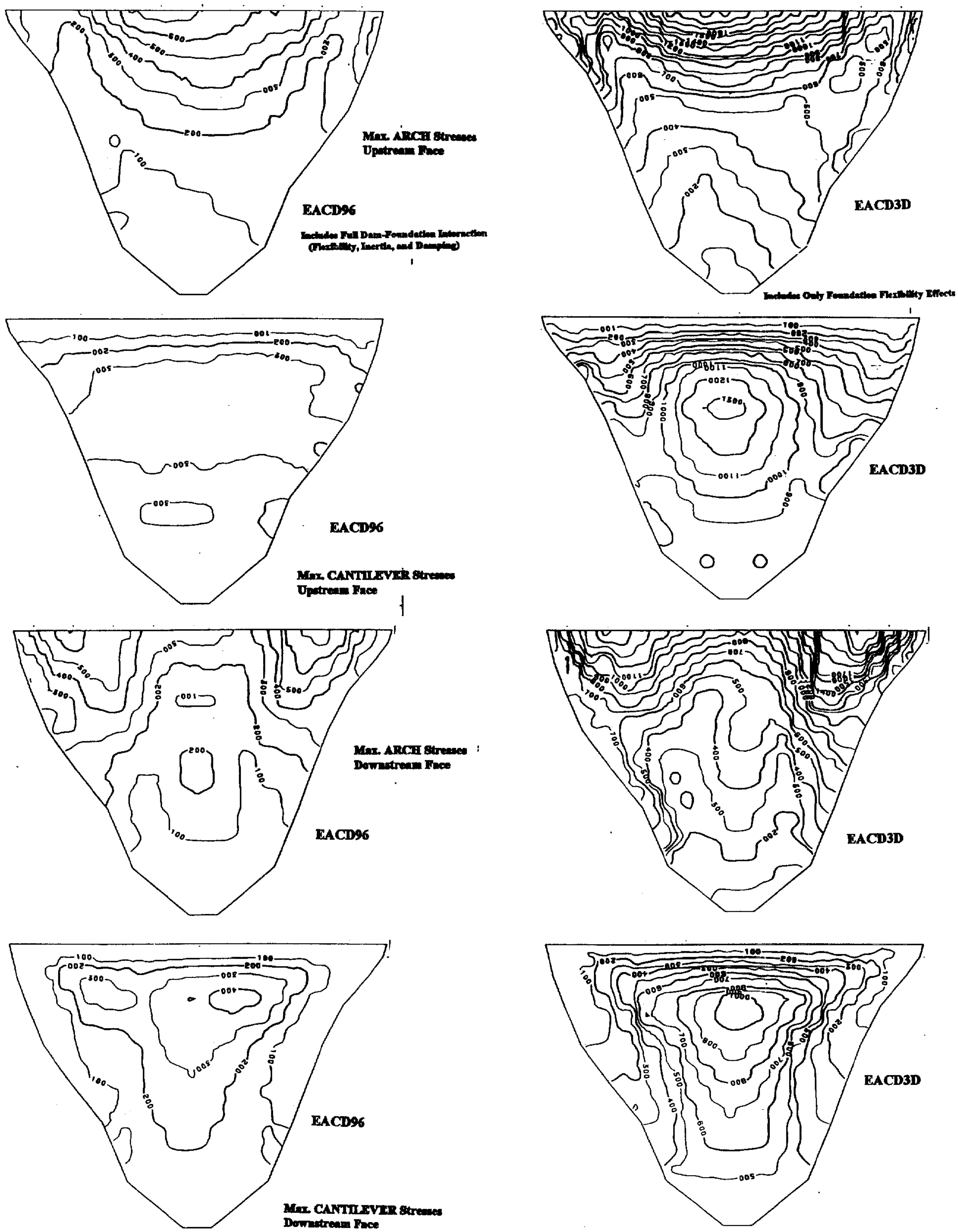



Figure 6 – Comparison of Maximum Arch And Cantilever Stresses
With Foundation Mass And Without Foundation Mass

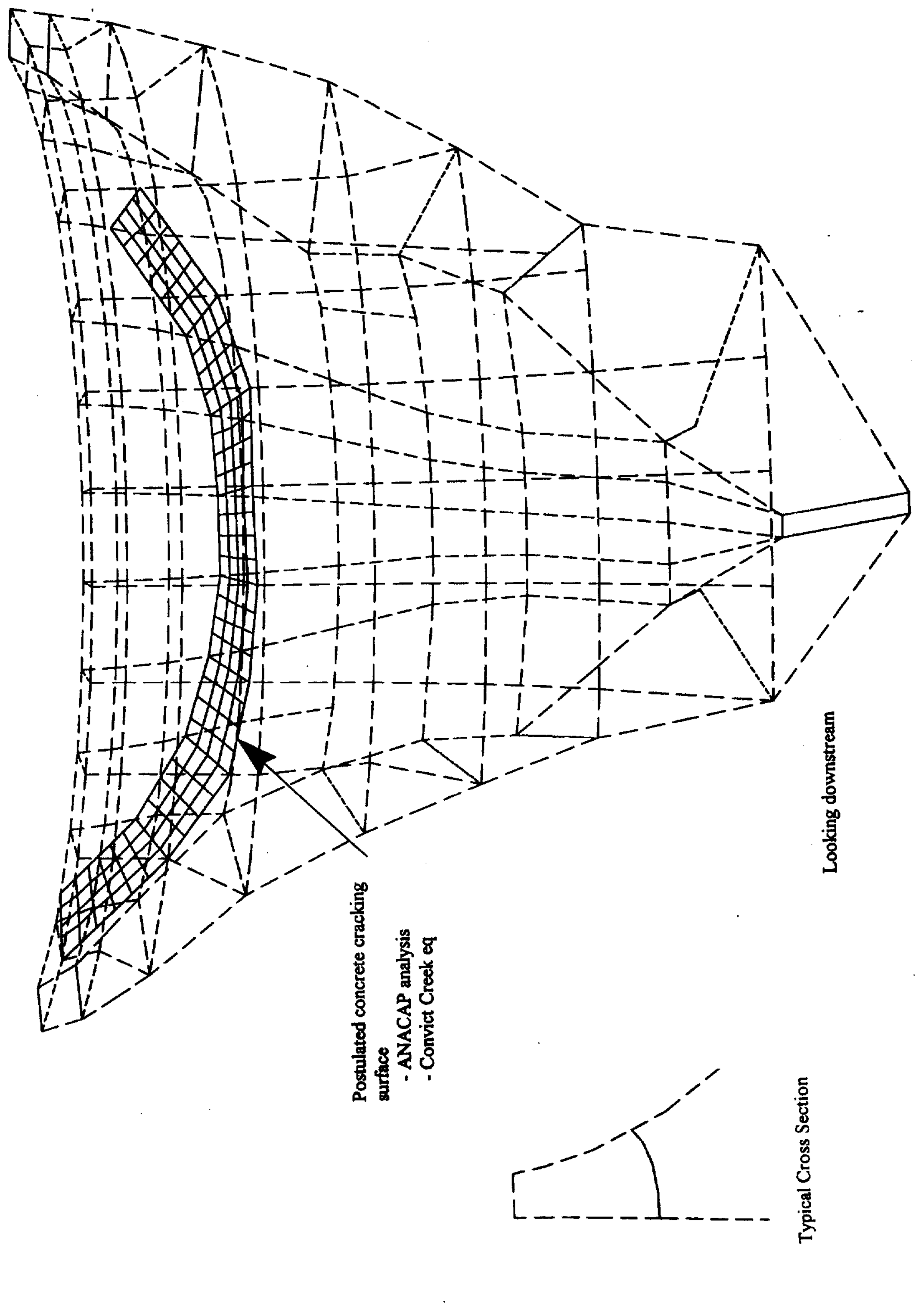



Figure 7 – Postulated Cracking Of Hoover Dam From A Non-linear Dynamic Analysis With A Massless Foundation

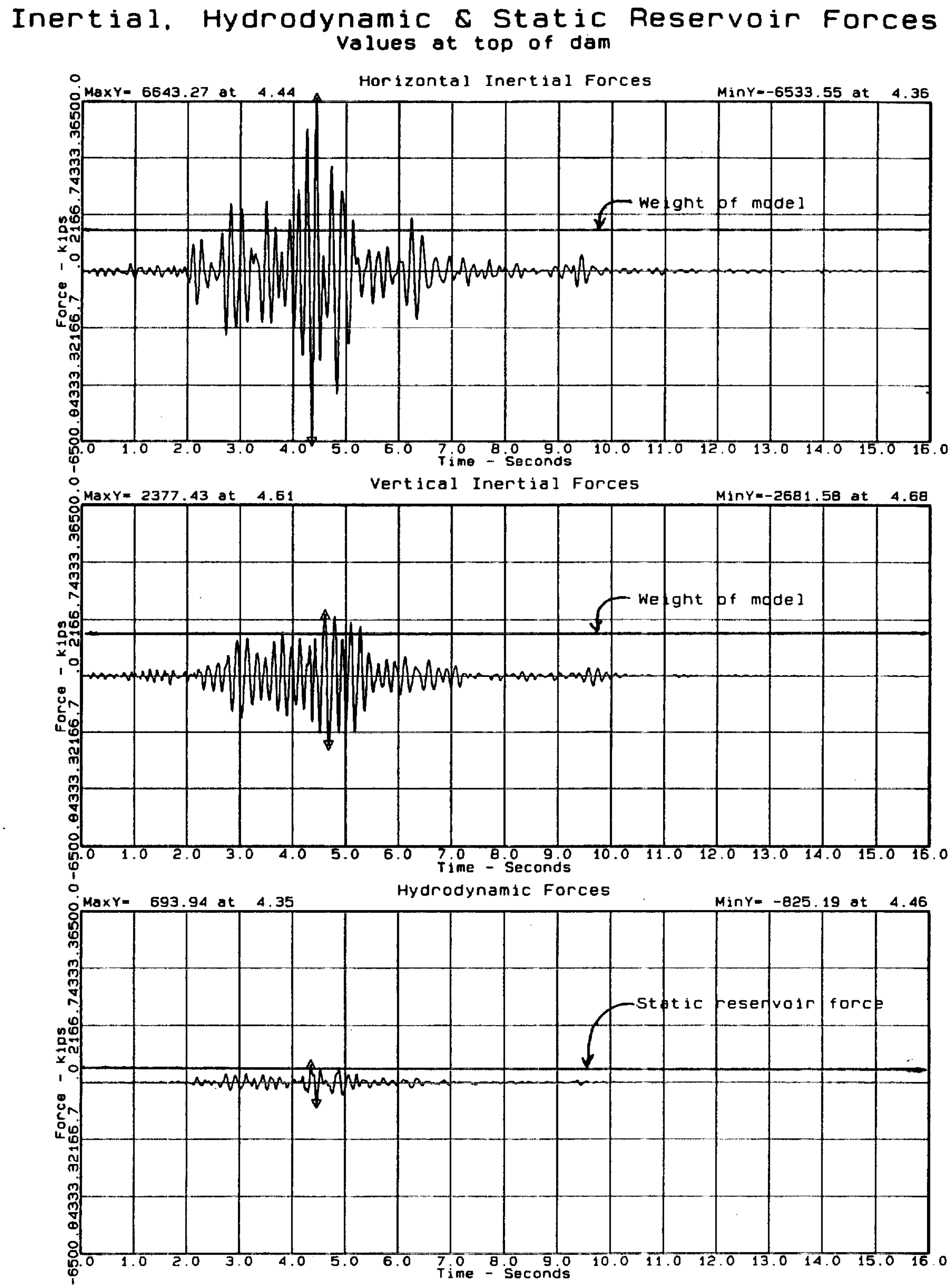



Figure 8 – Hydrodynamic And Inertia Forces At The Top Of Hoover Dam