SEISMIC ANALYSIS OF ARCH DAMS INCLUDING DAM-RESERVOIR-FOUNDATION INTERACTION EFFECTS BY AN EFFECTIVE PROCEDURE

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ABSTRACT:
A new effective procedure is proposed for evaluating the earthquake response of the concrete arch dams including dam-reservoir-foundation interaction effects in frequency domain. The modeling concept is based on the FE-(FE HE)-BE approach. The method is developed by integration of most recent techniques designed to save computational time in different parts of the dynamic analysis of the complete dam-reservoir-foundation system. These include employment of the modified-efficient three dimensional fluid hyper-element for modeling far-field of the reservoir, interpolation of the foundation impedance matrix, and efficient evaluation of coupled mode shapes of the dam-reservoir-foundation system or other alternatives for the main core of the procedure. The analysis of Morrow Point arch dam is presented as a numerical example and execution time savings are provided for different parts of this analysis. It should be also mentioned that the FFT algorithm is utilized to obtain the time history of different responses. Furthermore, the ground motion recorded at Taft earthquake is selected for the free-field ground acceleration of the seismic analysis.

KEYWORDS:
Dynamic analysis, frequency domain, fluid-structure interaction, fluid hyper-element, boundary elements.

1. INTRODUCTION

There are different alternatives for dynamic analysis of concrete arch dam-reservoir-foundation rock system In general, these procedures may treat the problem in the time or frequency domain [1]. Of course, researchers have most often preferred the latter alternative due to existence of two semi-infinite regions in the system (i.e., reservoir and foundation rock). In this case, the rigorous modeling of the reservoir far-field and the foundation rock are each dependent on calculation of certain impedance matrices at each frequency which are computationally the most demanding part of the procedure. It is also well-known that the modal approach is much more efficient than the direct method for systems with large degrees of freedom. However, this could become complicated and quite different from usual modal analysis for normal structures if the true coupled fluid-structure mode shapes are to be utilized in this process. This is fundamentally due to the fact that total mass and stiffness matrices of the system are unsymmetric. It should be mentioned that in some cases, researchers have developed dynamic analysis techniques for this problem which totally avoids the extraction of these coupled modes [2, 3]. The present paper is concerned with the description and numerical implementation of a new effective procedure to evaluate the earthquake response of the concrete arch dams in frequency domain. The modeling concept is based on the FE-(FE-HE)-BE approach. This method allows for the inclusion of fluid-structure interaction, reservoir boundary absorption, and dam-foundation rock interaction in a rigorous manner.

2. FE-(FE-HE)-BE PROCEDURE

The rigorous analysis of concrete arch dam-reservoir foundation system is based on the FE-(FE-HE)-BE method (i.e., Finite Element-(Finite Element-Hyper Element)-Boundary Element). This means, the dam is discretized by solid finite elements, while, the reservoir is divided into two parts, a near field region (usually an irregular shape) in the vicinity of the dam and a far field part (assuming uniform channel), which extends to infinity. The former region is discretized by fluid finite elements and the latter part is modeled by a three-dimensional fluid hyper-element. Furthermore, the foundation rock domain is represented by utilizing a three-dimensional boundary element formulation. It should be also mentioned that in this approach, the geometry of canyon could be quite arbitrary and this has become possible due to the fact that a 3D boundary element formulation is applied for foundation rock domain. The analysis is carried out in frequency domain by sub-structuring techniques. The comprehensive formulation can be found elsewhere in detail [4]. Meanwhile, the usual procedure for calculating the required impedance matrices in this approach and its final equation solving based on direct approach is computationally very time consuming due to following facts:

- The usual method for calculating the impedance matrix of the 3D fluid hyper-element is dependent on the solution of a complex eigen-value problem for each frequency. Obviously, this would be a very time consuming process.
- The dimension of system's equation would often become very large due to great number of degrees of freedom corresponding to the structure and the fluid domain totally. Therefore, the direct solution of this usually large system of linear equation with complex numbers would not be very efficient.
- A significant amount of the computational time is spent for the calculation of foundation impedance matrix at each frequency by applying 3D boundary element method.

To overcome these limitations, some of the previously proposed techniques were decided to be integrated. These are reviewed briefly in the following sections. In fact, all these methods combined could lead to an efficient technique for dynamic analysis of concrete arch dams which is the objective of this study.

3. FLUID HYPER-ELEMENT

As mentioned, the three-dimensional fluid hyper-element is utilized to model the reservoir far-field region. This part of the water domain is assumed to be as a uniform channel with an arbitrary geometric shape in the vertical plane and extends to infinity in the upstream direction (see Fig. 3). Although, this is a three-dimensional semi-infinite fluid element, its discretization is performed in the vertical plane perpendicular to channel axis, which is referred to as the reference plane. Therefore, the element consists of several sub-channels, which extend to infinity and all the nodes of the hyper-element are located on the reference plane. The usual formulation of the fluid hyper-element is explained elsewhere in detail [5]. The impedance matrix of this element depends on the solution of the complex eigen-value problem which must be solved repeatedly for different required frequencies. Therefore, the calculation of the impedance matrix is very time consuming and cumbersome, and a major portion of the numerical calculation time spent is due to the solution of this complex eigen-value problem.

To remedy this, an efficient procedure was proposed [5] which greatly reduces the computational time. In this manner, it is not required anymore to solve a complex eigen-value problem for each frequency. In other words, the procedure will merely depend on the solution of the initial eigen-problem corresponding to $\omega = 0$. It is worthwhile to mention that, this can be solved by standard eigen-solution routine and it doesn't involve any complex number arithmetic. From accuracy point of view, although the method is considered to be very accurate in most practical conditions, it was estimated that it would introduce errors in the range of 10% under certain circumstances.

To reduce this amount of error, the modified-efficient method was proposed [6], which is summarized below. Herein, the impedance matrix is calculated similar to the efficient method. However, some terms have different meaning and they correspond to the modal matrix for the unique case of $\omega = \overline{\omega}$, which $\overline{\omega}$ can be selected as any arbitrary value (e.g., the first natural frequency of the system or wherever one is interested to decrease the error introduced due to this approximation). Also, similar to the previous approach, it is not required anymore to solve a complex eigen-value problem for each frequency and the procedure depends merely on the solution of the eigen-problem for an arbitrary frequency. The main advantage of the modified efficient method could be more accurate hyper-element impedance matrix, which will ultimately transform into a decreased error in response of the dam in certain frequencies. This was examined thoroughly in reference [6]. It was concluded that the modified-efficient method also simplifies the procedure significantly, and results in great computational time saving. Moreover, it was shown that the modified efficient procedure is extremely accurate under all practical conditions. It is worthwhile to mention that percentage error was decreased to the maximum value of about 0.5% in the case of modified efficient procedure which was an incredible improvement.

4. MODAL ANALYSIS

As mentioned above, the usual direct approach in frequency domain is carried out by solving the dam-reservoir foundation equation for different excitation frequency. Of course, this is not very efficient from execution time point of view due to the usual large dimension of that linear equation. On the contrary, the modal technique in frequency domain is a good alternative which is utilized in the effective procedure. In this method, the unknown vector is written as a combination of mode shapes which are obtained by solving the related eigen-problem which is the same as free vibration equation of undamped system. The actual coupled eigen-vectors of the dam-reservoir system are obtained by considering the original eigen-value problem. These mode shapes are very suitable for modal analysis and in general can lead to more accurate response calculation. Of course, standard eigen-value solution routines are not applicable due to the fact that the corresponding matrices are not symmetric.

However, in a previous study [7], an efficient technique was proposed for the calculation of coupled modes of fluid-structure systems. This was referred to as pseudo symmetric subspace iteration method. It has to be mentioned that the algorithm of that procedure was presented with symmetric matrix operation mentality such that one feels that a symmetric eigen-problem is being solved. The method is explained in full details in the above-mentioned reference. Alternatively, one can also work with decoupled eigen-vectors [3]. These are extracted through a variation of original eigen-value problem which is obtained by eliminating the coupling matrix. The eigen-problem of this form can be easily solved by standard routines. It should be mentioned that these vectors can be envisaged as Ritz vectors in that case, and it can be shown that it would lead to exact answers if all decoupled modes are utilized. Also, the "ideal-coupled mode shapes" may be utilized as another option. This can be considered as a modification of "decoupled mode shapes" [8]. Therefore, there are several suitable techniques to obtain the fluid-structure mode shapes which they could be utilized in the related efficient modal approaches.

5. FOUNDATION IMPEDANCE MATRIX

As mentioned before, the foundation rock is represented by applying a three-dimensional (3D) boundary element formulation. Therefore, the geometry of canyon could be quite arbitrary and no limitations are required to be imposed. Also, the full-space frequency dependent fundamental solution for the viscoelastic media is utilized, and the foundation surface is only discretized. Therefore, an accurate procedure is prepared to analyze the foundation with all its effects of flexibility, inertia and damping. However, it may be known as an un-efficient approach, due to employing boundary element method in this part. This restriction could be easily remedied by applying the method of Tan and Chopra [1]. In this approach, the impedance matrix is calculated only at certain frequency points and interpolated for intermediate frequencies by utilizing the cubic interpolation scheme. This procedure is also implemented in the effective approach.

6. MODELS AND BASIC PARAMETERS

Two idealized symmetric models of Morrow Point arch dam are considered as numerical examples, which are considered as a "coarse" and "fine" mesh (Fig. 1). The geometry of the dam may be found in reference [9]. In the coarse mesh, the dam is discretized by 40 isoparametric 20-node solid finite elements (Fig.1). The water domain is divided into two regions (Fig. 2). The near-field part is considered as a region, which extends to a specified length L=0.2 H (H being the dam height or maximum water depth in the reservoir), which is measured in upstream direction at dam mid-crest point. The far-field region starts from that point and extends to infinity in the upstream direction. Both these regions combined are assumed to form a uniform reservoir shape to be consistent with the work of Tan and Chopra [1]. The near-field region is discretized by 80 isoparametric 20-node fluid finite elements, while the far-field region is modeled by a fluid hyper-element which itself is constructed from 40 isoparametric 8-node sub-elements. Furthermore, the foundation rock is modeled by 178 isoparametric 8-node boundary elements considered at the foundation surface. Also, the canyon shape is assumed uniform (Fig. 3) as in the Tan and Chopra study [1].

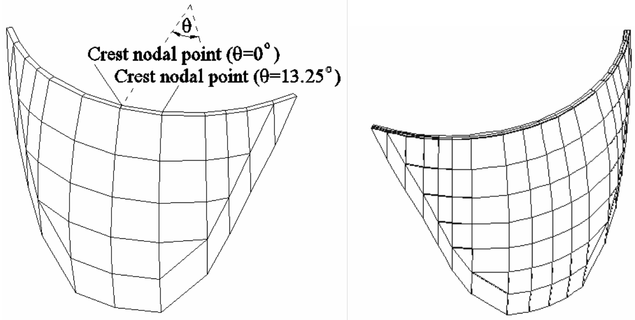

Figure (1) – Discretization of the dam body (coarse mesh and fine mesh)

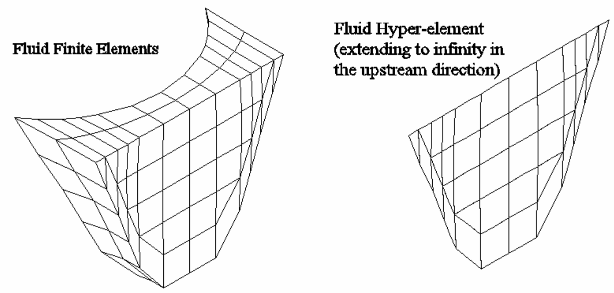

Figure (2) – Discretization of the reservoir domain by fluid finite elements
and the fluid hyper-element (only coarse mesh)

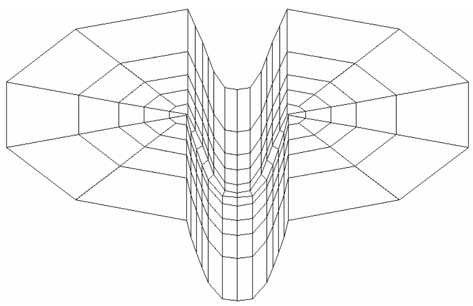

Figure (3) – Boundary element discretization of foundation rock (only coarse mesh)

The fine mesh consists of 168 finite elements for the dam body (Fig. 1). There are two layers of elements along the dam thickness in this case. Also, the reservoir is modeled by 168 fluid finite elements for near-field part and 84 fluid sub-elements for far-field region. The foundation surface is discretized by 264 boundary elements. The dam concrete is assumed to be homogeneous with isotropic linearly viscoelastic behavior and the following main characteristics:

Elastic modulus = 27.5 GPa, Poisson's ratio = 0.2, Unit weight = 24.8 $\mathrm{kN/m^3}$, Hysteretic damping factor = 0.05

The impounded water is taken as inviscid, and compressible fluid with unit weight equal to 9.81 $\mathrm{kN/m^3}$, and pressure wave velocity C=1440 m/sec. The foundation rock is idealized by a homogeneous, viscoelastic domain. The basic properties of this region are:

Elastic modulus = 27.5 GPa, Poisson's ratio = 0.2, Unit weight = 26.4 $\mathrm{kN/m^3}$, Hysteretic damping factor = 0.05

The analyses are carried out by a special purpose computer program [DACAD86] which was enhanced based on the above-mentioned effective approaches. The program has several options for calculating the mode shapes of fluid-structure interaction systems, or utilizing the efficient approaches for fluid hyper-element.

7. Results

7.1. Frequency Response Functions

Initially, the frequency response functions of the dam are presented due to different types of excitation based on several techniques which are reviewed in the article. In all these cases, the modified efficient fluid hyper-element is implemented, and the foundation rock impedance matrix is interpolated. These results are also compared against the direct approach results which can be visualized as the exact response. It should be also mentioned that response quantities presented as frequency response functions are the amplitudes of the complex valued radial accelerations for two points located at dam crest (Fig. 1). The radial acceleration at dam crest is presented due to upstream, vertical and cross-stream excitations, respectively. These are obtained by considering wave reflection coefficient α equal to 0.5. This value represents relative reflection of waves impinging at reservoir foundation boundaries, as it is implemented in [1]. In all cases, the foundation rock is assumed flexible with elastic modulus equal to elastic modulus of dam.

Fig. 4 shows the results of two modal approaches (i.e., coupled and decoupled methods) against the direct one. It should be mentioned that 100 coupled modes are applied to obtain the coupled results. Also, the same number of separated modes of the fluid and the structure are employed in the decoupled modal technique. As it is apparent from this figure, the coupled method is more accurate than the decoupled one, especially for the upstream excitation in the vicinity of the first peak. Therefore, the next analyses are carried out by the coupled modal approach and utilizing 100 modes.

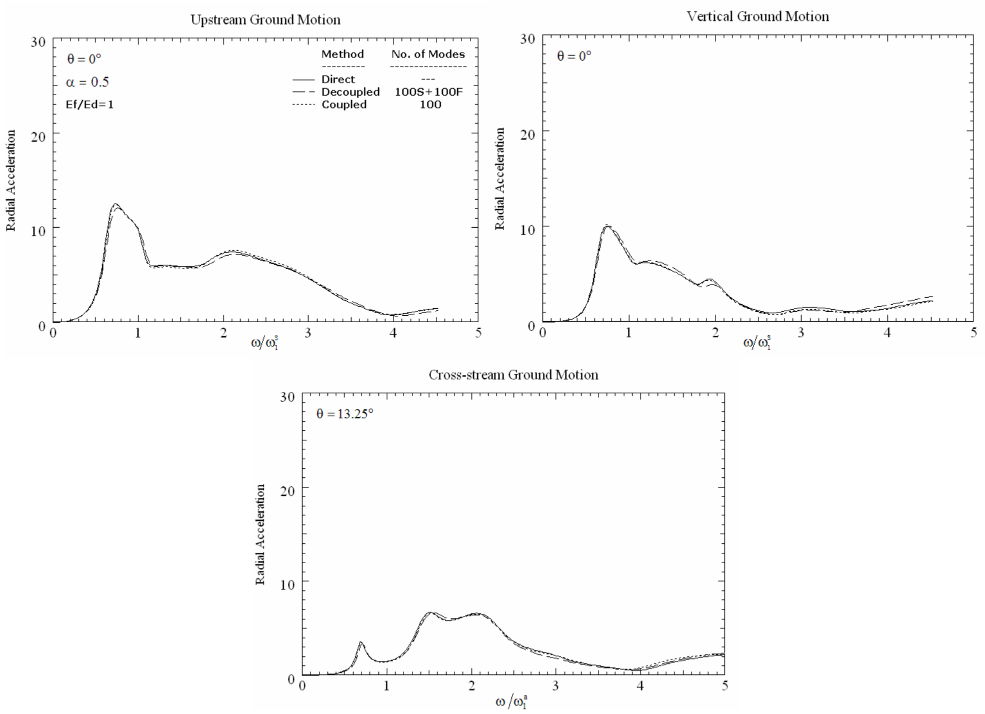

Figure (4) - Frequency-response functions by applying the coupled and the decoupled modal approach.

Subsequently, the effective procedure is evaluated from the efficiency point of view. The following table includes the execution times required for response analyses of the dam-reservoir foundation rock system. Analyses are actually carried out at 240 selected frequencies from 0 to 120 rad/s with the increment of 0.5 rad/s.

As it is apparent, the reduction in the computation times of the effective procedure is very significant. It is worthwhile to mention that more details about the computational time comparison can be found in [10].

Table 1. Computation time for each part of the analysis for both coarse and fine mesh

Domain	Method	Execution time (sec.)	
		Coarse mesh	Fine mesh
Fluid hyper-element	Ordinary	140.8	1349.8
	Efficient	20.8	129.8
	Modified-Efficient	21.1	159.4
Foundation	Ordinary	51840	155520
	Efficient (7 point)	1512	4536
Analysis	Direct	924	15847
	Modal (100 modes)	57	249

7.2. Time History Response

To obtain the time history of different responses, the FFT algorithm is utilized. Also, the ground motion recorded at Taft Lincoln School tunnel during the Kern County, California, earthquake of 21 July 1952 is selected as the free-field ground acceleration for the analysis of Morrow Point dam. The excitation acting in the upstream (-y), vertical (z) and cross-stream (x) directions is defined as the S69E, vertical and N21E components of the ground motion record, respectively. These three components are shown in Fig. 5 along with their peak accelerations. It should be mentioned that the data utilized is exactly the same as the one implemented in the work of Tan and Chopra [1]. Apart from some differences in the type of dam elements (20 node solid elements against the thick-shell elements) and boundary element mesh (3D mesh against 2D mesh), the other properties are almost similar in the present study and that study. Therefore, different responses should be more or less comparable with their results. For a general verification purpose, a complete analysis of Morrow Point dam was performed and different responses was obtained due to its weight, hydrostatic pressure and the simultaneous action of the upstream, vertical, and cross-stream components of Taft ground motion. Fig. 6 represents the time history of the radial displacement at mid-crest point for the full reservoir and flexible foundation case. It is noted that the response matches very well with the corresponding results from the work of Tan and Chopra provided in the same figure.

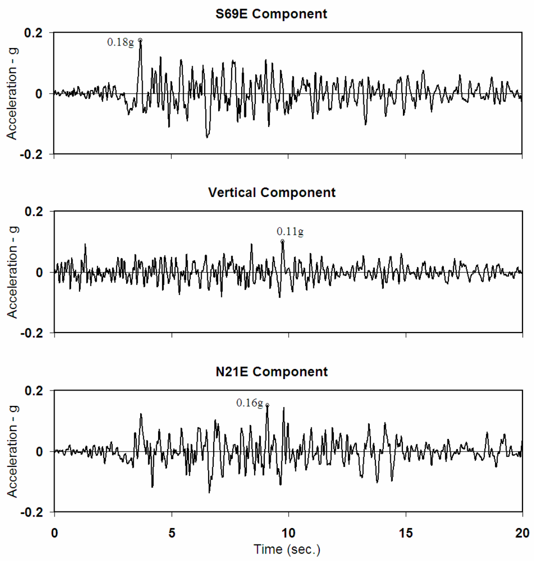

Figure (5) – Ground motion at Taft Lincoln School Tunnel, Kern County, California, earthquake 21 July 1952

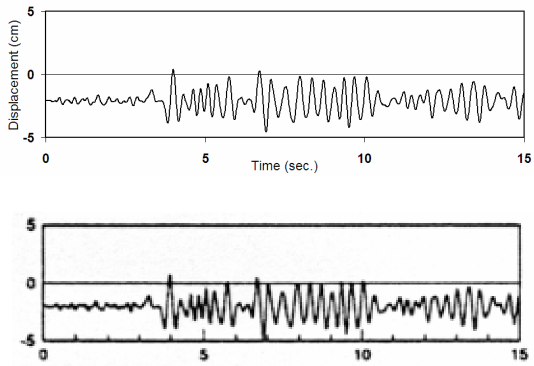

Figure (6) - Displacement response of mid-crest point of Morrow Point Dam (above: present study; below: the work of Tan and Chopra [1])

Also, Fig. 7 shows the envelope of the maximum tensile arch and cantilever stresses on the upstream and downstream faces of the dam. Similar results taken from the work of Tan and Chopra [1] are provided for comparison purposes.

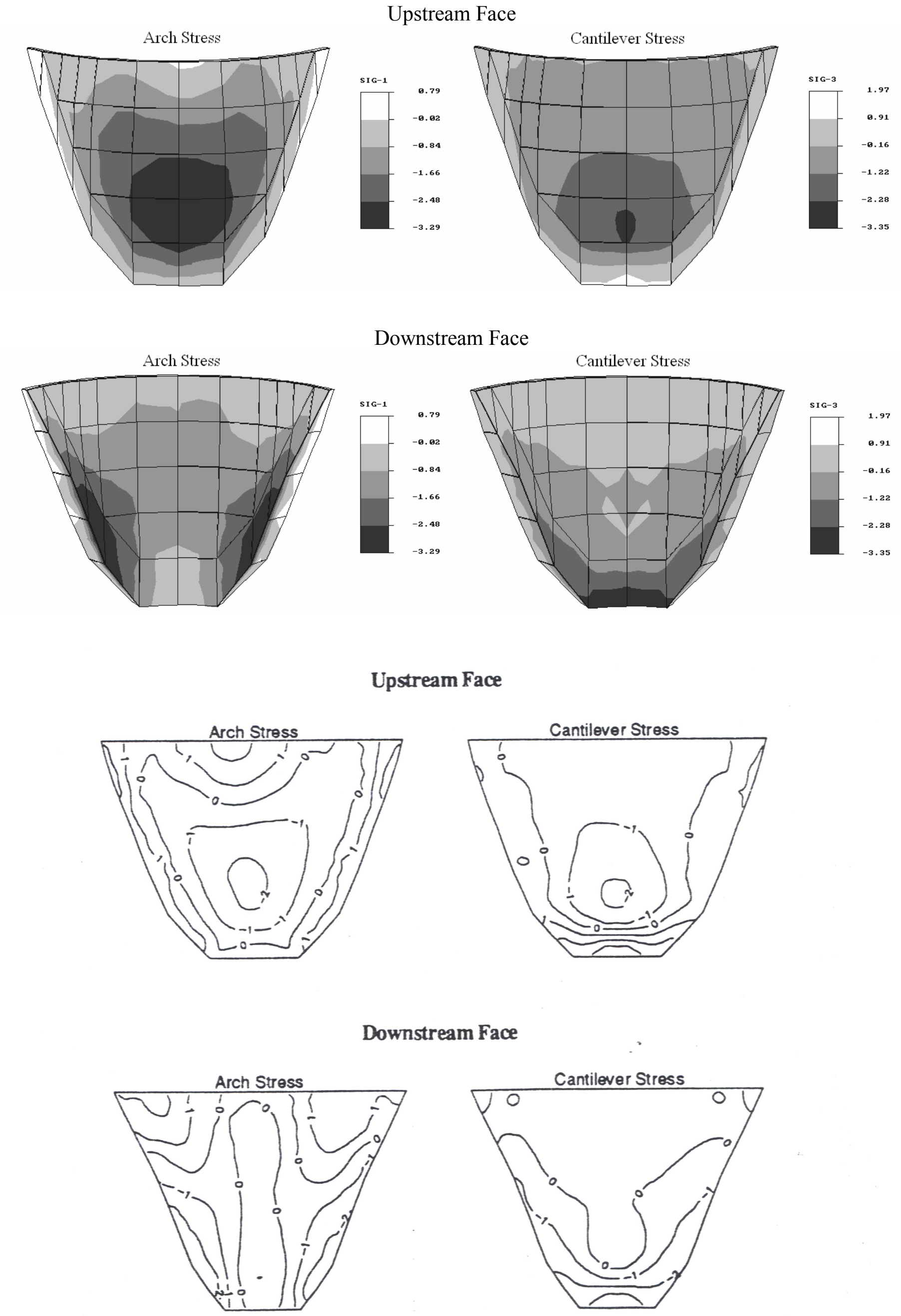

Figure (7) - Envelope values of the maximum arch and cantilever stresses (in MPa) due to upstream, vertical and cross-stream components, simultaneously, of Taft ground motion
(above: present study; below: the work of Tan and Chopra [1])

8. Conclusion

Some new techniques are integrated to develop an effective procedure to evaluate the earthquake response of the concrete arch dams including all relevant interaction effects in frequency domain. Of course, this procedure is based on the rigorous FE-(FE HE)-BE method. The improved ingredients of the effective approach can be summarized as follows:

- As mentioned, the 3D fluid hyper-element is normally utilized to model the reservoir far-field region, which may be considered as a very time-consuming process. To remedy this, the modified-efficient procedure was utilized, which greatly reduces the computational time. It was previously shown that the modified efficient procedure is a very robust and accurate method and it behaves extremely well under different conditions. It was noted in the present study that this helps to calculate the required impedance matrix throughout the frequency range for about seven times faster than the ordinary method. Therefore, this definitely forms an important part of the effective procedure as a suitable approach to model the far field part of the reservoir.

- The foundation impedance matrix is usually computed by the boundary element method. However, the computation of the foundation impedance matrix is a very time-consuming process. In the effective procedure, this impedance matrix is calculated only at a few selected frequencies and a cubic interpolation scheme is utilized to compute it for other frequencies, similar to the work of Tan and Chopra. It is worthwhile to emphasize that the main advantage of the present approach is that there are no limitations imposed as to the geometric shape of the canyon.

- Obviously, the modal techniques are more advantageous computationally in comparison to direct method due to large amount of degrees of freedoms present in a practical dam-reservoir-foundation rock discretization. However, there are different alternatives available for modal analysis of these systems. Herein, some new techniques are reviewed as approximate methods. Most of these approaches are relatively simple and avoid the programming complications encountered in the true modal approach of the dam-reservoir system. Additionally, the Pseudo symmetric subspace iteration method was employed as an alternative to solve the exact unsymmetric eigen-problem of the system and the true coupled modal approach was utilized subsequently. The effective approach is completely defined by selecting either one of the above-mentioned modal techniques. In other words, there are several options available for this part of the routine and the efficiency of each alternative is problem dependent and one cannot strongly recommend one over the others for all cases. However, one thing is certain that the coupled modal approach would produce the most accurate results for a fixed number of mode shapes utilized among different available alternatives mentioned for this part of the routine.

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