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SEISMIC WAVE PROPAGATION EFFECTS ON ARCH DAM RESPONSE

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SUMMARY

A finite and infinite element coupling system and a seismic input procedure for modelling arch dam performance during earthquake are presented. Taking into consideration the wave transmitting behavior of the system and wave propagation mechanism of the procedure, the free field motion along an arch dam canyon upon different incident waves can be obtained.Thus,the response of arch dams subjected to seismic waves can be evaluated. As an example of application, the response of the Er-Tan arch dam under the seismic wave propagation was analyzed. The results show that the dam response obtained by using the presented method is much smaller than that by using the homogeneous boundary input procedure.

INTRODUCTION

Numerical techniques for dealing with aseismic design and analysis of arch dams have been developed in recent years. In the aspects of dam and foundation interaction, one can view the foundation as a certain limited portion of flexible rock material by finite element discretization which is usually being used in arch dam design practice worldwide.As for the seismic input procedure,the common technique is to input earthquake motion or spectrum uniformly from artificial truncated boundaries assuming the foundation rock to be massless. This assumption ignores two important factors: spatial variation around the canyon in earthquake excitation and effects of radiation damping due to infinite foundation. Many authors have developed various techniques to consider these two factors. In this respect, a free field input method was developed by R.Clough[1]; various techniques called transmitting boundary for simulation of infinite foundation were also developed[2]; a direct seismic wave input procedure was provided[3]. Unfortunately,because of the scarcity of earthquake data,it is difficult at present to use these new techniques in aseismic design practice for arch dams. Nevertheless,to present these new techniques for taking into account the spatial variation of the motion around the canyon and the radiation damping of the infinite foundation still has an important significance in terms of aseismic analysis for arch dams.

A wave-input procedure for a finite and infinite element coupling system is presented herein.The seismic waves propagating from the far field are transformed into nodal dynamic loadings action on the finite element boundary where the reflecting waves from canyon surface can be transmitted back into the far field through the finite and infinite element system.The model is capable of simulating wave propagation and scattering mechanisms of an arbitrarily geometrical and some restricted geological conditions.The formulation of the model and wave input procedure has been described. The main effort of this paper was devoted to the application of the presented model to the seismic analysis of a 240 M high arch dam --Er Tan arch dam. The results of the dam response are compared with those of the traditional design and analysis procedure to obtain some insight as to the difference in the dam response between the new model and the traditional procedure.

ELEMENT FORMULATIONS AND WAVE INPUT PROCEDURES

In dealing with the wave propagation problems of canyon with geometrical irregularities and geological complexities, a coupling system of 2D finite and infinite elements has proved to be an effective procedure. The formulations of 3D infinite elements shown in Fig.1 have been discussed in [4].By coupling the infinite elements with finite elements the far field and near field for the canyon can be simulated.

As shown in Fig.2(A) the dam foundation is discretized into interior domain Ω_I(near field) modelled by finite elements and exterior domain Ω_E(far field) by infinite elements.The intersection boundary is also divided into input boundary Γ_λ and non-input boundary Γ_0 as shown in Fig.2(B). Assuming the input boundary Γ_λ between finite and infinite elements to be fixed, reflected stress at the fixed boundary due to input S and P waves can be evaluated. Imposing $-P_\lambda$ as nodal loads on to the boundary Γ_λ as shown in Fig.2(C), thus, the interaction problem between the structure and the foundation under a seismic wave input can be considered as the superposition effects of Fig.2(B) and Fig.2(C). Acturally,for the near field response only Fig.2(C) will give the final results of the problem since no response will occur in the near field under the fixed boundary condition shown in Fig.2(B).However,for the far field effects,both Fig.2(B) and (C) must be considered and superposed. For the model in Fig.2(C), assuming the media material has hysteretic properties, the dynamic equilibrium equation has the form:

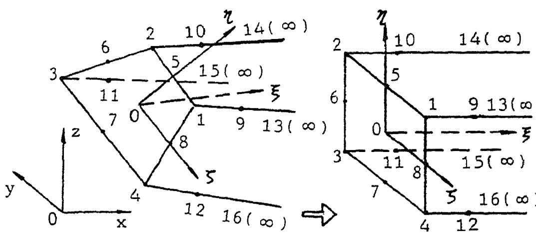


Fig.1 3D Infinite Element

$$\left\{ -\omega^2 \begin{bmatrix} m_{\lambda\lambda} & m_{\lambda o} \\ m_{o\lambda} & m_{oo} \end{bmatrix} + (1+i\eta_d) \begin{bmatrix} K_{\lambda\lambda} & K_{\lambda o} \\ K_{o\lambda} & K_{oo} \end{bmatrix} \right\} \begin{Bmatrix} \Delta_\lambda \\ \Delta_o \end{Bmatrix} = \begin{Bmatrix} P_\lambda \\ 0 \end{Bmatrix} \tag{1}$$

Where,Δ_λ and Δ_o represent the displacement vectors related to input degrees of freedom and remaining ones; η_d is the viscous coefficient;P_λ is the dynamic nodal load vector which can be evaluated by reflected stress at fixed boundary Γ_λ.

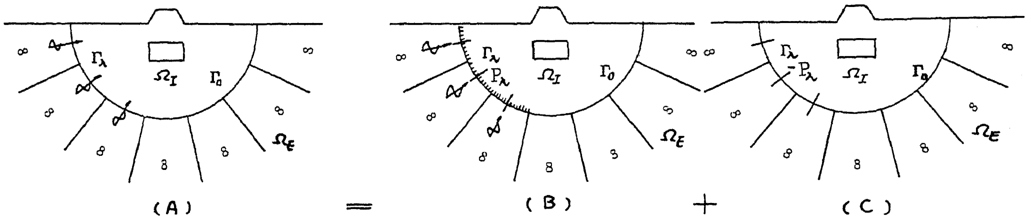


Fig.2 Coupling Model of F.E.M. and I.F.E.M.

The subvector for element e is given by

$$\{ P_\lambda \}^e = - \int_s [N]^T \{ \sigma \}^e \, ds \tag{2}$$

In which, $\{\sigma\}^e$ represents the reflected stress vector;and $[N]$ is the interpolation function matrix of the finite elements.The seismic wave input procedure mentioned above can be used in 2D and 3D structure and foundation systems under the harmonic wave propagation. As for the input of earthquake motions, the solution is obtained in the frequency domain by using Fourier analysis and synthesis. If a harmonic load vector $\{P_\lambda\}$ is acting at n nodes of the boundary, the displacement vector $\{w\}$ can be expressed as:

$$\{w\} = [H(\omega)]\{P_\lambda\} \tag{3}$$

Where, $[H(\omega)]$ is the transfer function matrix and has the form:

$$[H(\omega)] = [\ \{H_1(\omega)\}\ \ \{H_2(\omega)\}\ \ldots\ldots\ \{H_n(\omega)\}\ ] \tag{4}$$

Where, $\{H_i(\omega)\}$ is a vector of transfer function, i.e. the displacement response distribution due to a unit harmonic load acting at node i. If the same amplitude and phase of load $P_{\lambda o}$ for all n nodes are assumed then:

$$\{w\} = P_{\lambda o} \sum_{i=1}^{n} \{H_i(\omega)\} \tag{5}$$

ACCURACY VERIFICATION OF THE MODEL

Accuracy verifications of 2D and 3D problems were performed on a 2D semicircular canyon under harmonic SH wave propagation and a 3D dynamic impedance computation of a rigid foundation on an elastic half space.The results are satisfactorily accurate when compared with the analytical solution. Because of space limitation here, refer to [5] for detailed information.

SEISMIC WAVE RESPONSE OF THE ER-TAN ARCH DAM AND COMPARISON WITH THE RESULTS BY TRADITIONAL PROCEDURE

Er-Tan is a 240M high,double-curved arch dam and has a crest length of 700M and maximum thickness at the bottom of 70M.The seismic intensity at the dam site designated as MM VIII equivalent to peak acceleration of 0.2g is considered as the Design Earthquake. Two procedures, namely, the Wave Propagation Method (WPM) presented here and the Homogeneous Excitation Method (HEM) commonly used in arch dam aseismic analysis [6] were studied for comparison.

For WPM, the dam and the near field foundation were discretized into 70 16-node 3D isoparametric elements. The far field foundation was simulated by 78 3D infinite elements which were extended into 3-directions to model the semi-infinite foundation. The discretization of the system is shown in Fig.3. The parameters of the material are assumed as $E_c=E_r=3.15\times10^6 T/M^2$, $\gamma_c=\gamma_r=2.4\ T/M^3$, $\mu_c=\mu_r=1/6$.For HEM, the dam and rock foundation were simulated by 20 shell elements and 64 3D brick elements respectively. The foundation rock which extends to one dam hight in each direction was modelled as a massless spring.Other parameters of the material used in the HEM are exactly the same as the WPM. With regard to the components of the input waves, only SH wave input was considered for WPM and comparison was made with upstream-downstream excitation for HEM.

1. Input of Harmonic Wave

Three frequencies being ω_1=10 Rad/s; ω_2=30 Rad/s; ω_3=50 Rad/s of harmonic waves were chosen which come close to the fundamental; 10th to 11th; 20th to 21st mode frequencies of the system. Two angles of wave incidence including $\theta=0^\circ$ and $\theta=90^\circ$ equivalent to vertical underneath and horizontal wave propagation respectively are chosen for WPM while the excitations are homogeneously acting on all boundaries for HEM. Because of space limitation, only the concluding remarks are mentioned here. For detailed information refer to [5].The results indicated that the maximum displacement amplitude for HEM is 2 to 5 times as great as for WPM, but the displacement curve shapes are quite similar for the two models.The reason for such a great difference of the maximum displacements between the two models is, from the authors' point, mainly due to the phase and amplitude difference along the canyon wall, which has been clearly observed in the WPM but can not be considered in the HEM. Secondly, radiation damping for WPM may also take away a lot of wave energy to the far field and cause a reduction in the dam response.

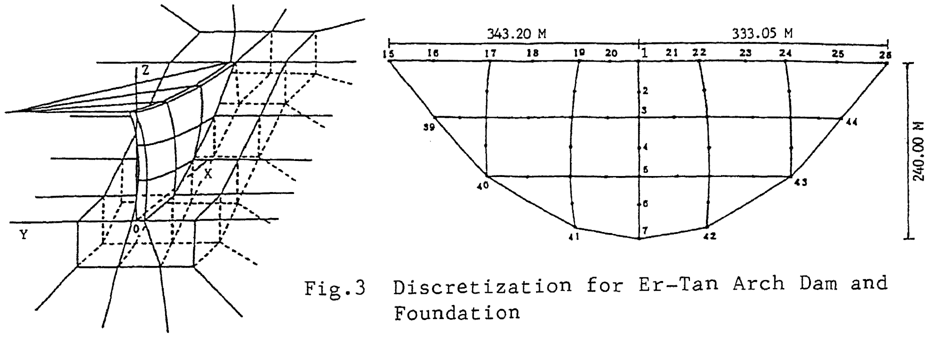


Fig.3 Discretization for Er-Tan Arch Dam and Foundation

2. Input of the Park Field Earthquake Motion

The time history of the Park Field Earthquake of June 27, 1966 was chosen as the input earthquake for both WPM and HEM. Only horizontal incident wave ($\theta=90^{\circ}$) was considered for WPM. The maximum acceleration of the Park Field record is 0.365g and was proportionally scaled to 0.2g based on the design criterion. The results are shown in Figs. 4–7 and following findings have been gained from the results.

1) Fig.4 shows displacement time histories of dam response at node #1(at the crown of the dam top)in up-downstream direction noting that the total displacement value was defined for WPM while the relative displacement with reference to the input boundary was defined for HEM. Evidently,both response frequencies are close to the fundamental frequency(10.8 Rad/s)and a similar wave shape can be seen for both models. Integrating the input earthquake acceleration twice to obtain displacement of the ground motion and adding it into the relative structure response given by HEM, an envelope of the total displacement along the top arch and crown cantilever can be obtained and is plotted in Fig.5 and compared with that given by WPM. The maximum displacements at the crown are 5.1cm and 3.0cm for HEM and WPM respectively.The displacements are 1.95cm and 0.95cm at the left abutment and 1.95cm and 0.3cm at the right abutment for HEM and WPM respectively. Evidently,the displacement distribution is basically symmetric for HEM while it shows an oblique pattern for WPM with the location of maximum displacement shifting to the left, and a very different response value between the left abutment from which the input wave is propagating in and the right abutment from which the output wave is transmitting away. Comparing the results with harmonic wave input conditions in [5] the same conclusion-significant reduction of the response by WPM-can still be drawn, but not as drastically as in the harmonic case. It is probably because of the averaging effect of the dam response due to different frequency components of the earthquake.

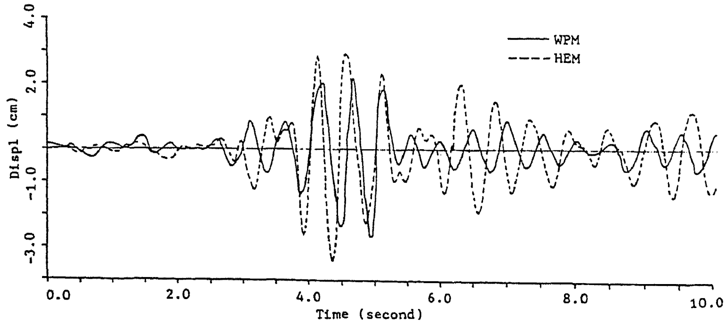


Fig.4 Displacement Time History at Node # 1

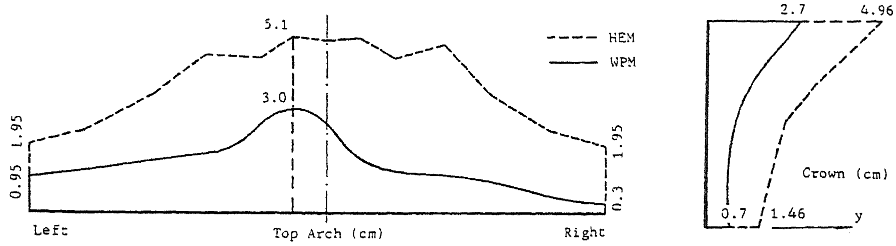


Fig.5 Maximum Displacement Envelope in Y Direction

2)Fig.6 shows iso-stress distribution in arch and cantilever direction. Like the displacement distribution, a symmetric pattern of the iso-stress curve for HEM is again observed, but a rather non-symmetric picture with a greater response occurring on the left portion is also evident for WPM. Maximum stresses are 18.5kg/cm^2 and 29.9kg/cm^2 in cantilever and arch for HEM and 8.7kg/cm^2 and 15.3kg/cm^2 in cantilever and arch for WPM which are about one half of the value of HEM. The locations in which the maximum stress occurs for WPM are near the upper part of the dam for arch stresses but near the lower part for cantilever stresses. The time histories of the maximum stresses are shown in Fig.7.

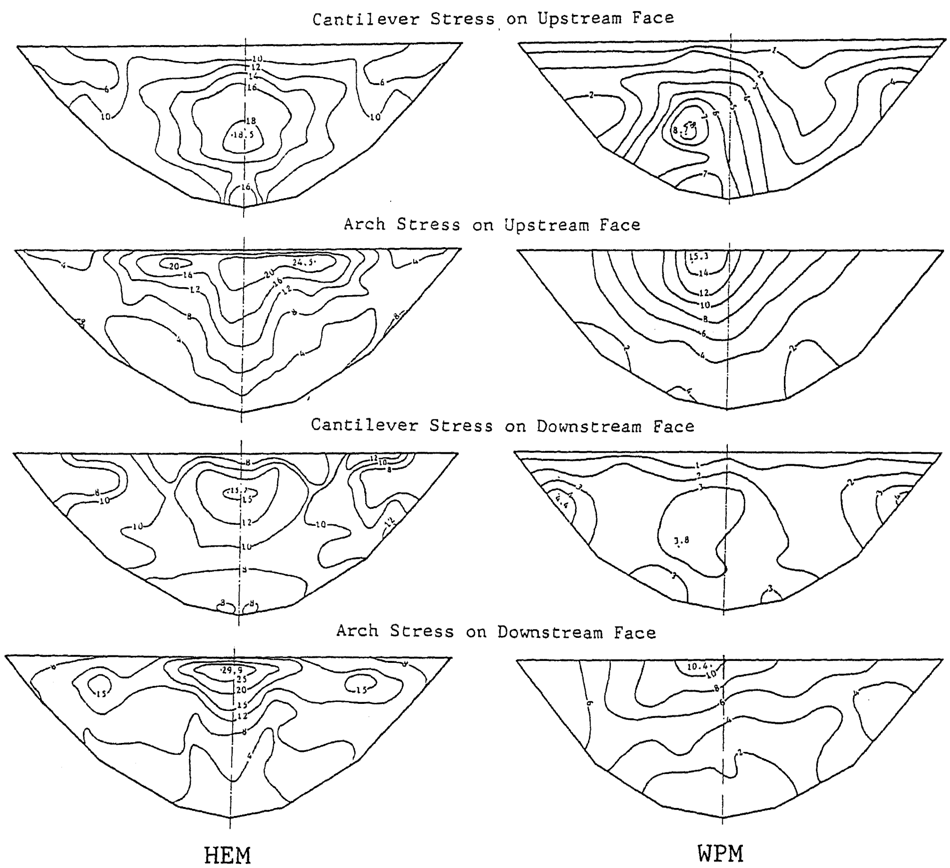


Fig.6 Maximum Stress Contour

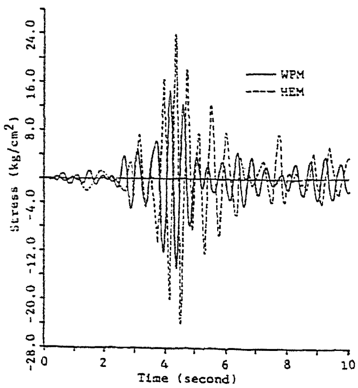
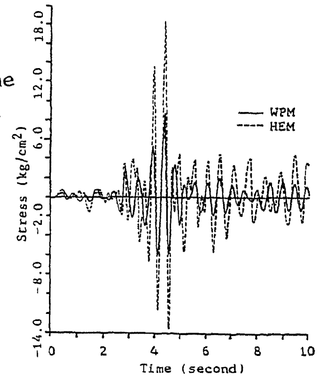


Fig.7 Maximum Stress Time History on Upstream face

Arch Stress

Cantilever Stress



CONCLUDING REMARKS

A new seismic input mechanism for arch dams-wave propagation method WPM--was presented and compared with the traditional homogeneous excitation method HEM. Drastic reductions of dam response for WPM upon harmonic waves and earthquake waves have been observed. Amplitude and phase difference around the canyon wall and radiation damping of the infinite foundation may be the explanation for such a reduction.The remaining problem is how to define the far field input earthquake wave and its spatial distribution. Much future research should be devoted to this aspect, especially to field measurement of the actual earthquake around the dam canyons. In any case, the study has revealed that the traditional method may overestimate the seismic response for long span structures such as arch dams and apparently needs to be improved.

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REFERENCES

1. Clough,R.W.,Chang,K.T.,Chen,H.Q.,Ghanaat,Y., Dynamic Interaction Effects in Arch Dams, Research Report UCB/EERC, UC Berkeley, June 1985.
2. Lysmer, J.,Kuhlemyer,R.L., Finite Dynamic Model for Infinite Media, J. Eng. Mech. Div., ASCE, EM4, 859-877 (1969).
3. Wong, H.L.,Trifunac, M.D., Scattering of Plane SH Waves by a Semilliptical Canyon, Earthquake Engineering and Structure Dynamics, 3, 157-169 (1974).
4. Zhang Chuhan, Zhao Chongbin, A Simulation of Elastic Wave Propagation for Dam Canyons, Euro-China Joint Seminor on Earthquake Engineering, June 9-14, 1986, Beijing, China.
5. Zhang Guangdou, Zhang Chuhan, Zhao Chongbin,Wang Guanglun, A New Seismic Wave Input Procedure for Arch Dam Foundations, Proceedings of China-US Workshop on Earthquake Behavior of Arch Dams, June 1-5, 1987, Beijing, China.
6. Clough, R.W.,Rapheal,J.M.,Mojtahedi, S., ADAP-A Computer Program for Static and Dynamic Analysis of Arch Dams, Research Report NO. EERC 73/14,UC Berkeley, June 1973.