https://doi.org/10.36375/prepare_u.iei.a121

A Review on Seismic Response of Concrete Arch Dam

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Abstract - Seismic safety of concrete arch dams are of significant concern as it may exhaust the social and economic wellbeing of humanity. Dam –Foundation and Dam-Reservoir interactions greatly influenced the dynamic behavior of arch dams. Under earthquake excitations, geological features of dam systems behave rigorously. Therefore, the evaluation of concrete arch dam involves the comprehensive inquisition of responses from the far–field and free-field boundaries. Models developed so far with simplified assumptions explicit the need for the identification of factors in the analysis and design of dam structures. Traditional analytical methods result in over-rigid dam structures that can upshot over-estimated stresses and strains. In the earlier researches, the foundation rocks were assumed massless. It easily simplifies the uncertainty in inertia and damping but gives inaccurate solutions. Thus, approximations in the dam-water-foundation system by ignoring the mainframe parameters play a crucial role in analyzing structure. Finite Element Method with relevant factors under consideration brings up the solution with most negligible errors. FE model calibrated with appropriate parameters will predict the exact behavior of dam structures under seismic excitations. This paper presents the review of research conducted on the concrete arch dam focusing on dam-foundation, dam–water interactions, massed and massless foundation, water compressibility, thermal variations, spatial variations in the ground motion, etc.

Keywords - Concrete Arch Dam; Dynamic analysis; Earthquake excitations; Foundation.

INTRODUCTION

Arch dam are the structures constructed across the canons for various purposes like irrigation, electricity. Under International Humanitarian Law, massive structures like dams should consider as ‘installations containing dangerous forces’ as their impact may result in the extermination of humanity. Therefore, seismic assessment of these structures is of prime importance in the current scenario. Dam structures primarily consist of three domains- Reservoir domain, Foundation domain, and Dam structure domain. During earthquake excitation this domain behaves unpredictably, resulting in a coupling system. Thus, the interactions of this system govern the seismic safety assessment of concrete arch dam.

Fig.1 Morrow Point Dam, Colorado.

Ka-lun Fok and Anil K. Chopra [1] studied the effect of dam- water interaction in the dynamic responses of Morrow Point arch dam subjected to Taft ground motion. Paul S Nowak and John F. Hall [2] investigated the effects of non-uniform earthquake input on the response of concrete arch dams. Orlando Maeso *et al.* [3] presented Boundary Element (BE) technique to analyze the seismic response of dam structures. This technique incorporated various masked parameters in the previous studies. However, most of the standard analysis introduced in the determination of concrete arch dam considered only the effect of foundation flexibility. Hanchen Tan and Anil K. Chopra [4] identified a new analytical technique to point out the importance of foundation inertia and damping effect in the interaction studies of an arch dam. Orlando Maeso *et al.* [5] discussed influence of the spatial distribution of earthquake wave input on the performance of dam structures. Anil K. Chopra [6] investigated on the various factors, which have to study for the entire dynamic behaviour of concrete arch dam. He found that dam-water interaction, dam-foundation interaction, water compressibility, spatial variation of earthquake excitation has a profound impact on the realistic response of arch dam.

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A. Effect of Dam -Foundation Interaction

Orlando Maeso and Jose Dominguez [3] investigated the seismic response of Morrow Point arch dam in 1993, considering the dam-foundation interaction in empty reservoir conditions. Boundary Element (BE) technique was developed in the frequency domain for the earthquake analysis of the dam foundation system. Boundary elements of the dam structure were idealized as triangular and quadrilateral elements. The foundation rock of the structure was assumed linear viscoelastic and damping, mass properties was incorporated in the study. Vertically Incident P waves and S waves were applied to the structure to stimulate the condition. It was concluded from the study that the fundamental resonant frequency of the compliant foundation dam was considerably reduced compared to the rigid foundation. Peak response of the dam was also reduced due to the foundation interaction and travelling - wave effects.

Hanchen Tan and Anil K Chopra [4] proposed a Morrow Point Arch dam model with dam body as combined finite element, reservoir as continuum idealization of the impounded water body, and foundation rock idealized with Boundary element formulation. The dam system was excited to Taft ground motion with upstream (x), vertical (y), and cross-stream (z) components of accelerations. The analytical procedure presented in the paper concluded that standard procedure of analysis only considered the flexibility feature of the foundation rock, which overestimates earthquake-induced peak stresses on the dam body. Dam-foundation interaction increases the tensile stresses, but it does not affect the overall stress distribution on the dam faces. The impounded reservoir behind the dam has more significant influence in determining stresses induced in the dam body but had the least hand once the foundation rock interactions was considered.

Xiuli Du, Yanhong Zhang, and Boyan Zhang [5] investigated the influence of foundation properties in the non-linear seismic response of arch dams. The study was carried out on the Xiaowan arch dam and discussed the influences of energy dispersion, nonlinearity, and non-homogeneity of foundation rock in the seismic responses of an arch dam. The dam -foundation system discretized into an interior region for dam body, and its near field foundation is idealized with natural geological properties and infinite far-field foundation with homogeneous features. The proposed model was a combination of explicit FEM and transmitting boundaries. It is concluded that energy dispersion in infinite foundation reduced the arch and cantilever by 20-40%and also increases the principal stresses in the upstream and downstream surfaces near the abutments.

A. Ferdousi [6] performed a non-linear dynamic analysis on the seismic performance of arch dam, considering the effect of material properties of a discontinuous foundation. Karun-4 Dam was chosen for the case study analysis. A 3 D model was set up in ANSYS to simulate the geometric characteristics and dimensions of the dam. FE models created was applied with both static and dynamic loads. Several cases of the massive foundation were modeled in the time domain to study the effect of foundation interaction during seismic excitations. The results obtained from the study concluded that seismic responses of dam-reservoir foundation system were significantly influenced by the material nonlinearity, presence of various discontinuities and its non-homogeneity and far field boundary condition.

Zhang L, Liu YR, Yang Q, and Chen Y [7] investigated the stability analysis of the Baihetan arch dam using the comprehensive analysis method. A geo-mechanical model test and 3D finite element analysis set up to study the arch dam's failure pattern and deformation behavior. A comprehensive method of analysis coupled the effect of overload from upstream and strength reduction effects of weak structural planes. The results from the study showed that the Baihetan arch dam meets the stability criterion but proposed reinforcement treatment in the middle-upper part of the left dam abutment

B. Effect of Dam- Reservoir Interaction

Ka -Lun Fok and Anil K. Chopra [1] investigated hydrodynamic effects in the seismic response of arch dams. Response of Morrow point Dam to the Taft motion subjected to study for various reservoir boundary materials. The study focused mainly on the effects of reservoir boundary by taking various assumptions and disregarded the effect of inertial and damping effects. Hydrodynamic effects can increase the displacements and stress responses in upstream and downstream faces. The study concluded that Dam-water interaction increases the responses of arch dam subjected to seismic forces, whereas the reservoir boundary absorption decreases the same. Assumption of rigid reservoir boundary condition overestimates the arch stresses and cantilever stresses in both sides of an arch dam.

Rihui Yang, C. S. Tsai and G.C. Lee [8] presented a study on the far-field modeling of the impounded reservoir in the dam-reservoir interaction of arch dam. Reservoir region of dam modeled as newer field with nonlinear properties and far-field with a linear and uniform cross-section. This transmitting boundary developed for 3D analysis could take up radiation conditions and water compressibility. Idealization of near end of reservoir with far end need better discretization in terms of static load and boundary nonlinearity. The incorporation of transmitting boundaries in the finite element model represents the exact boundary condition to a certain level.

Orlando Maeso and Jose Dominquez [3] investigated the response of arch dam under the influence of dam-water interaction by incorporating BE technique. The reservoir domain in the finite element model was studied with infinite open reservoir and closed symmetric and unsymmetric reservoir. The size of the domain was determined based on the wavelength of water waves. Responses observed had greater influences when the reservoir is in full condition. Different geometry conditions of the reservoir with rigid and compliant foundations must be studied with greater importance as it can upshot the responses of an arch dam.

Du Xiuli and Wang Jin ting [9] investigated the effect of water compressibility in the earthquake response of the Xiaowan Arch dam. The study focused on comparing f added mass model and compressible reservoir model in terms of absolute maximum tensile and compressive stresses, displacement, and acceleration. Reservoir modelled for average water level and low water level in the history of the dam site. The study concluded that the absolute maximum displacement and acceleration of the dam at both water levels were substantial in added mass model. Maximum compressive and tensile stresses were overestimated compared to the compressible water model. Moreover, arch tensile stresses at the crown portion were found to be 20% more than the conventional method of analysis.

Baris Sevim, Alemdar Bayraktar, and Ahmet Can Altunisik [10] studied the finite element calibration of Berke Arch Dam using Operational Modal Testing. The study involved both experimental and analytical parts in which a 3D finite element model of the Berke arch dam modelled using ANSYS software. In order to find the natural frequencies, mode shapes, and damping ratios, Enhanced Frequency Domain Decomposition Technique was used experimentally. Differences in analytical and experimental methods minimized after calibrating the FE model with real material properties. Calibrating FE model with actual material properties minimizes the difference in analytical and experimental results.

C. Effect of Spatially Varying Ground Motion

Orlando Maeso, Juan J. Aznarez, and Jose Dominguez [11] investigated the influence of the spatial distribution of seismic excitation and geometry of canon on the seismic response of Morrow point arch dam. A three-dimensional boundary element model was set up for understanding the interaction effects in arch dams. P waves, SV waves, SH waves, and Rayleigh waves were allowed to impinge on the dam from different directions. It was found from the study that the direction of propagation had profound influence on the seismic response of arch dam when the reservoir is in modelled full condition. Displacement values of uniform canyon geometry massively altered canyon geometry was modeled irregular. From the study, it was concluded that stress pattern on the dam surfaces was similar. However spatial variations in ground motion caused larger values of cantilever stresses in the region of the dam closer to the dam foundation rock.

Anil K. Chopra and Jin-Tin Wang [10] studied the responses of two arch dam, namely; Mauvoisin Dam and Pacoima dam, to spatially varying excitations. A linear analysis program was developed in EACD-3D-2008 model that included foundation mass and water compressibility. Compression and shear wave excitations have impinged on dam system, and appropriate time delay was also applied. Peak values of tensile and cantilever stresses were prominent in spatially varying ground motion.

Jin-Ting, Feng Jin, and Chu-Han Zhang [12] studied the non-linear response of arch dam to spatially varying ground input. A comprehensive model developed which accommodates radiation damping in the canyon and non-homogeneity in foundation rock. The seismic damage of the Pacoima dam was analyzed with the model and found to agree precisely with the actual crack pattern on the dam surface. Incident waves and free waves are introduced in the model at the foundation rock bottom and the dam foundation interface, respectively. Studies showed that the earthquake input mechanism had a profound influence on the dam failure pattern..

Enrico Zacchei, Jose Luis Molina, and Reyolando M.L.R.F [13] investigated degradation analysis of Arch dam blocks using deterministic and probabilistic earthquake excitations. Earthquake input generated from the probabilistic and deterministic seismic analysis. A plasticity model has been generated with a reduced value of elasto-plastic modulus. The studies concluded that reduced elastic-plastic modulus could increase the flexibility of the dam in 3D analysis.

D. Effect of Vertical contraction joints in concrete arch dam

J R Mays and L. H Roehm [14] found the effect of vertical joints in arch dams using a discrete crack model in ADINA software. A linear and non-linear analysis of East canyon Dam with three vertical contraction joints modeled in the study. In the linear analysis, water load was applied as the hydrostatic load applied in a single step whereas several step loads have impinged on the dam in non-linear analysis. The three components of Koyna earthquake, factored to some scale was used as seismic excitations. The study concluded that nonlinear analysis with vertical contraction joints reduced the arch tensile stresses from11.6 N/mm^2 to 6.9 N/mm^2.

M.T Ahmadi, M. Izadinia, and H. Bachmann [15] investigated the non-linear dynamic response of Morrow point Arch Dam using the discrete crack joint model. Half of the dam model modeled with three contraction joints in ANSYS software. It was revealed from the study that the dam body with contraction joints was shifted up to 8cm permanently in the upstream face.

Conclusions

From the comprehensive literature review, the following conclusions can be drawn

- Neglecting the effect of nonlinearity and discontinuity on the foundation strata, damping effect can overestimate the principal stresses in the dam system by a factor of 2-3. Flexibility parameters in foundation strata reduce the amplitude and fundamental frequency in dam structure. Foundation modelled as non-homogenous and discontinuous can induce maximum sliding joints in the system.
- Reservoir with the empty and full condition has more significant influence in the seismic response of arch dam. The inclusion of impounded water in the dam system can increase crest displacement, and arch/ cantilever stresses, especially on the upstream face.
- Angle of incidence of seismic waves has profound influence in response of arch dam since the fundamental frequency can be altered up to 20% [14]. Stress pattern on the dam surfaces was found similar in both uniform and non-uniform excitations, but peak values of stresses increase in spatial non-uniform excitations.
- Literature surveys show that incorporating vertical contraction joints make the dam responses more realistic to the actual conditions.

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