Present and Future Roles of Nonlinear Numerical Procedures in the Seismic Analysis of Concrete Dams

by

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ABSTRACT

This purpose of this paper is to discuss the present and possible future roles of nonlinear numerical procedures in the seismic analysis of concrete dams. The application of nonlinear analysis procedures is pivotal for the rigorous seismic evaluation of these critical structures. The objective of these analysis procedures is to quantify accurately the extent of seismically induced damage. These type of approaches have the potential for determining the ultimate capacity of existing concrete dams by the appropriate modeling of nonlinear phenomena such as material behavior, interaction of monolith vertical joints, and behavior of horizontal lift joints. Some numerical procedures have been successfully developed to model the material nonlinear properties. Other procedures have been formulated to represent the dynamic behavior the joints. However, because of their inherent complexities and the difficulties involved in the determination of their parameters, nonlinear analyses may not be particularly suited for the design phase. On the other hand, linear analyses usually render a great amount of insight into the expected behavior of the system, but they can not predict accurately the extension of damage that may occur under moderate or strong ground motions. This situation opens an alternative avenue for the application of nonlinear models, in the form of the development of assessment tools based on nonlinear parametric studies, which can be used to obtain an estimate of the real performance of the system using the information provided by a linear elastic analysis.

KEYWORDS: Concrete dams; nonlinear response; tensile cracking; joint behavior; smeared crack model; scaled model experiments.

1. INTRODUCTION

A significant body of research has been devoted in the last thirty years to the study of the dynamic behavior of concrete dams under seismic excitations. Several extensive numerical studies have evaluated the influence of different interaction phenomena influencing the dynamic response. Many of these analyses were based on linear models and performed in the frequency domain. Although restricted by the linearity assumption, undoubtedly these types of studies still provide a great deal of information about the earthquake response that can be expected under more realistic conditions (NRC Panel, 1990). However, it is clear that severe ground motions could trigger different response mechanisms not predicted by the linear analysis. For example, dynamic stresses caused by strong earthquakes may create areas of localized damage, mostly associated with the low tensile strength of the mass concrete. In particular, seismically induced cracking is likely to occur along lift joints, which constitute inherent planes of weakness. Another nonlinear effects are related to the contraction joints between monoliths, which may move relative to each other during the seismic event, thus inducing the cyclic opening, closing and sliding motion of the joint. Additionally, the overall response of the system under severe excitations may be influenced by the spatial variation of the ground

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motion. In summary, the characteristics of the system when exposed to strong ground motions are such that the response will differ from that obtained under the assumption of linear behavior. The rigorous evaluation of the seismic response should take into account these features. However, the situation is complicated by the fact that any sophisticated constitutive model should be used in conjunction with a set of material parameters that can be experimentally determined with some appropriate confidence level.

It is widely accepted that the nonlinear behavior of concrete under compressive states it is not one of the most critical factors affecting the characteristics of the seismic response of dams (NRC Panel, 1990). On the other hand, the appropriate constitutive modeling of the material behavior under tensile conditions constitutes a substantial feature that undoubtedly needs to be incorporated into the analysis. Some of the most relevant efforts presented in the literature aiming to incorporate these nonlinear characteristics into the analysis are discussed next. This is not intended to be a state-of-the-art review, but just a description of only some of the relevant contributions in the field.

In a pioneering work, Pal (1986) studied the two-dimensional seismic response of the tallest non-overflow monolith of Koyna Dam (India), using a smeared crack approach to model tensile cracking. The smeared crack model is a finite-element modeling approach intended to capture the characteristics of the response under tensile conditions. This model monitors the stress/strain conditions at pre-specified points in the finite-element mesh. Crack initiation and propagation are defined in terms of some appropriate local criteria. After cracking, the local material properties are modified by introducing an orthotropic constitutive model whose orientation depends on the cracking plane. Mlakar (1987) studied the nonlinear response of three different gravity dam sections subjected to seismic ground motion. The dam sections, with different heights, were selected to be representative of the most common designs. A commercial, general-purpose finite element code was used, with a linear constitutive model in compression and tension, coupled with a smeared crack model. Approximate strain rate enhancements were used to define the material parameters, and particular consideration was given to the selection of the time history used for analysis. The hydrodynamic effects were approximated using Westergaard's assumption, which was implemented through lumped added masses distributed along the upstream face. The numerical simulations showed that the example sections cracked completely across the width, with most of the cracking phenomena initiating at the upstream edge of the base, and at the locations of abrupt slope change along the downstream face. The study demonstrated that the approximate representation of damage by means of additional damping in the corresponding linear model does not capture the characteristics of the nonlinear response. Mao and Taylor (1997) performed the same type of parametric study, but focusing on the response of medium-height gravity dams. They reported similar numerical behavior, with cracked areas usually concentrated near slope changes, which propagated almost instantaneously after initiation once the intensity of the excitation exceeded a critical value.

Vargas-Loli and Fenves (1989) carried out an extensive numerical study of the two-dimensional seismic response of Pine Flat Dam (USA) using a smeared crack model based on an equivalent tensile strength criterion. The tensile strength was defined as a function of the element size and the fracture energy of the material, but the computed values were considered too small and they were arbitrarily scaled up. The internal damping effects in the dam were modeled by damping proportional to the tangent stiffness matrix. The fluid domain was modeled using a mixed pressure-displacement formulation, which resulted in a symmetric matrix description for the coupled fluid-structure system. The reservoir model was truncated at a finite length with an appropriate boundary condition. Also, a partially absorbing boundary condition was used to model the bottom of the reservoir. Both empty and full reservoir conditions were examined, using ground motions scaled to various peak acceleration values to investigate the influence of the excitation amplitude on the nonlinear response. This study showed that diffuse cracking patterns are likely to occur near stress concentration areas. In most cases, the ground excitation levels that induced crack initiation also generated severe damage by extensive crack propagation, forcing the structural system to reach its ultimate condition. In this context, the ultimate condition is defined as the system's condition immediately before loss of convergence in the numerical solution.

Another comprehensive study of the nonlinear seismic response of Pine Flat Dam was presented by El-Aidi and Hall (1989a, b). By defining a fictitious length normal to the two-dimensional dam section, they modeled the effects of the flexible foundation by using a frequency-independent approximation of a three-dimensional viscoelastic half-space. The hydrodynamic effects were incorporated by means of a displacement-based finite element model of the reservoir, truncated at a finite length. The irrotationality condition for the fluid domain was enforced through a penalty formulation, and a bilinear pressure-volumetric strain relationship was used to account for cavitation phenomena. Energy dissipation effects at the boundaries of the reservoir model were incorporated through an approximation based on the one-dimensional wave propagation problem normal to the corresponding interface. Following the approach commonly used for frequency-domain linear analyses (Hall and Chopra, 1982), the energy dissipation characteristics associated with a non-rigid reservoir bottom were defined in terms of a constant parameter, referred to as the reflection coefficient. The tensile behavior of the concrete was represented using the smeared crack approach. Crack propagation was governed by an element-dependent strength criterion applied to the elements ahead of the crack tip. The numerical simulation of the system response was performed in an interactive environment, where the propagation of cracks was ultimately controlled by the analyst, in an effort to avoid spurious cracking patterns. Global damping characteristics were modeled by a damping matrix proportional to the elastic stiffness matrix, with removal of the damping contributions corresponding to cracked elements. The numerical results showed that, in general, the occurrence of cracking in a dam is associated with a reduction of the dynamic pressures in the fluid domain, therefore decreasing the importance of cavitation phenomena.

The behavior of contraction and lift joints constitutes another important source of nonlinear effects. Lift joints could be introduced in the model as planes of weakness with low tensile strength (attributed to inter-lift bonding), whereas contraction joints should be in most cases treated directly as discontinuity planes. Ideally, the numerical models for both types of joints should account for the opening, closing and frictional sliding of the interfaces with the associated energy dissipation mechanisms. These planes of weakness could be introduced in the finite-element model by using the smeared crack approach with pre-defined crack orientations corresponding to the joints. Alternatively, the joints could be modeled explicitly using special elements. For example, the joint interfaces could be connected through a set of nonlinear spring elements acting in parallel. This arrangement introduces many additional degrees of freedom, because it requires a double-node discretization of the interface in which the spring ends connect the corresponding nodes of each surface defining the interface. In an attempt to partially circumvent this drawback, Hall and co-workers (Hall and Dowling, 1985; Dowling and Hall, 1989) developed a nonlinear element to model the two-dimensional opening and closing of joints for the analysis of arch dams. The advantage of this element is that it can be used straightforwardly with a single-element discretization of the dam, because it does not depend on additional degrees of freedom along the thickness direction. The joint behavior is represented by only two nonlinear torsional and translational springs. Equivalent stiffness parameters, as well as the offset of the translational spring are calibrated by numerically solving a representative problem in which the joint is modeled by means of a multi-spring arrangement, which spans the width. The proposed element was used to simulate the seismic response of Pacoima Dam (USA). The analysis took into account the effects of the elastic foundation and the impounded reservoir, both modeled also by finite elements. The compressibility of the fluid was neglected, and a heuristic scheme was applied to incorporate the matrices corresponding to the foundation and fluid domains after condensation of the non-relevant degrees of freedom. The numerical results showed that significant separation of the contraction joints could be expected even under moderate levels of excitation. This would indicate the need to expand the analysis by including the possibility of relative sliding of the interfaces, which was not considered in the proposed joint element. Hall (1998) recently presented a study of the effects of cracks and contraction joints on the response of arch dams. The numerical model was based on the smeared crack approach. In this particular implementation of this versatile approach, the orientation of the cracking planes was pre-determined to simulate only the cracking induced by the cantilever stresses. As in previous works, the foundation was considered elastic and massless, and the fluid was assumed incompressible. Joint sliding effects were introduced in the formulation in the form of friction criteria limiting the magnitude of the corresponding shear stresses. The numerical results showed that the proposed formulation is able to capture the most important features of the nonlinear dynamic response with a reasonable computational cost.

2. LIMITATION OF PRESENT ROLES

As discussed in the previous section, several analytical procedures have been formulated to predict the two- and three-dimensional nonlinear seismic response of concrete dams. However, the structural response predictions obtained by means of these nonlinear analytical procedures are directly dependent on the availability and quality of the input parameters used to define the model representing the nonlinear behavior. While data is readily obtainable for simple material experiment or scaled model experiments, this is not the case with the full-scale data necessary for the proper validation of these complex procedures.

The response measurements needed to describe the actual seismic behavior of a concrete dam can be obtained from actual earthquake events, full-scale experiments, and scaled model experiments (Hall, 1988). There have been several cases of concrete dams suffering moderate or significant damage caused by seismic excitations. However, since no concrete dam has ever failed from earthquake ground motions, measurements of the dynamic response of a concrete dam beyond its ultimate capacity have not been recorded. A very well known case of damage to a concrete dam occurred in 11 December 1967 to the Koyna Dam (India). The damage to this structure consisted of significant cracking in the upper section of several monoliths, with cracks initiating near the points of abrupt slope change in the downstream face. The Sefid Rud (Iran) and the Hsinfengkiang (China) are concrete buttress dams that experienced cracking in the upper sections as a result of earthquake ground motions. The left thrust block and abutment of the Pacoima Dam (a concrete arch structure) experienced some damage during the 1994 Northridge earthquake. Since it is at best difficult to predict which dams are going to be subjected to earthquake ground motions, the effective placement of the instrumentation needed for interpretation of any observed seismic damage becomes practically impossible.

Forced vibration prototype experiments have been performed on many different concrete dams (Hall, 1988). These experiments have determined the dynamic properties of these complex structures and have identified the importance of interactions between the reservoir, foundation rock, and the concrete structure. The data from these experiments provides fundamental results, which can be used to validate linear elastic numerical procedures. However, forced vibration experiments do not reproduce the performance of these structures during an earthquake since the external excitation is placed on the crest of the dam. The use of explosives to generate the excitation provides an alternative approach to determine the characteristics of the dynamic performance of a dam, as shown by Ghanaat and co-workers (1993) through a series of experimental tests performed on the Dongjiang Dam (China). The results of these experiments validated the fact that the high frequency ground motions generated by controlled explosions can be effectively used to excite the low frequency fundamental dynamic characteristics of the system. This type of experiments shows the advantage of simulating more closely a real earthquake event, since they excite the structure with hydrodynamic loads and with ground movements, thus providing important data for the study of the complex dam-foundation-reservoir interaction phenomena. It is clear that these experiments must be performed in extremely controlled conditions and they must be limited to exciting only the linear elastic response of the structure, avoiding the occurrence of damage.

The lack of measured data that describes the response characteristics under conditions of extreme damage, and the practical limitations of the approaches currently used for full-scale experiments have emphasized the importance of scaled model studies. This type of experiments provides a very effective framework for the study of the dynamic nonlinear performance of concrete dams. Nonlinear scaled model experiments must follow certain laws of similitude. In order to model the hydrodynamic loads on a dam neglecting the foundation effects, the ratio of the density of the model fluid to the density of the water in the reservoir must be identical to the ratio of the model concrete density to the prototype concrete density (Donlon, 1989). Since the density of most heavy fluids is no more than a factor of two greater than that of water, scaled model studies cannot accurately model all the influences of fluid-structure interaction. Even though exact similitude laws have not been followed, these experiments have provided useful data for investigating the nonlinear seismic response of concrete dams.

3. FUTURE ROLES

Currently, there are several sophisticated numerical models that can be used to represent the nonlinear response of concrete dams. The central issue is their calibration by using experimental results obtained at the appropriate scale. The focus of the calibration process should shift from representing accurately the response to a particular ground motion to reproduce accurately the average response characteristics when the system is subjected to an ensemble of ground motions. The final decision regarding the safety of the dam should not be based only on the accurate description of a particular crack, at a particular elevation, for a particular excitation. The uncertainties in the material input data and the underlying approximations in the numerical implementation do not seem to encourage an engineer's decision based only on the results of time-history nonlinear analyses without consideration of the influence that changes in the input parameters might have on the global response. It is clear that the results of even the most rigorous nonlinear numerical procedures need to be coupled with the appropriate engineering judgment.

The analyst should be provided not only with a reliable nonlinear numerical model of the dam-foundation-reservoir system, but also with an effective and rational tool for the proper interpretation of the corresponding results. In this framework, computationally efficient nonlinear models could be used in large-scale parametric studies, aiming to provide the engineer with enough information and facilitating a sound decision when the analyst is faced with a particular situation. Sensitivity analyses should provide an adequate framework to establish the importance and relative influence of the parameters used to describe the nonlinear behavior of the system. This is facilitated by the fact that extensive parametric studies are now feasible with a reasonable computational cost. In turn, this type of studies could be used to calibrate assessment tools based on linear analysis results. These assessment tools could use the results from linear analyses to identify the severity of the average damage that could be expected for a particular situation. In principle, one could perform this by means of regression analyses, aiming to establish a relationship between the characteristics of the ground motion, the characteristics of the structure and the level of damage that can be expected. This relationship between the input excitation, the system characteristics and the resulting damage is expected to be highly nonlinear and it would depend on the response parameter(s) used to quantify the damage level. Perhaps, a more efficient and flexible approach is the use of neural networks and fuzzy systems to render an approximate quantification of the expected damage for a given set of input and system parameters. Cret and Katayama (1992) used a model for damage prediction of lifeline systems based on fuzzy logic. The proposed model generates a quick estimate of the severity of the earthquake-induced damage in terms of selected ground motion characteristics. Molas and Yamazaki (1995) proposed a damage-estimation system based on a neural-network model, which is used to correlate certain ground-motion indices with the damage suffered by building structures. The spectrum intensity and the peak ground acceleration, velocity, and displacement values were among the different indices used to describe the ground-motion characteristics. A representative nonlinear structural system was selected for training, and the damage suffered by the structure for a given ground motion was quantified in terms of the corresponding ductility factor. This work shows the applicability and potential usefulness of neural-network based systems for damage estimation. Once the system has been trained for an appropriate ensemble of ground motions, estimation of expected damage can be performed in a simple and quick way. The only computational burden lies on the training process, though in most cases it could be handled speedily by current computational resources.

4. CONCLUSIONS

The rigorous seismic evaluation of concrete dams requires an accurate quantification of the damage that can occur under earthquake excitations. Nonlinear analysis procedures can identify the ultimate capacity of existing concrete dams taking into account the most critical nonlinear phenomena controlling the response. However, the complexity of these procedures and the scarcity of appropriate calibration strategies frequently force the analyst to interpret the corresponding results using the best engineering judgment. The influence of the input parameters and ground excitation on the nonlinear dynamic response should be investigated by sensitivity studies that aim to identify the most critical conditions. The available nonlinear analysis schemes could be used to develop a rational assessment tool, which could provide a systematic estimation of the expected average damage based on the input ground motion characteristics and the material and geometric parameters defining the structural system. This would provide the analyst with a useful reference framework for the adequate interpretation of results.

5. ACKNOWLEDGEMENTS

This study was sponsored by the Civil Works Earthquake Engineering Research Program of the U.S. Army Engineer Waterways Experiment Station in Vicksburg, MS. We appreciate the cooperation of the authorities at the U.S. Army Engineer Waterways Experiment Station, which permitted us to prepare and present this paper. Permission to publish this paper was granted by the Chief of Engineers, U.S. Army Corps of Engineers.

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