ICOLD Symposium on Sustainable Development of Dams and River Basins, 24th - 27th February, 2021, New Delhi

ROAD MAP FOR ADVANCED STRUCTURAL ANALYSIS OF CONCRETE DAMS

J.W. SALAMON
U.S. Bureau of Reclamation, USA

B. JEREMIC
University of California, Davis, USA

ABSTRACT

The Advanced Structural Analysis (ASA) has become a primary tool in structural assessments of concrete dams. Expanded computing power currently available to engineers allows conducting com-plex structural simulations of dam behavior for static and seismic loads, which are used to describe the potential failure modes of the structure. The outcome of such analyses serves as a baseline for estimating risk in dam safety investigations.

In this paper, a road map for the ASA of concrete dams is presented, together with a general dis-cussion on the uncertainties of such analyses. A hierarchy of computational model verifications of concrete dam simulations is also discussed. The authors start with a general discussion on conceptual and mathematical models for concrete dams and verification tests for computational models. In addi-tion, available physical tests are reviewed, and their suitability for validation is assessed.

Finally, a flowchart (road map) for modeling and simulation of concrete dams is presented. Exam-ples are used to illustrate the points discussed above, and draft practical guidelines are presented with the aim of stimulating further discussion.

1. INTRODUCTION

The Advanced Structural Analysis (ASA), defined here as a static or dynamic analysis with nonline-arities, is an essential part of a risk assessment for concrete dams. During the last three decades, time history analyses with material and geometric nonlinearities, together with nonlinear boundary condi-tions, have been increasingly used in the engineering practice. Technical complexity and mathemati-cal advancement of such analyses require the analysts to have a high-level technical education, knowledge and experience in numerical solutions of structural problems, good skills in using the software, and expertise in concrete dams.

The primary concern is the level of confidence in modeling and the accuracy evaluation of the analysis results. Verification and validation (V&V) of such computational simulations are the primary methods used to build such confidence and are used for quantifying accuracy of the solutions.

Importance of the V&V process in the ASA of concrete and earth dams has been emphasized and discussed in various publications of the International Commission on Large Dams (ICOLD) (ICOLD 1994, ICOLD 2001, ICOLD 2013) and at ICOLD and the United States Society of Dams (USSD) benchmark workshops.

2. ROADMAP FOR ADVANCED STRUCTURAL ANALYSIS

The ASA of concrete dams requires application of a unique approach that differs significantly from the techniques used in common engineering practice. In order to develop confidence in the results of the ASA, it is vital that analysts using commercial programs have an in-depth understanding of the terminology and principles used in the ASA.

The general road map for the ASA, as it applies to concrete dams, is presented in the flowchart (Fig. 1). Although the key terms used in Figure 1 are primarily based on definitions provided in ASTM 2006 and ICOLD 2013, some terms were adapted or enhanced for specific application to ex-isting concrete dam analyses. In this paper, the authors are presenting the V&V procedure for the ASA of concrete dams based primarily on the ASME concept.

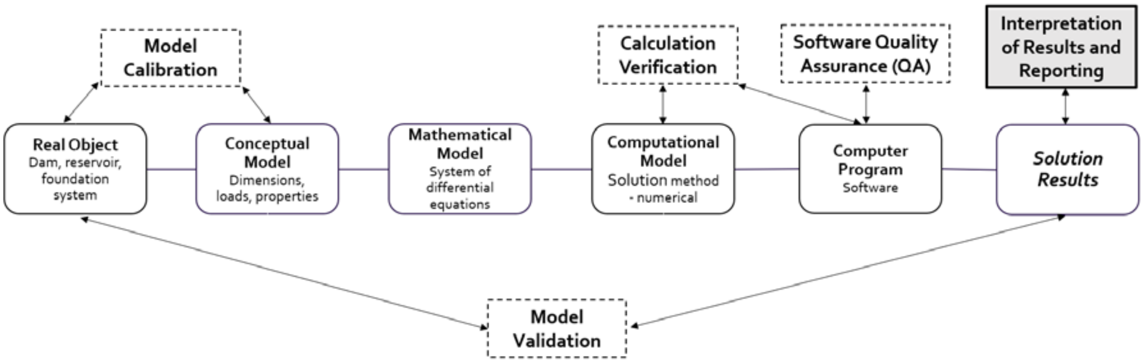


Figure 1 :. Road map for the ASA of existing concrete dams.

An interpretation of the flowchart in Figure 1 begins with the Real object, which represents the physical dam structure, foundation, and reservoir together with all the operating conditions.

A conceptual model is a "virtual image" of the *real object*. The conceptual model of an existing concrete dam is defined by the nominal dimensions, estimated material properties, and the loads act-ing on the dam in a form of pressure, body loads, seismic excitations, and temperature. Parametric uncertainties, that originate from variability in material properties, loads, and the model geometry, are taken into account by model calibration.

The *mathematical model*, expressed by a system of partial differential equations with the boundary and initial conditions, is a mathematical representation of the conceptual model.

The *computational model* is represented by the analytical or numerical solutions of the mathemat-ical model. The number of the available analytical solutions related to concrete dam modeling is very limited; as a result, in such simulations the numerical methods are commonly used instead. The pri-mary uncertainties in the analysis are related to selection of the proper numerical method and its parameters, convergence of such method, and estimations of solution accuracy.

The *computer program (Software)* is an automatization process of the *computational model.*

The *V&V* process is of particular importance in the advanced analysis. It starts with the realization of uncertainties introduced into analysis through simplifying assumptions made for the conceptual, mathematical, and computational models.

Calibration is a process of adjusting physical parameters in the conceptual model to improve agree-ment with experimental data (Oberkampf et al. 2010) or the field measurements. It is assumed that if most physical parameters of the conceptual model are properly calibrated, simulation results will well represent realistic behavior of the real object.

In addition, a very important aspect of the ASA is proper interpretation of the analysis results and presentation of those results in terms commonly used by the engineering community. Accurate post-processing and proper presentation of the analysis results are critical for defining confidence in risk estimations and for enabling regulatory agencies (decisionmakers) to take appropriate action.

3. VERIFICATION AND VALIDATION

3.1 Overview

A variety of definitions exist for the term *"verification and validation"* in the various technical disciplines. Oberkampf and Roy (Oberkampf et al. 2010) provide a historical overview of the fundamental terminology and present a general concept of the V&V associated with solid mechanics.

The first definition of V&V was formally developed by the Society of Computer Simulation in 1979. The definition was then enhanced by the Institute of Electrical and Electronics Engineers and the U.S. Department of Defense (DoD) in the 1980s. A *Guide for the Verification and Validation of Computational Fluid Dynamic Simulation*, published by the American Institute of Aeronautics and Astronautics in 1998 (AIAA 2002), was the first document defining key terms and standardizing the methodology in V&V. Similarly, for the applications to solid mechanics, a Guide for Verification and Validation in Computation Solid Mechanics was published by the American Society of Mechanical Engineers (ASME 2006), defining verification as the process of determining that a computational model accurately represents the underlying mathematical model and its solution. A common definition for validation was adopted by the agencies listed above as *the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.* The concept of verification and validation in computational solid mechan-ics is illustrated in ASME (2012).

The terms verification and validation are very often used interchangeably in common engineering language; however, they describe two different types of activities. The difference between verifica-tion and validation is explained best by Roache (1998) where:

- Verification means solving the equations right.
- Validation means solving the right equations.

ICOLD bulletins (ICOLD 1994, ICOLD 2001, ICOLD 2013) use the terms verification, validation, and justification for the software qualification, however, they do not refer any of the DoD, AIAA, or ASME publications on the subject.

3.2 Verification of ASA for concrete dams

Referring to the ASME guide (ASME 2006), verification could be otherwise described as a process of determining that the computational model correctly and accurately represents the mathematical model and its solution. Structural engineers, analysts, program users, and software developers verify that the computational model is correctly implemented in the computer programs.

There are several techniques that can be utilized to verify computational models implemented in computer software (Bathe 1980, CSB 2003, Noh et. al 2013). Some practical methods for verifying the ASA for concrete dams include:

- Check the input parameters,
- Check the computation results for symmetry, conservation of energy, and general structure behavior,
- Test sub-models of a conceptual model – each feature of the computational model is veri-fied separately (for an example, refer to Section 4),
- Compare the results with analytical solutions, if such results are available (refer to the example in Section 4),
- Compare software-to-software – conduct analyses with various software (refer to the ex-ample in Section 4),
- Perform sensitivity studies – compare analysis results for a range of settings and a range of model parameters (refer to the example in Section 4),
- Compare the results with a suite of benchmark tests specific for concrete dam structures (USSD and ICOLD benchmark workshops),
- Evaluate discretization error evaluation,
- Perform convergence tests,
- Perform order-of-accuracy test.

Some aspects related to verification of the computer software are covered by the software devel-oper quality control/ quality assurance program. Although such a quality control procedure is a stand-ard practice in development of the commercial software, relying on such a procedure alone is not sufficient to build confidence in using the software for engineering applications. The engineer/analyst conducting the ASA for concrete dams is fully responsible for selecting and properly using the soft-ware, as well as for verifying and delivery accurate analysis results.

3.3 Validation of ASA for concrete dams

According to ASME (2006), validation could be described as a process of determining the degree to which a conceptual model is an accurate representation of the real world for the intended use for physical phenomena that is modeled. The validation process provides evidence that the selected con-ceptual model is correct.

For the ASA of concrete dams, validation takes place by using the field measurement data obtained from the real dam structures and/or their components, as well as from the laboratory model test results. It focuses on assessing the accuracy of mathematical models via experimental measurements.

Validation is a very important part of the V&V analysis procedure for concrete dams. Because it requires special attention and enhanced discussion, the authors will elaborate on the subject in a sep-arate publication.

4. ROAD MAP FOR CONCRETE DAM ADVANCED STRUCTURAL ANALYSIS

4.1 Pine Flat Dam

The road map (Fig. 1) and the V&V procedure are illustrated in this section using the Pine Flat con-crete dam as an example. The dam, constructed in California in 1954, consists of 36 monoliths with a width of 15.25 m and 1 monolith with a width of 12.2 m. The length of the straight gravity dam is 561 m, and the tallest nonoverflow monolith is 122 m high.

4.2 Conceptual dam model

The conceptual model of Pine Flat Dam (Fig. 2), considered in this article, was defined in the ICOLD 2019 Benchmark Workshop formulation for Theme A. The 2D model shown in Figure 2 consists of a 122-m-high concrete dam structure and a 700-m-wide and 122-m-deep foundation block. For the same concrete and rock elastic material properties (modulus of elasticity: 22,410 MPa; density: 2,483 kg/m3; Poisson ratio: 0.2; shear wave velocity: 1,939 m/s), a seismic excitation is applied at the base of the foundation.

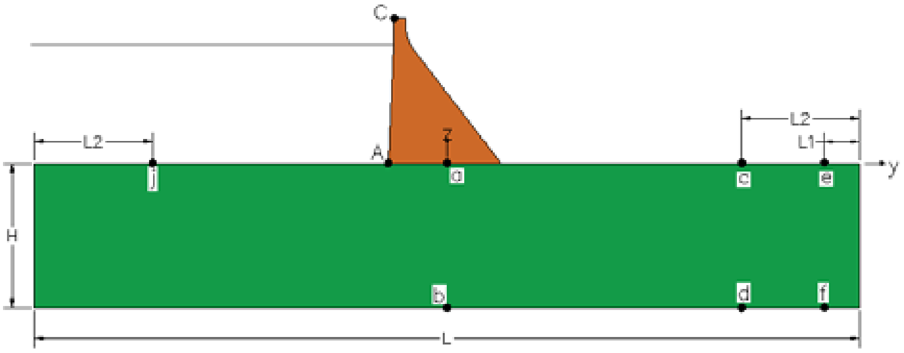


Figure 2 : Conceptual model of Pine Flat Dam.

The investigation's primary interest relates the seismic wave propagation in a semi-infinite elastic space and the analysis problems that arise when using reduced-domain models of a semi-infinite me-dium. Thus, an absorbing boundary condition must be applied to the side and base of the foundation to avoid artificially trapping seismic energy within the finite-domain model. In this analysis, we used a variation of the boundary condition described by Lysmer and Kuhlemeyer (Lysmer et al. 1969). An additional, so-called free-field boundary condition is needed for the reduced-domain model to keep the motions at the side boundaries equivalent to what they would be in the semi-infinite medium.

4.3 Mathematical model

In the continuum theory of mechanics, the set of basic equations (which includes equations of motions, geometric equations, and material constitutive law, together with boundary and initial conditions) defines a mathematical formulation of the conceptual model of Pine Flat Dam. Applying the standard procedure for derivation of the virtual power principle and considering geometric relationships between the displacements and strains, constitutive equations, and the initial conditions, the finite element (FE) discretization of the Galerkin variational formulation of the preceding equations results in the following system of second order differential equations:

$$\mathbf{M}_S\ddot{\mathbf{U}} + \mathbf{C}_S\dot{\mathbf{U}} + \mathbf{K}_S\mathbf{U} = \mathbf{F}_g + \mathbf{F}_p$$

where: **Ms, Cs**, and **Ks**, are the mass, damping, and stiffness matrices, respectively.

The unknown vector of nodal variable **U** represents the relative displacements at the nodes of the FE mesh. Vector $\mathbf{Fg} = \mathbf{M}_S\ddot{\mathbf{U}}_g$ contains forces generated by the ground acceleration applied to the

model. Vector Fp represents the reservoir induced hydrodynamic forces acting on the upstream face of the dam, and it is related to the unknown vector of nodal pressures.

4.4 Computational model

To solve the mathematical problem formulated in the section 4.3 the time domain, both the implicit and explicit methods are employed. For the fluid-structure interaction, the "acoustic fluid" approach and the "fluid-like material model" approach are implemented.

4.5 Software

In this paper, verification is conducted by using the two commercial FE programs LS-DYNA (https://www.lstc.com/products/ls-dyna) and DIANA (https://dianafea.com/), and a software Real-ESSI (real-essi.info), developed at the University of California at Davis.

4.6 Solution

The analysis results for the Pine Flat Dam benchmark study were submitted by the authors of this paper (Salamon et al. 2019) and (Yang et al. 2019) to the workshop organizers and, together with 30 other contributions, were presented during the workshop in Milan, Italy, in September 2019. The benchmark results are summarized in the workshop proceeding; therefore, they are not duplicated in this paper. To illustrate selected aspects of the verification process, however, additional studies have been completed and are presented in Section 5 below.

5. ILLUSTRATION OF VERIFICATION PROCESS

5.1 Sub-modelling

In the initial phase of the verification process, the conceptual model of Pine Flat Dam (Fig. 2) is separated into two sub-models: (1) the dam-reservoir and (2) the foundation block system. The fluid-structure interaction for the dam-reservoir submodel was examined previously by Salamon & Manie (Salamon et al. 2017); therefore, it is not presented in this paper, however, a detailed description of the verification process for the foundation block system sub-model is further explained below.

5.2 Verification of the sub-model

Verification of the foundation block sub-model is selected to examine problems of using reduced-domain models of a semi-infinite medium. The authors use a FE analysis to simulate a pulse wave propagation in an elastic medium. In the comparison study, the model with "nonreflecting" (absorb-ing) boundary conditions only, and with the combined absorbing and free-field boundary conditions at the block sides, is investigated.

The verification procedure for the foundation block sub-model presented in this paper includes:

- Comparing the FE analysis results with an analytical solution,
- Comparing the analysis results obtained by various FE programs,
- Performing a parametric study for various mesh sizes and different time steps.

5.2.1 *Comparison with analytical solution*

The free-surface motion at the top of the foundation (points a, c, e, and g, as shown in Figure 3) can be determined theoretically from the equivalent upgoing motion in an elastic homogeneous half-space. The incident motion in the form of a high-frequency pulse record (Fig. 4) is a vertically-prop-agating plane S-wave, and the theoretical free-surface motion is simply twice the upgoing wave. The theoretical motion is the same at all points on the free surface.

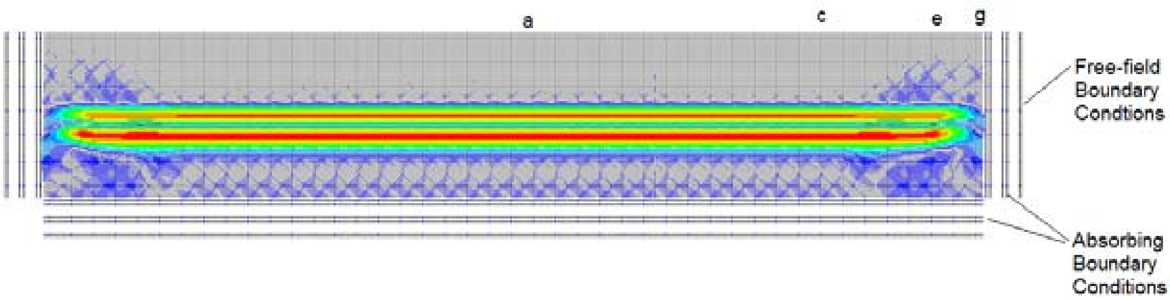


Figure 3 : Foundation block sub-model with indicated boundary conditions. High-frequency, horizontal velocity, pulse upward propagation shows nonuniform wave distribution along the foundation width when the free-field boundary conditions are not applied to the block sides.

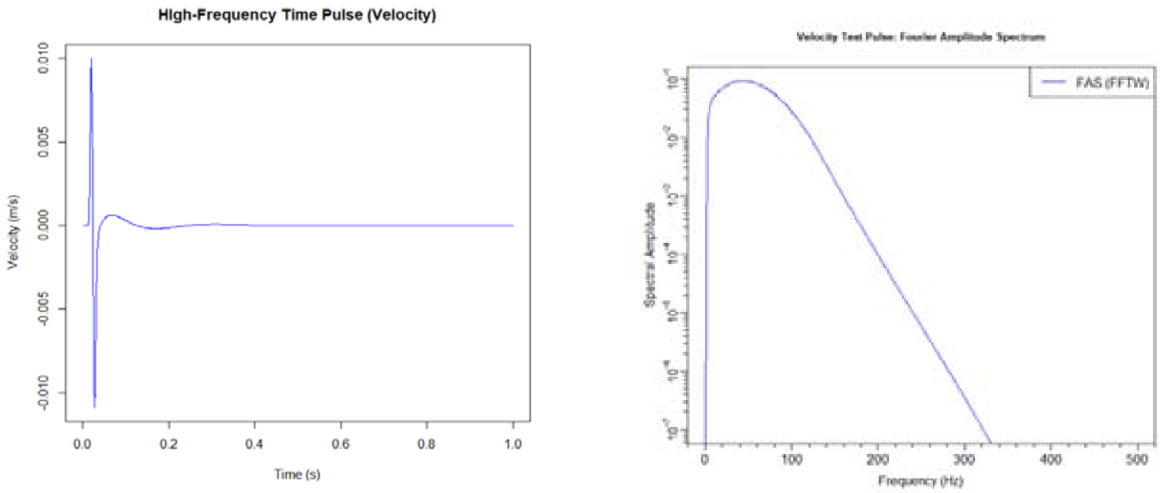


Figure 4 : Velocity impulse time history and its Fourier amplitude spectrum.

Results comparing the computed and theoretical free-surface motions at points a, c, e, and g for the high-frequency pulse (Fig. 4) are shown in Figures 5-6 for the free-field and nonreflecting boundary conditions (Salamon et al. 2019) and (Yang et al. 2019).

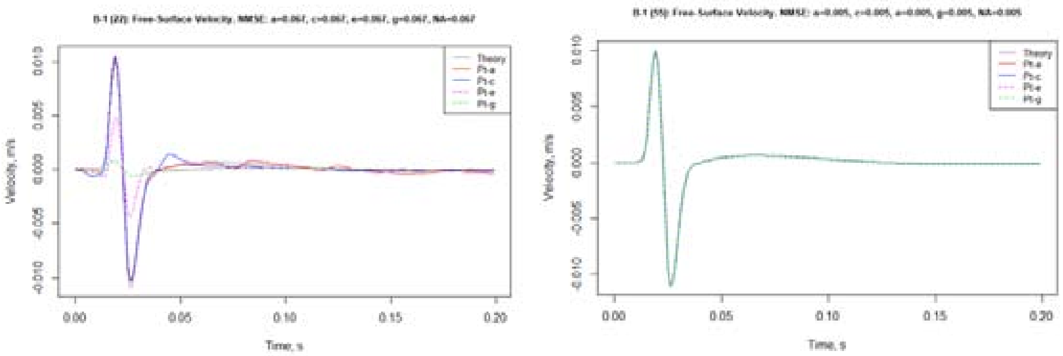


Figure 5 : Velocity time history at points a, c, e, and g per Figure 3 for nonreflecting (left) and free-field (right) boundary conditions.

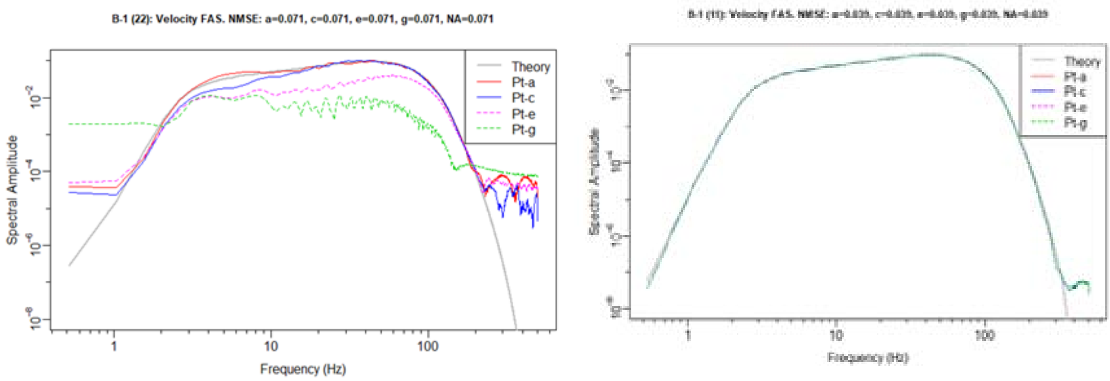


Figure 6 : Spectra comparison at points a, c, e, and g per Figure 3 for nonreflecting (left) and free-field (right) boundary conditions.

Results obtained from models with free-field boundary conditions are in very good agreement with the theoretical solution (right side of Figs. 5-6). The uniformly applied wave at the base of the function block remains uniform at the top of the foundation block. For "nonreflecting" boundary conditions, however, the relatively good agreement with the theoretical solution is observed only at the center of the foundation block, with significant differences at the distance away from the block center (Figs. 3, 5 (left), and 6 (left)).

5.2.2 *Comparison results obtained with various FE programs*

The analysis is validated here by comparing the results obtained by 3 FE programs listed in Sec-tion 4.5 (Software). The results comparing the computed free-surface velocities at points a, c, e, and g of the foundation block sub-model for the high-frequency pulse (Fig. 4) are shown in Figure 7. The difference in the results is primarily related to the type of boundary conditions implemented in each of these FE programs.

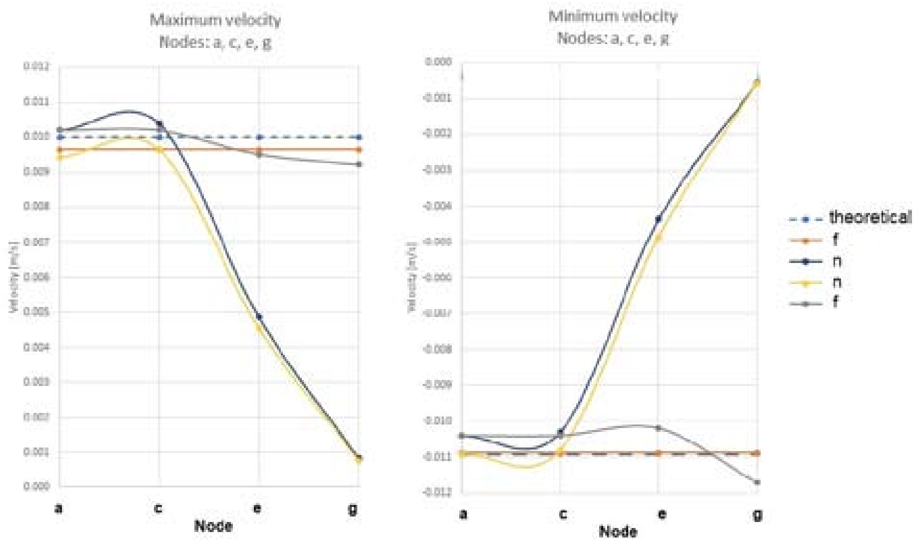


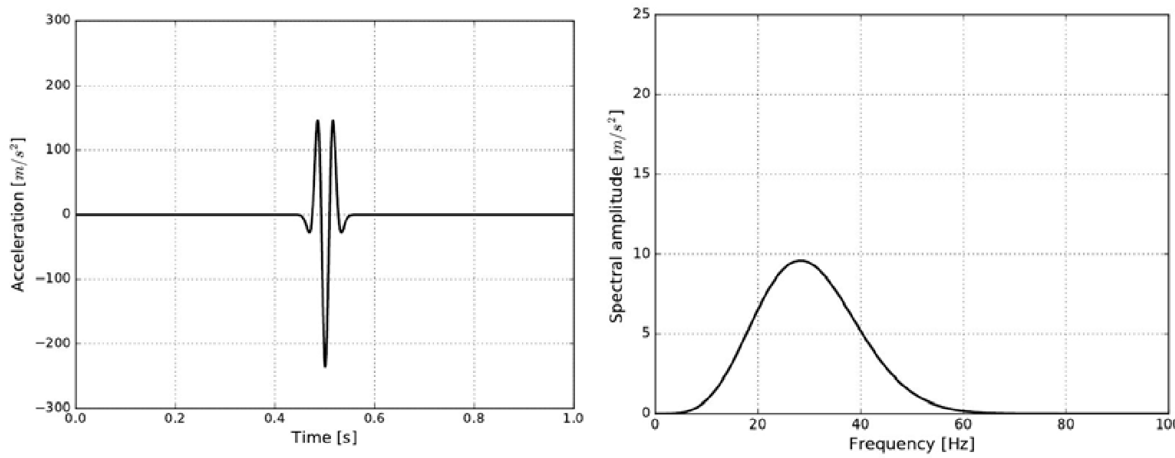
Figure 7 : Distribution of horizontal maximum and minimum peak velocities at points a, c, e, and g of the foun-dation block. Results for the free-field boundary conditions are indicated by "f," the nonreflecting boundary conditions by "n," and the theoretical solution by the blue dashed line.

The plot of velocity "n" in points e and g in Figure 7 is related to the contour map of the velocity wave shown in Figure 3. The analysis shows that the nonreflecting boundary conditions do not properly model a seismic wave propagation of a semi-infinite medium.

5.2.3 *Parametric study for time step size and finite element mesh size*

This set of results shows the influence of a time integration step size and the FE mesh size on propa-gation of a simple Ricker wavelet with predominant frequency of 25 Hz. The main reason for using Ricker wavelet is that it contains a clean, simple signal; thus, any deviation from the signal in the propagated wave becomes obvious. The wave signal was applied to the base of the foundation block sub-model with constraints applied (Fig. 3).

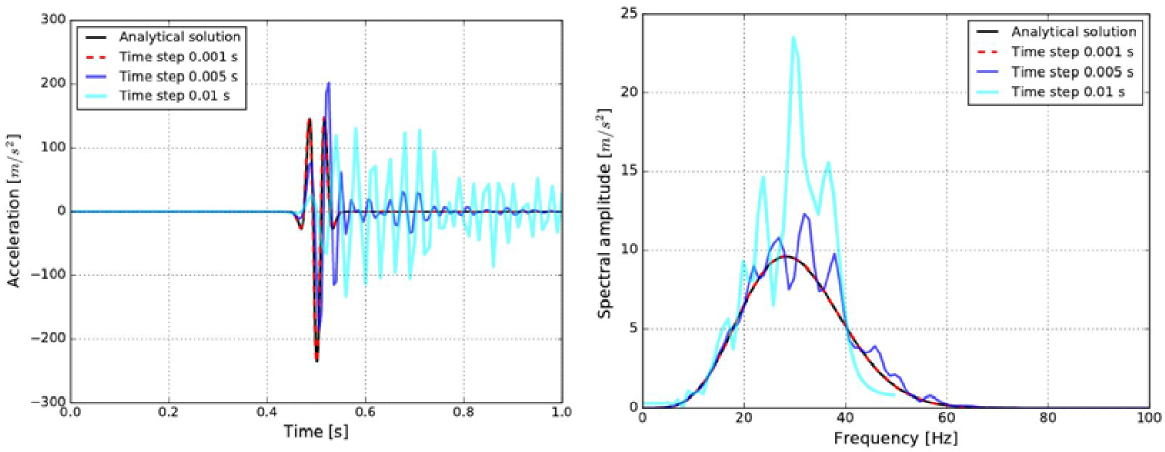
Figure 8 shows input Ricker wavelet signal that was used as a surface seismic motions record that was then deconvoluted to the foundation block bottom, and then propagated upward, using the Do-main Reduction Method (Bielak et al. 2003). Wave propagation was only considered for one component of a shear wave polarized in vertical plane.



(a) Input acceleration time history (b) Input acceleration spectrum

Figure 8 : Input Ricker wavelet signal in time and frequency domain.

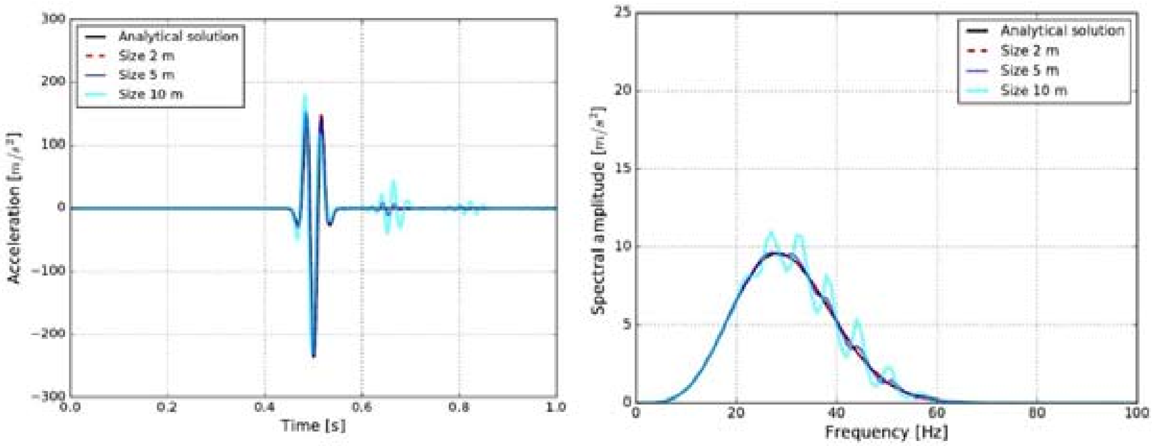
Figure 9 shows the influence of time step size of 0.001, 0.05, and 0.01 second on the recorded accelerations at the center of the block upper surface (point a, Figure 3) for the uniform mesh size of 2 m. For the 0.001 second time step, the computed accelerations are in very good agreement with the theoretical solution, but they vary for larger time steps of 0.01 second and 0.005 second.



(a) Top acceleration (b) Top spectrum

Figure 9 : Influence of time step size on propagation of a Ricker wavelet at point a of Figure 3.

Figure 10 presents computed accelerations at the center of the upper surface of the foundation block with the uniform FE mesh sizes of 2, 5, and 10 m and the time step of 0.001 second. Very good agreement between the FE analysis results and the theoretical solution was obtained for 2-m mesh, and relatively good agreement was obtained for 5-m mesh size. Significant variations between the theoretical and FE commutations are observed for the 10-m mesh.



(a) Top acceleration

(b) Top spectrum

Figure 10 : Influence of finite element mesh size on propagation of a Ricker wavelet at point a of Figure 3.

6. SUMMARY AND CONCLUSSIONS

The ASA is an important method in structural assessments of concrete dams and in risk estimations of dam safety investigations. Accuracy and confidence in the outcome are the primary concerns of such analyses conducted by the FE programs. In this paper, a road map for the ASA, as it applies to existing concrete dams, is provided, together with general guidelines for verification of the computa-tions, illustrated for a case involving the Pine Flat concrete dam. Also, definitions of related termi-nology are provided to clarify and unify terms that are not always correctly used in common engi-neering language.

It is important that FE programs, including the commercial software, are verified by the analysts before they are used in the structural analysis of dams. The authors outline a path by which the com-putational model or its sub-model can be tested against any available theoretical solution, compared with the results obtained by other programs, or evaluated by parametric studies.

Although this paper may not address all aspects related to the ASA of concrete dams, it may con-tribute to a discussion on developing unified guidelines for verification and validation of detailed FE analysis for concrete dams. The focus of these guidelines will be on establishing accuracy, credibility, and confidence in the results of concrete dam modeling and simulations intended: (1) to be used in dam safety risk estimations and (2) to support policy decisions for approval of potential modifications.

REFERENCES

AIAA 2002, Guide for Verification and Validation in Computational Fluid Dynamics Simulations, American Institute of Aeronautics and Astronautics, AIAA G-077-1998, Reaffirmed 2002.

ASME 2006, Guide for Verification and Validation in Computational Solid Mechanics, An American National Standard, ASME V&V 10-2006, Reaffirmed 2016, The American Society of Mechanical Engineers.

ASME 2012, An Illustration of the Concept of Verification and Validation in Computational Solid Mechanics, An American National Standard, ASME V&V 10.1-2012, The American Society of Mechanical Engineers.

Bathe, K.J. 1980, Some Practical Procedures for the Solution of Nonlinear Finite Element Equations, Computer Methods in Applied Mechanics and Engineering, North-Holland Publishing Company, 1980.

Bielak J., Loukakis K., Hisada Y., and Yoshimura C. 2003, Domain reduction method for three-dimensional earthquake modeling in localized regions. part I: Theory., Bulletin of the Seismological Society of America, 93(2):817-824, 2003.

CSB 2003 (COMITÉ SUISSE DES BARRAGES), Groupe de Travail, « Methods of Analysis for the Prediction and Verification of Dam Behavior, Wasser, Energie, Luft, Heft ¾.

ICOLD 2013, Guidelines for Use of Numerical Models in Dam Engineering, ICOLD Bulletin 155, Technical Committee on Computational Aspects of Analysis and Design of Dams, 2013.

ICOLD 2001, Computational Procedures for Dam Engineering, ICOLD Bulletin 122, Technical Committee on Computational Aspects of Analysis and Design of Dams, 2001.

ICOLD 1994, Computer Software for Dam Validation, ICOLD Bulletin 94, Technical Committee on Compu-tational Aspects of Analysis and Design of Dams, 1994.

Lysmer J., and Kuhlemeyer R. L., Finite Dynamic Model for Infinite Media, Journal of the Engineering Me-chanics Division, vol. 95, no. 4, pp. 859-878, 1969.

Nielsen A. H., Absorbing boundary conditions for seismic analysis in ABAQUS. pp. 359-376.

Nielsen A. H., Boundary Conditions for Seismic Analysis, SECED Newsletter, vol. 21, no. 3, pp. 7-11, 2009.

Noh, G. & Bathe, K.J. 2013, An Explicit Time Integration Scheme for the Analysis of Wave Propagations, Computers and Structures, Elsevier Ltd, 2013.

Oberkampf, W.L. & Roy, C.J. 2010, Verification and Validation in Scientific Computing, Conference, Cam-bridge University Press.

Roache, P., 1998. Verification and Validation in Computational Science and Engineering, Hermosa Publishers, ISBN 0-913478-08-3.

Salamon, J.W. & Manie, J. 2017, Numerical Assessment of Hydrodynamic Loads Induced during Seismic In-teraction between Reservoir and Concrete Dams, USSD Conference, Anaheim, California, April 2017.

Salamon, J.W., Wood C., Manie J. & Geister, A. 2019, Evaluation of Seismic Wave Propagation in the Analysis of Concrete Dams, 15th International Benchmark Workshop on Numerical Analysis of Dams, Theme A – Seismic Analysis for Pine Flat Concrete Dam, International Commission on Large Dams, Milan, Italy, Sep-tember 9, 2019.

Yang H., Wang H., Jeremic, B. & Salamon, J. 2019, Earthquake Soil Structure Interaction Analysis of a Gravity Dam, 15th International Benchmark Workshop on Numerical Analysis of Dams, Theme A – Seismic Analysis for Pine Flat Concrete Dam, International Commission on Large Dams, Milan, Italy, September 9, 2019.