Experimental and numerical analyses of a base-excited model of a concrete gravity dam monolith

Horyna, Tomas[1], Black, Cameron J.[2], and Rudolf, Jachym[2]

ABSTRACT

This paper describes the methods and the results of experimental and numerical studies of a concrete gravity dam model unbonded at the base. The objective of the work was to determine the amounts of horizontal sliding of a concrete block preloaded by a constant horizontal force and subjected to prescribed base excitations using a shake table. The base excitations varied in type, frequency content, and intensity. The initiation of sliding, rate of displacement, and dynamic/static force ratios were determined. Simple rigid-body models were developed to simulate shake table tests. The agreement of the experimental and numerical results was good for low frequency excitations but not as good for higher frequencies. Similar trend was apparent in the results using a finite element model. The finite element model was successful in capturing some of the more complex nonlinear behavior observed during the experiment.

INTRODUCTION

Background information

The stability of a concrete gravity dam against excessive sliding at its base must be assured during strong base excitations caused by an earthquake. Tools to evaluate this stability are mostly analytical, ranging from the traditional pseudostatic check of a factor of safety against sliding to the calculation of the amount of the dam sliding through non-linear dynamic analysis. The pseudostatic, or seismic coefficient method, is most conveniently used in seismic risk analysis, when a relatively large number of stability checks are to be made and a fast numerical procedure is preferred.

Current state-of-the-art analysis tools to evaluate sliding of gravity dams are rarely used for seismic risk evaluations because of time constraints, but they can yield valuable results to verify simpler methods (Fan & Sled 1992). Experimental data is another source to verify simple analytical methods. As there is no reported evidence of excessive sliding of any actual gravity dam subjected to severe shaking, it is desirable to conduct shake table testing of dam models to verify analytical predictions.

This paper describes the results of an experimental study including a series of shake table tests conducted on a scaled model of a concrete gravity dam monolith. It also describes results of numerical studies to simulate the shake table tests. The studies were conducted as Phase II of an ongoing collaborative project to investigate various aspects of the dynamic behavior of concrete gravity dams. This project is carried out by the British Columbia Hydro and Power Authority (BC Hydro) and the Department of Civil Engineering of the University of British Columbia (UBC), both of Vancouver, B.C., Canada. This phase of the project was a direct continuation of Phase I (Horyna et al. 1998).

Objectives and scope of study

The main objective of the study was to determine the magnitude of base excitation that would cause a specified level of horizontal sliding of a concrete monolith model resting unbonded at its base and preloaded by a constant horizontal force. This was done for varied friction characteristics of foundation interface and for base excitations of varied type and frequency content. Two conditions of model movement were selected as the specified levels of interest:

- Initiation of sliding of the model; and
- 30 mm of sliding in 10 seconds of excitation.

Using the measured displacements, it was possible to calculate the dynamic to static force ratios for the two conditions of model movement. During the subsequent numerical studies, simple numerical models as well as a finite element model were developed to simulate the experiment. It was beyond the scope of the study to investigate other effects, such as the influence of cohesion at foundation interface, hydrodynamic and uplift forces on the model, vertical earthquake excitation, or to apply the experimental and numerical results to predict the seismic performance of any concrete gravity dam prototype.

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1. Ph.D. Candidate, Dept. of Civil Engineering, The University of British Columbia, Vancouver, B.C.
2. Graduate Student, Dept. of Civil Engineering, The University of British Columbia, Vancouver, B.C.

EXPERIMENTAL STUDY

Description of testing facility

The tests were conducted using the shake table at the Department of Civil Engineering at UBC. The shake table measures 3 m by 3 m. Its motions are produced by up to five actuators in various configurations. It has a payload capacity of 156 KN, with a maximum displacement of +/- 7.6 cm in the horizontal direction. The actuators are controlled by a Multi Exciter Vibration Control Software program, which performs closed loop control. For the tests described in this report the table was set up to produce only unidirectional motion in the horizontal direction. More detailed description of the testing facility can be found in Horyna et al. (1997).

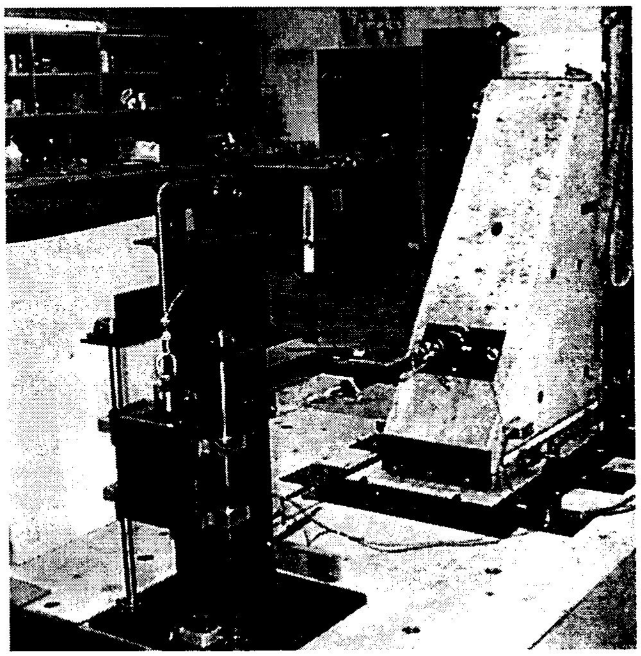

Figure 1: Photo of experimental setup

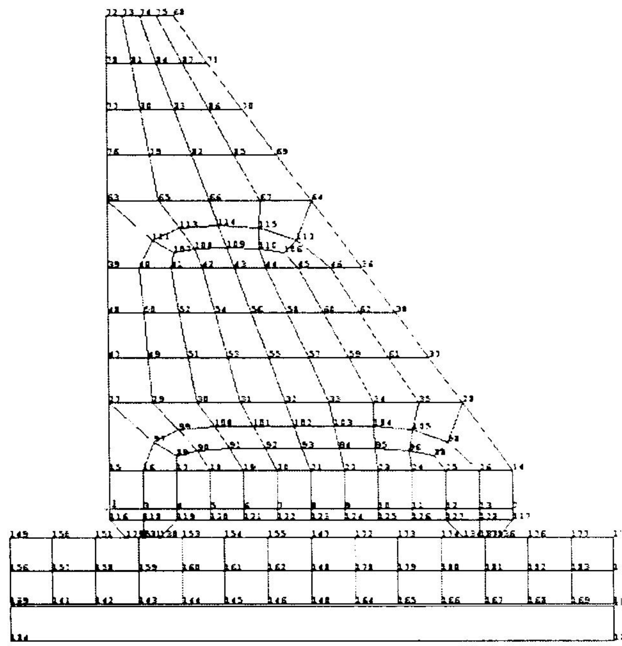

Figure 2: Schematic of finite element mesh

Experimental model

The experimental model consisted of three main parts: a dam monolith, pair of sliding surfaces and hydrostatic load simulator assembly. The monolith, shown in Figure 1, was about 1500 mm high and 480 mm wide. The material used was a mix with the following weight composition: 42.2% Portland cement, 40% water, 12.5% perlite, 3.6% silica fume and 1.7% Styrofoam. This mix was used in an attempt to satisfy similitude requirements between the inertia and elastic forces on the model and on an actual dam monolith (Mir & Taylor 1995). Sliding occurred between the upper plate attached to the bottom of the monolith and the bottom plate attached to the shake table. The contact between the two concrete plates was limited to raised areas under the toe (downstream) and heel (upstream) of the model in order to limit the effects of incidental unevenness of the plates (Horyna et al. 1997). The shape of the model can be seen in Figure 2, showing the schematic of the finite element model. Four pairs of plates were tested, two with smooth concrete finish (setups S1 & S2) and two with exposed-aggregate finish (setups R1 & R3). The total weight of the model including the upper sliding plate and all attachments was 480.6 kg.

The hydrostatic load was simulated by applying a pulling force in the downstream direction on the downstream face of the dam model. This force was provided by a hydrostatic load assembly attached to the shake table. A steel cable was attached to the model at a height corresponding to the resultant of the simulated hydrostatic load. The other end of this cable was attached to a hanging weight equivalent to the required force of 1050 N. The weight was free to slide vertically along two steel shafts but constrained horizontally.

Testing procedures and results

The concrete gravity dam model was instrumented to measure its response during five different test types. These included: harmonic, earthquake, static, cyclic and impact tests. The last three types of tests are not reported here but a detailed description can be found in Black et. al (1998).

The tests with harmonic and earthquake input were conducted using 10-second base excitation records with varying frequency content and amplitude. Nine dominant frequencies were selected between 5 and 25 Hz with a step of 2.5 Hz. The acceleration amplitudes typically ranged from 0.1 g to 0.75 g or higher, depending on the behavior of the model. In total, over 800 tests were completed.

The records for tests with earthquake input were developed using program SIMQKE (Gasparini & Vanmarcke 1976) from smoothed power spectral densities of recorded motions from three past earthquakes in California. These were: one record from 1992 Landers earthquake measured at Joshua Tree Fire Station, one record from 1994 Northridge earthquake measured at Tarzana Nursery Station, and one record from 1979 Imperial Valley earthquake measured at El Centro. Examples of an input displacement records and a relative model displacement record are shown in Figure 3.

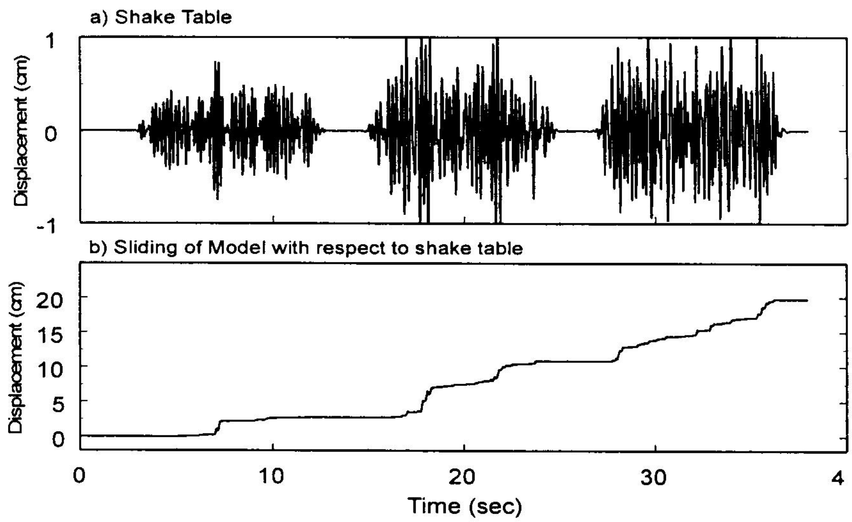

Figure 3: Typical base excitation and relative model displacement records (EQ 5 Hz, 1.0g, Setup R1)

Along with the dynamic tests, a series of static tests were performed to determine the effective static and kinetic coefficients of friction and their stability during testing. The shake table was moved at a speed of 5 mm/s while measuring the force required to hold the model stationary. The static friction coefficients were found to be close to 0.72 for smooth surfaces and 0.75 for rough surfaces. The dynamic friction coefficients were 0.70 and 0.73 for smooth and rough surfaces, respectively.

Based on observations during the experiment, the excitation frequencies were divided into three groups with the following characteristics of the model response:

- Group 1 - low frequencies 5 to 10 Hz

The model slid when friction was overcome. Sliding was always downstream. In-plane rocking was observed at higher amplitudes of excitation, with an uplift of the toe.

- Group 2 - frequencies 12.5 to 17.5 Hz

Sliding of the model was affected by its rocking and jumping (vertical vibration with a complete separation from the base) resulting in mostly larger amount of sliding than for the frequencies from Group 1. At 15 and 17.5 Hz, sudden changes in rate of sliding were observed during high-intensity tests. These changes were accompanied by a change in rocking mode from toe uplift to heel uplift.

- Group 3 - high frequencies 20 to 25 Hz

The response in this range of frequencies varied significantly between setups. The typical response of the model was an initial rapid slip downstream followed by slow-down at the onset of out-of-phase rocking with an uplift of the heel. A general decrease in the rate of sliding was apparent. An extreme condition of net displacement upstream occurred for setups S2 and R3 at high amplitudes of base excitation.

The measured total sliding of the model during each test was divided by the duration of the test, typically 10 seconds, to yield the average velocity or Rate of Model Displacement (RMD). A sample plot of the RMD variation with frequency and amplitude is shown in Figure 4. The general trends in the behavior given for Groups 1, 2, and 3 above, can be observed in the RMD plots.

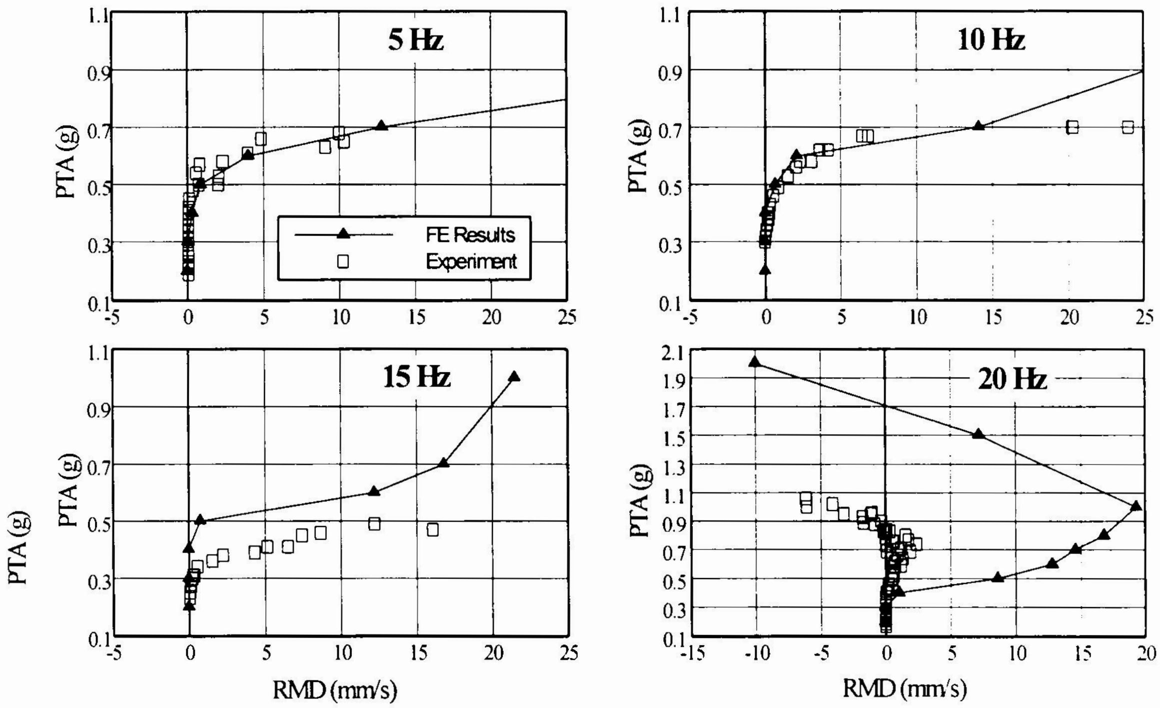

Figure 4: Rate of Model Displacement (RMD) versus Peak Table Acceleration (PTA) plots for harmonic excitation obtained from experimental setup R3 and FE analysis.

It was further possible to determine the peak table acceleration at the two conditions of interest: initiation of sliding, and RMD of 3 mm/s. The peak table acceleration was multiplied by the mass of the model to give a dynamic force. The dynamic/static force ratio, which can be thought of as an inverted dynamic amplification factor, was computed by dividing the dynamic force by the static force measured during the static tests. Representative examples of dynamic/ static force ratio plots are shown in Figures 5 and 6. It can be seen that the ratios at initiation of sliding were less than unity at all frequencies and decreased as frequency increased. The ratios were higher at RMD of 3 mm/s, but also decreased with increasing frequency of excitation up to about 15 Hz. The plots in Figure 6 do not show values for tests above 15 Hz of R3 setup which showed net upstream displacement. The response of the model during earthquake excitation was similar to the response due to harmonic excitation, thus leading to the conclusion that the response of the model was controlled more by the frequency content than by the type of excitation.

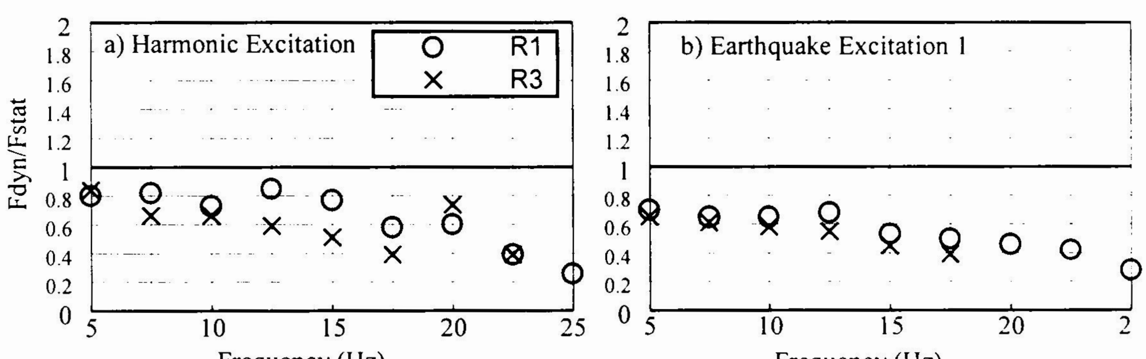

Figure 5: Dynamic/Static Force Ratios at Initiation of Sliding - Experimental Setups R1 and R3

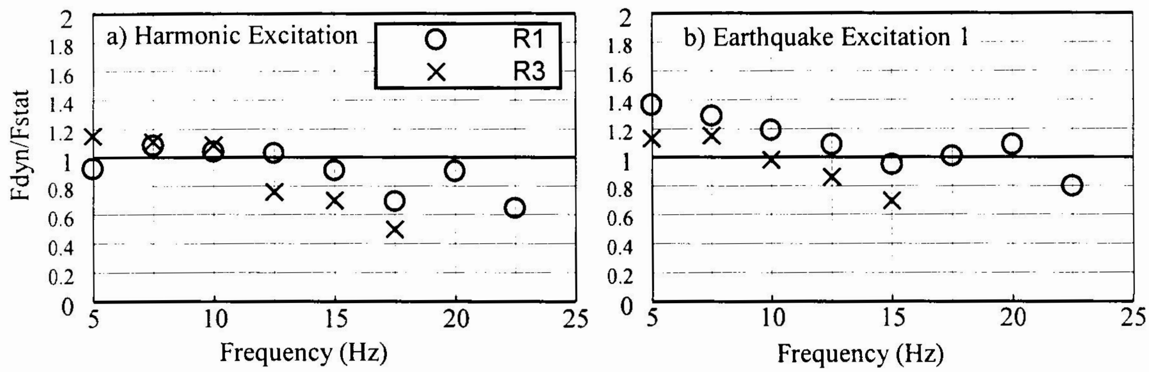

Figure 6: Dynamic/Static Force Ratios at RMD of 3 mm/s - Experiment Setups R1 and R3.

NUMERICAL STUDIES

Study using rigid body models

Simple numerical models were developed describing the sliding of a rigid block resting on rigid foundation, preloaded by a constant horizontal force and subjected to base excitations. It was a requirement that the models be simple, fast, and reliable. These characteristics would make them suitable for future risk studies which will require large sets of simulations. The following two numerical models were developed:

- Model using software Working Model (WM) from Knowledge Revolution (1996);
- Single Degree Of Freedom (SDOF) model of rigid block sliding on rigid foundation.

The WM model included a displacement controlled shake table, a force controlled actuator to simulate hydrostatic force and a 3-DOF dam monolith. The rigid model of the dam monolith accounted for sliding and rocking, which could lose contact with the base during analysis. The SDOF model simulated a rigid block on a rigid foundation constrained to a single horizontal DOF. The block and the base were always in contact.

Both numerical models were first tested using a closed-form harmonic base excitation and yielded almost identical results to each other. When compared with experimental results, the analysis predicted well the behavior for low frequencies, Group 1, and partially for Group 2. However, both rigid body models showed that they could not simulate satisfactorily the response of the physical model at high frequencies of Group 3.

Finite element study

The scope of the finite element (FE) modeling (Rudolf 1998) was to develop a simple two-dimensional model, capable of capturing some of the more complex modes of behavior observed during the experiment. Examples are rocking, jumping, sudden changes of rate of sliding, and upstream motion. Only a fraction of the experimental work was modeled. Specifically, one setup (R3) out of four was modeled and then subjected to a harmonic excitation of varying frequencies and amplitudes.

The dam monolith, the upper plate, and the shake table were modeled with a bilinear plane-stress element using a finite element program ANSYS Multiphysics/University (Swanson Analysis Systems, 1996). The FE model is shown in Figure 2. Contact between the upper plate and the shake table was provided by point-to-surface contact elements with friction capabilities. The combined flexibility of the physical shake table, the bottom plate, and the clamping devices was matched by contact springs of the contact elements. The stiffness properties of the monolith were calibrated to match the natural frequencies and mode shapes of the experimental model obtained from impact hammer testing. The mass matrix was built using the lumped mass option. A forced displacement static test was performed to verify the friction behavior of the model. The harmonic tests used closed-form harmonic base excitations with frequencies 5, 10, 15, 20, and 25 Hz, with amplitudes varying between 0.2 g and 1.0 g, or higher in some cases, and a duration of 10 seconds. Nonlinear dynamic analysis was performed using the Newmark implicit integration procedure with an amplitude decay factor of 0.005. The time step was automatically adjusted by the solver and varied between about 0.0025 and 0.0001 seconds. The solution time on a Pentium II 300 platform was around 8 hours for each 10-second test.

The experimental and FE results were compared and an example of such a comparison is presented in RMD plots in Figure 4. It can be observed that a good agreement was achieved in lower frequencies 5 and 10 Hz. The agreement was less satisfactory at higher frequencies. However, it can be seen that even at the higher frequencies that similar trends were followed. This could be attributed to the fact that the FE model captured some of the complex modes of behavior observed during the experiment. It was found that at the start of excitation - prior to sliding - the model significantly amplified the motions of the base. This amplification was more pronounced as the excitation frequency approached the first natural frequency of the system measured as 30 Hz. During sliding, an onset of rocking and separation from the table was accompanied by a rapid increase in the rate of model displacement. This typically occurred at table accelerations above 0.5 g and was present in all frequencies. At high frequencies of 20 and 25 Hz, with increasing amplitude of excitation, the rocking moved out of phase with the excitation and resulted in a decrease of RMD. Eventually, at 2 g, the model showed negative RMD, or upstream motion. This behavior was consistent with the experiment, although there it occurred more readily at lower levels of excitation. The FE study provided a valuable insight into the behavior of the physical model.

CONCLUSIONS

Series of shake table tests were conducted on a scaled model of a concrete gravity dam monolith. The model, unbonded at the base and preloaded by a simulated hydrostatic force, was subjected to harmonic and synthetic earthquake excitations of varied frequency content and amplitudes. The tests yielded amounts of model sliding for different combinations of base excitation parameters. The results showed a significant frequency dependence of the initiation and rate of sliding of the model. It also showed that the behavior became more complex than the anticipated simple sliding as frequency and amplitude of excitation increased. Two simple numerical models were developed to provide a fast method to simulate the behavior of the model. The amounts of sliding predicted by each numerical model showed good agreement for the simulations at low frequencies (5 to 10 Hz) but less satisfactory agreement for those at high frequencies (20 to 25 Hz). A finite element model was developed in an effort to capture the complex nonlinear behavior of the physical model at higher frequencies and amplitudes of excitation. The model succeeded in this objective, including the condition of upstream motion. It is unlikely that such phenomena as high-frequency rocking, jumping, or upstream motion have a significant relevance to the behavior of actual dams. The authors believe that the simple numerical models, after further development and calibration, can be used for seismic risk studies of concrete gravity dams.

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REFERENCES

Black, C.J., T. Horyna, C.E. Ventura & R.O. Foschi 1998. Shake table testing of a concrete gravity dam model unbonded at the base. Research report No. 98-01. Univ. of British Columbia, Dept. of Civil Eng., Vancouver, B.C., Canada, 1-112.

Fan, B.H. & J.J. Sled. 1992. Seismic Evaluation of Gravity Dams - Practical Aspects. Proc. of the 10th World Conference on Earthquake Engineering. Madrid, 4645-4650.

Gasparini, D.A. & E.H. Vanmarcke 1976. SIMQKE - A Program for Artificial Motion Generation, User's Manual. Massachusetts Institute of Technology, Dept of Civil Eng., Cambridge, Massachusetts.

Horyna, T., C.E. Ventura, R.O.Foschi & B.H.Fan 1998. Shake table studies of sliding of a concrete gravity dam model. Proc. Of the 11th Europ. Conf. On Earthquake Engineering. Paris, Sep. 1998. Balkema, Rotterdam.

Horyna, T., C.E. Ventura, & R.O. Foschi, 1997. Shake Table Testing of Concrete Gravity Dam Model Unbonded at the Base. Research report No. 96-06, Univ. of British Columbia, Dept. of Civil Eng., Vancouver, B.C. Canada, 1-67.

Knowledge Revolution 1996 Working Model 2D v. 4.0 - User's Manual. Knowledge Revolution, San Mateo, California

Mir, R.A. & C.A. Taylor 1995. An Experimental Investigation Into Earthquake-Induced Failure of Medium to Low height Concrete Gravity Dams. Earthquake Engineering and Structural Dynamics, 24:373-393.

Rudolf, J. 1998. Finite element verification of shake table testing of a gravity dam model. Research report No. 98-02. Univ. of British Columbia, Dept. of Civil Eng., Vancouver, B.C., Canada, 1-60.

Swanson Analysis Systems, Inc. 1996. ANSYS User's Manual for Revision 5.3, Volume 1, Procedures, Swanson Analysis Systems, Inc., Houston, Pennsylvania, USA.