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Finite Element Analysis of Concrete Gravity DamUnder Seismic Laods

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الملخص

السدود الثقاليةالخرسانية ذات القطاع المنتظم أو على شكل (U) يتم تحليهلها باستخدامالتحليل الانشائي ثنائي الأبعاد.ورغم ذالك السدود التي تقع في الوديان ذات طبيعة الارض المتغيره أو مع وجود انحدارات جانبيه حاده يتطلب تحليلالأبعاد الحقيقية للمنشأ باستخدام طريقة العناصر المحدودة وبوجه خاص أثناء تأثير أحمال الزلازل.الهدف الرئيسي من هذه الدراسة هو عمل مقارنه بين تحليلي ثنائي وثلاثي الابعاد للسدود الخرسانية الثقليه باستخدام برنامج (ANSYS 16). النموذج التحليلي تم تكبير مقياسه واختياره من الدراسات السابقه والتى تأكد من صحتها باستخدام تجربه معمليه مصغرة للنموذج. تم دراسة النموذج ثنائي الابعادبارتفاع يصل الى 45 م تحت تأثير زلزال حقيقي مكبر من هزه أرضيه يطلق عليها اسم(1985 Nahanni).وبعد ذلك تم عمل نموذجين مختلفين ثلاثي الأبعاد لمقارنتهما بالنموذج الاول. تم أخذ تأثير انفصال أو إزاحة منشأ السد عن الاساسات في الأعتبار مع وجود قوة الجاذبيه الأرضيه للمنشأ و الأحمال الجانبية للمياه في الخزان وتأثيرها أثناء الهزات الأرضية باستخدام طريقة (Added Mass). بعد التحليل والمقارنه اتضح انه يوجد أختلاف ملحوظ في قيمإنزلاقنموذج السد الخرساني وخاصتا اثناء مقارنة النموذج الاول والثالث معا ليصل الى فرق في النتائج يصل الى 24 في المائه.

Abstract

Concrete gravity dams with simple or U-shapesgeometry may be analyzed as two dimensional structures.However the dams located on canyon with stepped monolith or sharp edges slopes,the exact shape finiteelement analysis may be requiredto study the effect of the dam side abutments especially duringthe earthquake excitation.Themain objective of this paper is to perform a comparison between 2-D and 3-D of gravity dam monolith using ANSYS 16 APDL software.This paper deals with modal shapes numerical analysis for concrete dam that scaled from experimental prototype model extracted from literature study. Then the dam model with 45m height non overflow section is simulated as a two dimensional finite element model to study its behavior duringscaled 1985 Nahanni earthquake.The model was simulated also as three dimensional model with two different geometric changes. The structural and foundation interaction was considered during the seismic analysis. The loads existed in the model were the gravity dam load, hydrostatic load anddam-Water pressure effect during the earthquake. The reservoir effectwas considered by applying the hydrodynamic influence during the seismic conditions on the upstream surface of dam monolith using the added mass approximation approach. The two different 3-D F.E.M.results werecompared with the corresponding 2-D model. There was a significant change in the dynamic results for model I and model III. The sliding behavior difference reached to more than 24 percentages during the selected scaled ground motion analysis.

Keywords: Concrete gravity dam · Seismic response · Nonlinear analysis · Sliding failure · Time history analysis.

1. Introduction

Concrete gravity dams are complexstructures which impound huge reservoirs for various purposes such as flood protection, hydropower, water storage, irrigation, etc(Chopra, 1968).The cross sections of gravity dams are nearly triangular in shape, with increasing width towards the bottom. This design has been made to resist the various kinds of forces acting on it by its own weight (Léger and Katsouli, 1989). In the past two decades, a number of massive concrete gravity dams have been built in a lot of countries.

The dam failure shall obviously be a disastrous event in nature, create loss of life, and heavy destruction to properties through sudden release of its reservoir.Therefore dam safety becomes an important issue with great concern.The dams are required to be safe and strong therefore the design procedures have a lot of factors and details that should be taken into consideration. The dams are affected by its surrounding environmental such as hydrological, meteorological and seismic loading. The Bureau of Reclamation (1987) and U.S. Army Corps of Engineers (1995) mentioned the forces and pressures exist on the dam such as the own weight loads, reservoir and tail water loads, uplift, silt pressure, Wind, and Seismic forces.

The seismic loads that are existed on the dam monolithrely in general on the amplitude and the duration of the ground motions. There are combined effects of the interaction among dam's bodies during the earthquake excitation. They are the reservoir and foundation interaction which may influence the structural response of concrete dams and can lead to excessive failure.The magnitudes of maximum compression and tension stresses at the dam's faces (toe and heel) rapidly change during the earthquakes as a result huge variation in stresses can be observed.Hence, there is a significant importance to study the several aspects that influence the seismic response behavior of the concrete gravity dams for its safety.

The modeling and analysis of the complicated applicationslike concrete dams needs to understand the structural behavior in the static and dynamic loading, boundary conditions of the system, and the redistribution of the loads on the structural elements during failure mechanism. With the advance of powerful finite element analysis (F.E.A) techniques, these problems have been solved over the past few decades in the application of concrete structures.Theoretically, to take the advantage of the dam's geometrical characteristics most dams structural analyses were performed as a 2-Dplane element assumption. However, in some cases the comparison between 2-D and 3-D are required due to the variation of the rigidity and boundary condition along the dam monolith like the dams that are constructed in V-shaped or irregular valleys.These will lead to increase the stresses at the upstream or the downstream faces of the dam body.

A number of small-scale models experimental tests on prototypes of concrete gravity dams had been produced in the last years. A lot of these were conducted using shake tablethat can be used to evaluate seismic performance of structures. It helped to predictstructural response that associated with failure, such as in increasing in maximum stresses and the concrete gravity dam sliding.The main issue of these tests is to study the responsevalidation between the designed finite element models and the prototypes of the concrete gravity dams.

This study focused on the dynamic response of a concrete gravity dam. The dam model was selected fromthe literature thesis of Tomas Horyna in1999. He studied thesliding of a scaled (1:30) prototype response of a single monolith with a low to medium height concretegravity dam at the failure stage. The work includedmodal shapes of the scaled model, 2-D and 3-Danalytical studies using ANSYS 16 commercial software.

2. Numerical methods of ANSYS

ANSYS 16 software is a tool which provides the ability to simulate every structural aspects, including linear and nonlinear analysis, modal analysis that determines vibration characteristics and advanced transient phenomena involving dynamic effects & complex material behavior (ANSYS, Inc.).

PLANE42 is the element type which used to represent the 2-D modeling of solid structures. This element can be used either as a plane element stress or strain having two degrees of freedom at each node.Solid65 and solid185 are used for the three-dimensional modeling of the solid concrete structures. For structural dynamics problems, the principle of virtual work of ANSYS software specifies the linear finite element semi-discrete equation of motion Eq. (1):

$$[M]\{\ddot{U}(t)\}+[C]\{\dot{U}(t)\}+[K]\{U(t)\}=\{F^{a}(t)\} \qquad \text{Eq. (1)}$$

Where:

$[M]$ = structural mass matrix

$[C]$ = structural damping matrix

$[K]$ = structural stiffness matrix

$\{\ddot{U}(t)\}$= nodal acceleration vector

$\{\dot{U}(t)\}$= nodal velocity vector

$\{U(t)\}$= nodal displacement vector

$\{F^{a}(t)\}$= applied load vector

And the nonlinear semi-discrete equation of motion Eq. (2) is given as follows:

$$[M]\ddot{U}(t)+ [C]\{\dot{U}(t)\} + \{F^{i}((t)\}= \{F^{a}(t)\} \qquad \text{Eq. (2)}$$

Where:

$\{F^i(t)\}$= internal load vector

Westergaard technique is considered one of the famous finite element approaches for modeling the hydrodynamic pressure influence during the earthquake excitation and sometimes called added mass technique. Westergaard (1931) represented the dynamic water pressure as added mass acting in the interface between the water and the structural plane or solid elements. The added water mass ($m_{H.D.}(z)$) in a specific height of the dam surface can be determined using equation 3.

$m_{H.D.}(z) = \frac{7}{8}\rho\sqrt{HZ}$ Eq. (3)

Where ρ, H, and z are the density of water, the reservoir height, and the depth of water from the top surface respectively.

3. Finite element modeling implementation

The analytical model had the scaled coordinates of Tomas experimental model. Therefore the height of the model was 45 m with maximum water level of 43.2 m as illustrated in figure (1.a). The width of the monolith base was 36 m.The foundation rock was modeled 20 m below the base of the dam and the same distance for each upstream side and downstream side.The concrete material properties of the analytical model weremodulus of elasticity equal to 27000 MPa, mass density of 2580 kg/$m^3$and Poisson ratio of 0.22. These values were obtained from corestests conducted on one of BC Hydro dams of identical shape and size (Powertech Labs, 1996).The damping of the dam model was considered with the value of 2%. The foundation rock modulus of elasticity was assumed to be 15000 MPa, Poisson ratio of 0.25, and massless foundation property. The full scale dam finite element model for the prototype dam monolith was designed to be relatively simple with a coarse mesh as shown in figure (1.b) in order to keep the computational times of nonlinear time history analyses at an acceptable level. In addition, the model contained of contact elements interface distributed at the dam base to simulate the foundation interaction area between the monolith and the rock foundation. Moreover the model contained added mass elements on the upstream side nodes of the dam monolith to simulate the hydrodynamic reservoir effect through the ground motion.

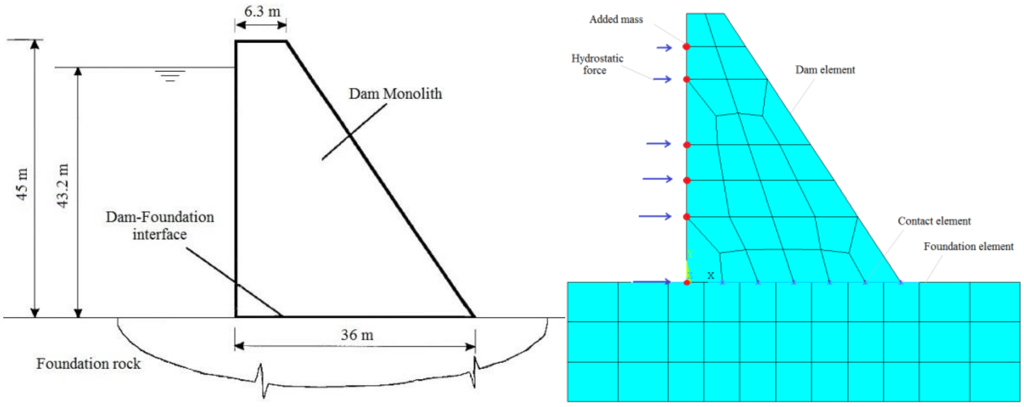

Fig.1.a dimension of the scaled model Fig.1.b the mesh of the F.E. model

Fig.1 The dimension and the mesh of the analytical model

4. Modal response of dam-foundation system

The objective of the modal analyses was to obtain the natural frequencies and mode shapes of the structural system. During the modal analysis of the dam model the contact elements acted as linear springs. The natural frequencies of the unbonded base model were presented in table 1 for the two dimensional dam monolith with full reservoir system. The results were compared by Tomas scaled dam results and they had the same values for the four modal shapes presented in the table. The natural frequencies of the dam monolith with the full reservoir were lower than those for the case without water. In order to clearly visualize the character of every mode, the deflection shapes of the first three modes were presented in figure 2.

Table 1.Natural frequenciesanalyses results

Mode No.	Tomas model natural frequencies (HZ)	This study model natural frequencies (HZ)
1	3.7	3.69
2	9.2	9.17
3	14.2	14.18
4	25.5	25.50

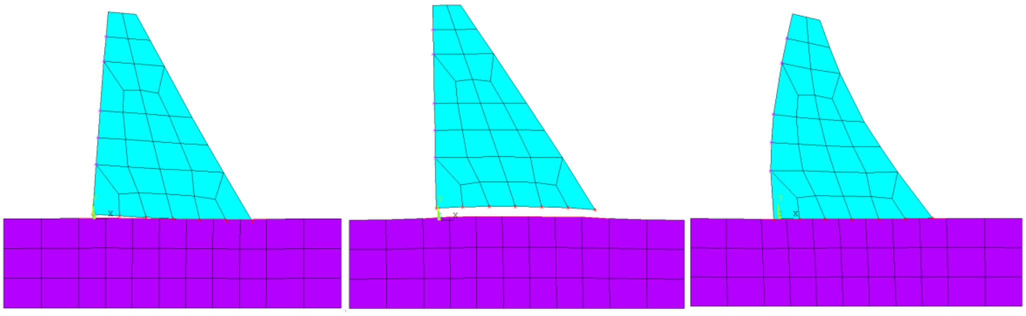

Fig.2.a mode 1 Fig.2.b mode 2 Fig.2.c mode 3

Fig.2 Modal shapes of 2-D dam model

5. Two and three dimensional dynamic analysis

Three different models were prepared to represent the influence of the two and three dimensional analysis during the sliding mechanism failure of the concrete gravity dam during the seismic load effect. The bottom and the end sides of the rock foundation were implemented with fixed supports for the finite element models. The three models were described as follow:

Model I: Two dimensional model (figure 1.b)

Model II: Three dimensional uniform cross section model (figure 3.a).

Model III: three dimensional model with side abutments effect(figure 3.b).

The dimensions of the three dimensional models were the same domination of the 2-D model with very close coarse mesh. The longitudinal dimension of the 3-D models was assumed to be three times the height of the dam.

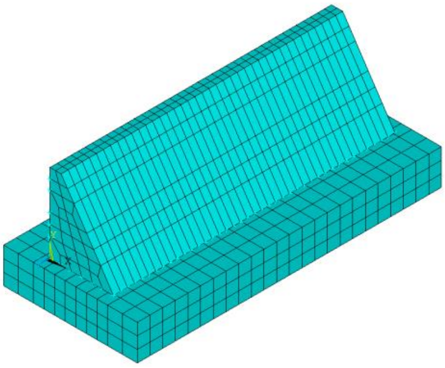

Fig.3.a Model II

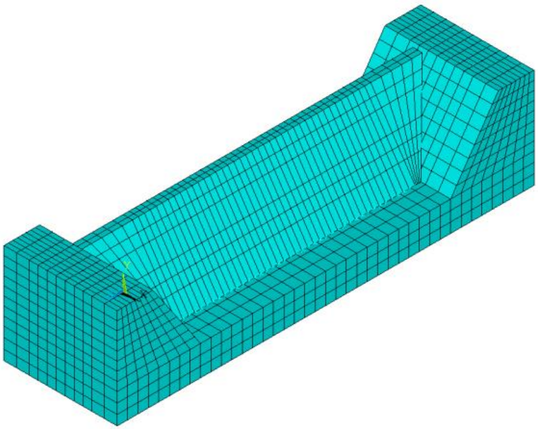

Fig.3.b Model III

Fig.3 Three dimensional F.E. Models for seismic Analysis

6. The Seismic Loading

The seismic excitation,usedin the analyses,wasscaled time history records of 1985Nahanni earthquake. This event included horizontal direction acceleration readings as shown in Figure 4 with peak ground accelerations 0.328 g in the transverse direction and 20 sec time duration. The ground acceleration readings were scaled to reach 1.04g peak ground acceleration in order to represent excessive seismic excitation.

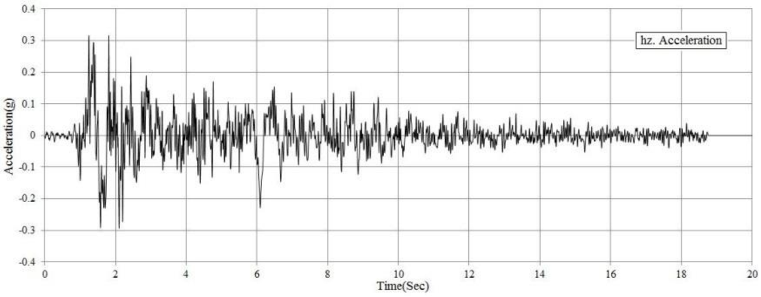

Fig.4 Horizontal component of 1985 Nahanni earthquake

Prior to the dynamic simulation, the finite element model was subjected to gravity loading and hydrostatic pressure along the dam upstream side. These loads were specified in two consecutive static steps and considered as being incrementally increasing until they reached their full magnitudes. The third step started with the dynamic analysis in which the horizontal ground accelerations were applied to all nodes at the base of the dam considering the hydrodynamic effect. A time increment of 0.005 sec had been chosen for the simulation. Uplift pressurewasnot been included in this study.

7. Seismic analysis results

The three models have been analyzed in time domain with different analyses types using Nahanni earthquake acceleration records as the input motion. After the completion of analyses, the stresses in y-direction at the heel regionof the three modelswere comparedas shown in table 2. The selectedcrosssectionslocation for model II and model III were the middle section of the longitudinal direction for the dam monolith.

Table 2. Y-Stress results for the gravity and hydrostatic analysis

Model No.	Grav. Analysis (pa)	Hyd.Analysis (pa)
Model I	1.70 E6	0.93 E6
Model II	1.56 E6	0.99 E6
Model III	1.59 E6	1.01E6

As shown in Table 2, the non-linear analyses results for 2-D and 3-D dam models were very close, where the peak Y-stress value at the dam heel in model III didn’t exceed 6.5 % from the 2-D resultsduring the dam own weight analysis. The static analysis which represented the hydrostatic pressure of the reservoir didn’t exceed 8.6 % for the comparison between the three models. However the sliding failure mechanism for the models may be differ. Therefore getting the sliding failure response during the ground motion analyses should be represented as shown in figure 5 for the three models.

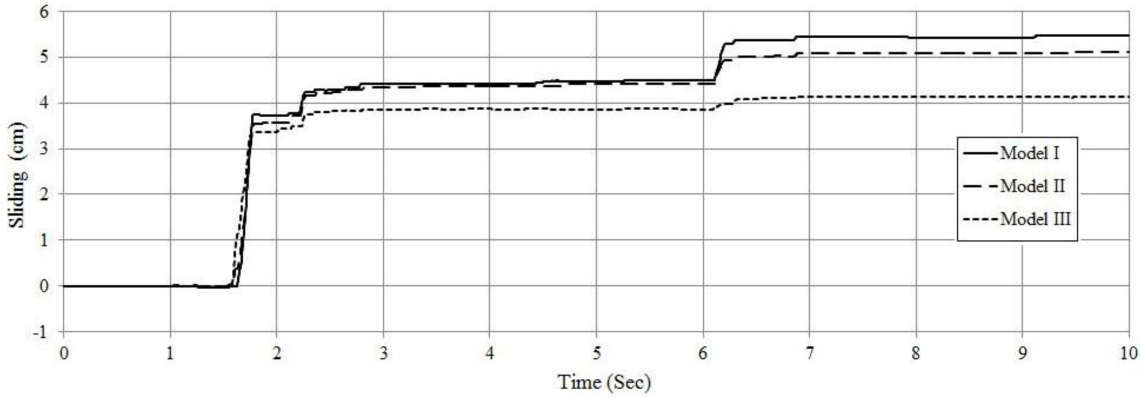

Fig.5 Sliding failure for the three models through Nahanni earthquake

Figure 5 showed the sliding analytical results of the three models during the duration 10 sec through the Nahanni earthquake. The sliding values were 5.47, 5.1, and 4.14 cm for model I, model II, and model III respectively. The difference between model I and model II didn't exceed 7 %. However there was a noticeable change in the slidingvalue of the third model when compared with first model simulation (model I) with difference reached to more than 24 percentages. The significant sliding response of the concrete dam model started at 1.6 second till 2 second. This excessive behavior caused from the peak earthquake acceleration magnitudes through 1 to 2 sec as shown in figure 4.

8. The conclusion

Generally the safety assessments of the concrete gravity dams consider the stability of the structure against sliding and overturning. Sliding stability is defined by the ratio between sum of vertical forces and sum of horizontal forces through the traditional design procedures. This method is characterized by easy calculation and safe the time of the structures design. However it does not take the interaction between the foundation and the dam structure into consideration and the influence of the longitudinal direction stiffness changes during the analysis.Sliding mechanism of the dam system is considered complicated issue especially in the dynamic analysis. Therefore the analyses using finite element softwareswere spreading through last years to assess the stability of the concrete structures during seismic loads.

The modal characteristics of the full scaled concrete dam model with unbonded base wereextracted using commercial ANSYS 16 software and compared with previous study.It was observed that thefinite element model results were very convenient through gravityand hydrostaticanalyses. Two and three dimensional full scaled dam models with different structural stiffnessin the longitudinal direction were used to assess the seismic responses of the concrete gravity dam. The comparison between the results of different models indicated significant difference in the peak sliding value during the dynamic interaction of dam-foundation system. The effect of the dam monoliths on the steep slope at both banks can be reducedthe sliding responses of the monoliths on the river bed into 24 percentages during the Nahanni ground motion. However the changing in the foundation homogeneity may lead to excessive structural rotation failureduring the dynamic loads.

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