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The Dynamic Behavior of Dam-Reservoir-Foundation Interaction System

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الملخص

تعتبر السدود الثقيلة من اهم وأضخم الإنشاءات الخرسانيه المدنية التي يبنيها الإنسان حيث ان انهيار هذا المنشأ يسبب كثيرا من الدمار وخسائر للأرواح البشريه. الطرق القديمه لتصميم هذه المنشئات الخرسانيه هي عملية التأكد من سلامة السدود من انهيارات الانزلاق والانقلاب وزيادة الاجهادات في الجسم الخرساني عن الإجهادات المسموح بها. هذه الطريقه التقليديه مازالت مستخدمه في التصميم مع انها لا تأخذ في الاعتبار تأثير الانفعالات بين جسم السد والأساسات ووجود مياه في الخزان وخصيصا أثناء أحمال الزلازل. هذه الدراسه صممت لدراسة نموذج ثنائي الأبعاد لهاذه المأثرات على جسم السدود الخرسانيه أثناء التحليل الانشائي لها بستخدام برنامج العناصر المحدودة (ANSYS 16). تم عمل هذه التحليلات الأنشائيه للسد الخرساني بإفتراض انها خطيه و تمثيل المياه بعنصر غير لزج وغير قابل للانضغاط. تم دراسة أيضا الزمن الدوري لعدة نماذج مختلفه للسدود لدراسة تأثيرها على الخواص الديناميكيه للمنشأ. النتائج العدديه لهاذه الدراسه أثبتت أهمية الأخذ في الإعتبار تمثيل المياه في الخزان والأرض أثناء التحليل الأنشائي للسدود الخرسانية. بالإضافه الى ذلك التأثير الملحوظ لمرونة أساسات السدود على تغير نتائج إجهادات الضغط والشد في جسم السدود الخرسانيه الثقلية.

Abstract

Gravity dams are considered one of the most important and complex concrete structure, while their failure consequent destructions and human loss. The traditional design procedures check the safety of the structure against sliding, overturning, and bearing capacity limits. However there are structural interactions for the dam body don't considered by the designer. In this study 2-D dam-reservoir-foundation system is analyzed using finite element modeling (ANSYS coding) to investigate the behavior of the reservoir and foundation on the dam monolith through seismic loads. Dam and foundation are assumed to be linear and elastic while reservoir's water is considered acoustic, inviscid and incompressible element. The present study involves also the dam modal shapes for different models. Numerical results show the merits of the suggested reservoir and foundation modeling for the gravity dam simulation. The results confirm also that the foundation flexibility significantly affects the compression and tension stresses of the dam model through the time history analysis.

Keywords: Concrete Gravity Dam, Earthquake Ground Motion, Soil-Structure Interaction, Acceleration Time History, Modal Analysis.

1. Introduction

A dam is the massive structure that is used in the development and management of water of the river basin. Dams classified according to several factors such as the construction materials and the design procedures. Concrete gravity dams are considered the stiffest types that resist all the kinds of external loads or pressures with the structural own weight. The forces that exist in the design of the concrete dam are the structural own weight, hydrostatic loads, seismic loads, hydrodynamic pressure, thermal loads, sediment loads, etc. Bureau of Reclamation, and U.S. Department of the Interior (1987) mentioned that this type of structure is most widespread and requires less maintenance compared by the other types of dams. It usually consists of two sections which are the non-overflow section and the overflow section or spillway section.

Failure of concrete dams leads to the tragic event during the sudden release of reservoir. Hence earthquake resistant design of concrete gravity dams is important issue. However the dynamic analyses of the solid structures are considered complicated problems. There are many assumptions and factors that taken into consideration during the design stage. Prior the geometric design or safety evaluation of the structural system, the boundary condition and the system interactions should be selected carefully to insure the validation of the structural model. Finite element softwares are used nowadays as powerful tools that can analyze the complicated structural systems with very good accuracy and least computational time.

The response of concrete gravity dams subjected to seismic loading is a combined effect of the interaction analyses (Ghaemian et al. 2005). There are the reservoir and dam structure interaction and the foundation-dam interaction. The inertia effect between the dam and the reservoir, causes the hydrodynamic forces on the dam, can be modeled in the finite element system by added mass approach or inserting the water element interaction in the model. In this paper the dam-reservoir-foundation interaction influence were studied during an earthquake excitation. For this purpose different finite element models of two dimensional concrete dam type were analyzed using commercial software ANSYS 16.

2. Analysis Model and material properties

Koyna concrete dam that is situated in Maharashtra is selected as a case study for this paper. This dam has a height of 103 m and width at its base of 70 m as shown in figure 1. The maximum observed reservoir height at the time of the earthquake was 91.75m. The dam was rested on 410 × 200 m rock foundation and the reservoir assumed to be full with length 200 m as shown in the figure. The dam body was modeled as 2-D plane stress element.it is simulated in ANSYS using PLANE 182 element. The reservoir and foundation were modeled in plane strain state. PLANE 182 and acoustic element FLUID 29 were used for the modeling of the foundation and reservoir respectively. The bottom of the foundation was assumed to be fixed with Symmetric boundary conditions of the both foundation sides. The ends of the foundation block and the reservoir had been simulated with this boundary consideration to represent the unbounded nature for the water and earth medium. Chopra et al. (1980) and Vargas et al. (1989) gave all the material properties of dam, foundation, and reservoir of Koyna dam and they were summarized in table 1. The material damping ratio was chosen with a value of 5 % for the first mode shape of the dam structure.

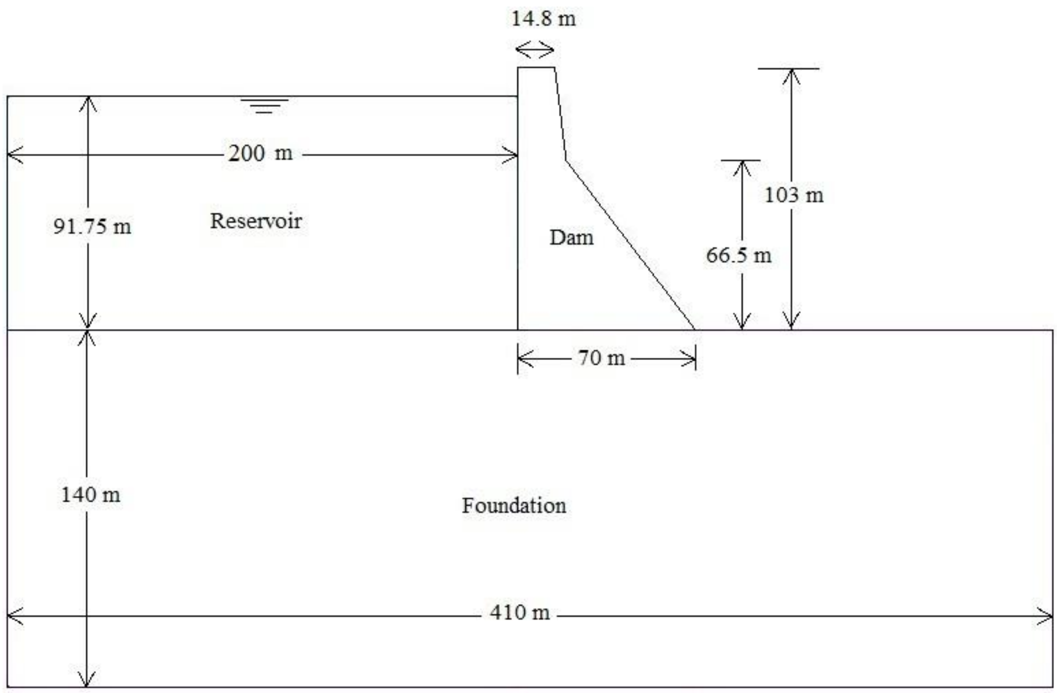

Fig.1 Reservoir-Dam-Foundation dimensions of Koyna dam model

Table 1: The material properties of the dam, water and foundation rock

Dam Body	Elastic Modulus (Mpa)	31027
	Mass Density (kg/m^3)	2643
	Poison’s Ratio	0.2
Rock Foundation	Elastic Modulus (Mpa)	62054
	Mass Density (kg/m^3)	3300
	Poison’s Ratio	0.33
Water	Mass Density (kg/m^3)	1000
	Speed of pressure wave (m/s)	1440
	Wave reflection coefficient	0.5

3. Modal analysis

The foundation and reservoir affect the modal frequencies and the dynamic response of dams structures during the earthquakes. A parametric study is performed here to indicate the combined effect of foundation and reservoir on the dynamic response of the dam. Figure 2 represents the differences of the natural frequencies for three dam models. The three cases are the Koyna dam with fixed support foundation and empty reservoir (case 1), the effect of the foundation with empty reservoir on the modal frequencies of the dam object (case 2), and the reservoir-dam-foundation interaction influence (case 3). It can be inferred that the natural frequency of dam model with rigid foundation and empty reservoir (case 1) is maximum. Furthermore a minimum value for the fundamental frequency is obtained when dam-reservoir-foundation (case 3) interaction is considered. There is 17% decrease of modal frequency for the first mode difference and more than 60% decrease of modal frequencies of other higher modes. This phenomenon occurs because when reservoir interaction is considered in the analysis the water causes increase in the inertial force acting on the dam structure by the effect of the hydrodynamic force. Hence the water in the reservoir leads to changes in the dynamic characteristics of the system by modifying the mode shapes and decreasing the frequency of vibration. Figure 3 shows the first three modes shapes of Koyna dam model with rigid base and empty reservoir.

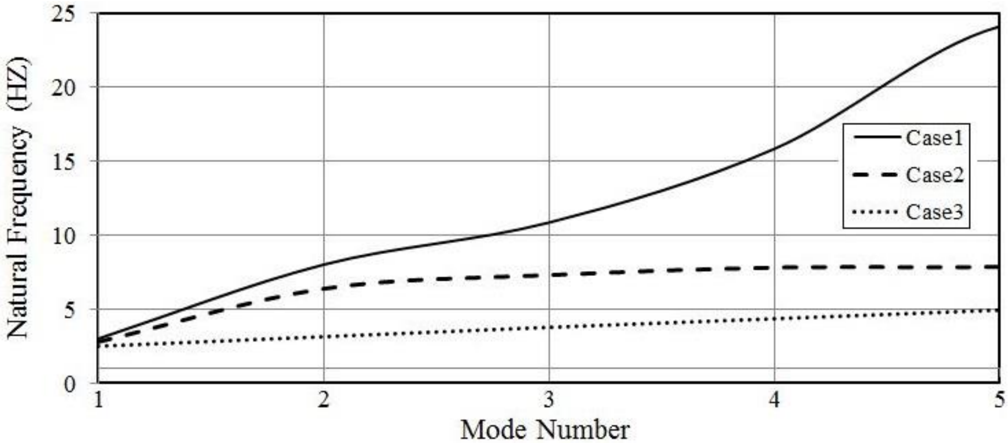

Fig.2 The modal frequencies three different dam models

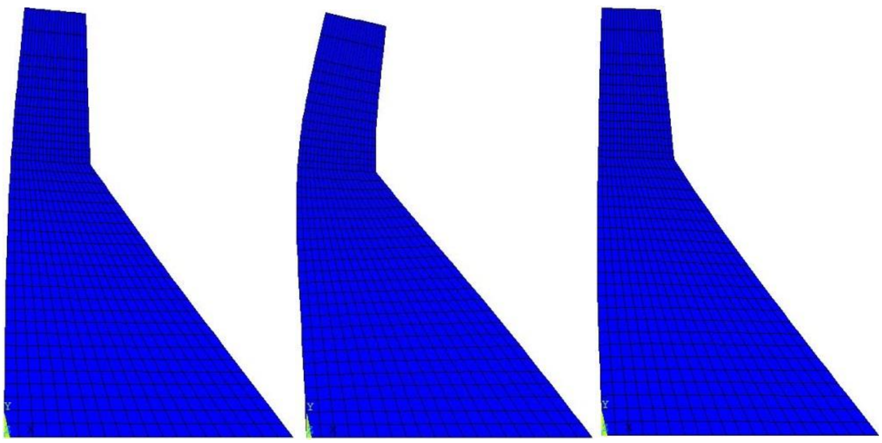

Fig.3.a mode 1 Fig.3.b mode 2 Fig.3.c mode 3

Fig.3 Modal shapes of case 1 model

4. Dam-Reservoir-Foundation system seismic analysis

The dynamic excitation used in the analysis is the acceleration records of 1967 Konya earthquake. This event included two components in the horizontal and vertical directions. These records are shown in Figure 4. The peak accelerations are 0.474 g in the transverse direction and 0.31 g in the vertical direction with 10 sec time duration for each case.

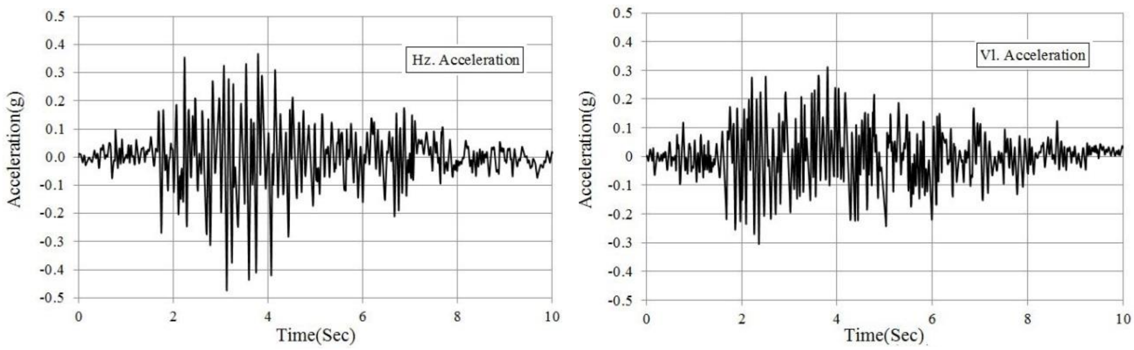

Fig.4.a Horizontal component Fig.4.b Vertical component

Fig.4. Koyna earthquake on December 11, 1967

Linear time history analysis has been carried out on dam-reservoir-foundation system using ANSYS 16 software. Figure 5 represents the crest horizontal displacement for the finite element model with maximum amplitude of 6.5 cm at time 4.53 second for the Koyna earthquake. The negative displacement value represents the movement toward the upstream direction and vice versa for the downstream movement. Figure 6 illustrated the variation in stresses in Y-direction at the zone of downstream slope change. These values vary with high amplitude during the ground motion analysis and exceed the tensile strength of Koyna concrete dam (2.9 MPa). Chopra and Chakrabarti (1971); Chopra and Chakrabarti (1973); Jansen (2012) observed that the damage occurred at this zone of the Koyna dam.

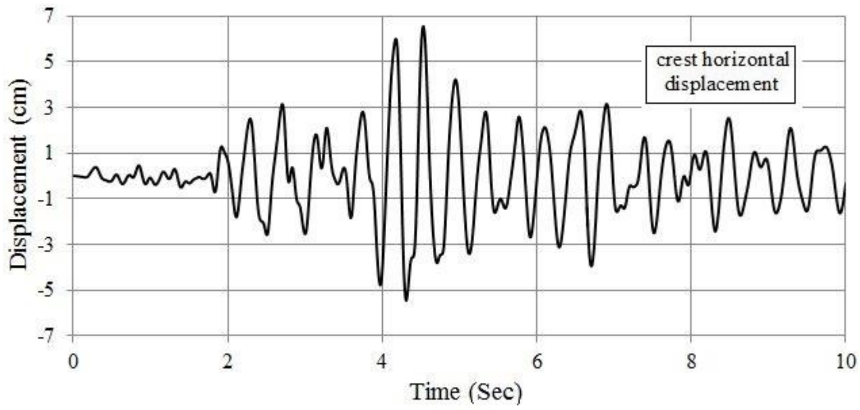

Fig.5. Dam crest horizontal displacement during Koyna earthquake analysis

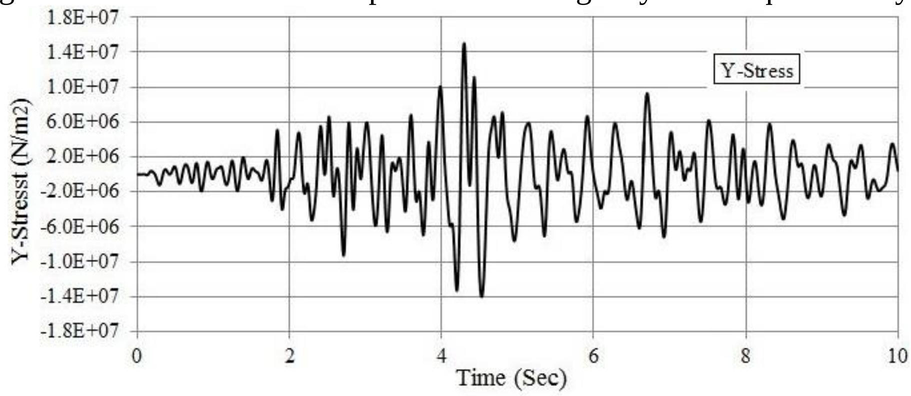

Fig.6. downstream Y-Stress values during Koyna Earthquake

5. Effect of foundation flexibility

Numerical parametric study was carried out to study the effect of foundation flexibility on Koyna dam model during the time history analyses. This study was performed for five values ratios from 1 to 5. The ratio was represent E_f $/E_c$, where E_f and E_c was foundation and concrete modulus of elasticity respectively. The comparison of Y-stresses component at heel and toe of the Koyna dam were summarized in table 2. The stress values illustrated the tension and compression peaks magnitudes for heel and toe respectively during the Koyna earthquake. It is obvious that the foundation flexibility affect the maximum stresses of concrete dam under seismic excitation. The maximum compression stress at dam toe is 3.05E+6 Pa for E_f/E_c=1, while least stress equals 7.96E+5 Pa for E_f/E_c=5.

Table 2: Results for Maximum Y-Stresses during seismic loads in Pa

E_f/E_c	Tensile stress at heel	Compression stress at toe
1	1.09E+07	3.05E+06
2	9.05E+06	1.76E+06
3	6.26E+06	8.23E+05
4	5.71E+06	8.08E+05
5	5.39E+06	7.96E+05

6. The conclusion

It can be inferred that the empty reservoir and fixed foundation maximize the natural frequency of the dam model during the modal analyses. Furthermore, a minimum value for the fundamental frequency was obtained when dam-reservoir-foundation interaction was considered. It is obvious that the water presence of in the reservoir and the foundation modeling affect the behavior of the dam model under seismic excitation. On the other hand the flexibility of the rock foundation in the finite element model affect the seismic dam response and the finite element results, while the increase of the modulus of elasticity for the foundation decrease the compression and tension stresses on the dam toe and heel respectively.

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