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Effect of Concrete Nonlinear Parameters on the Seismic Response of Concrete Gravity Dams

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Abstract—Behavior of dams against the seismic loads has been studied by many researchers. Most of them proposed new numerical methods to investigate the dam safety. In this paper, to study the effect of nonlinear parameters of concrete in gravity dams, a two-dimensional approach was used including the finite element method, staggered method and smeared crack approach. Effective parameters in the models are physical properties of concrete such as modulus of elasticity, tensile strength and specific fracture energy. Two different models were used in foundation (mass-less and massed) in order to determine the seismic response of concrete gravity dams. Results show that when the nonlinear analysis includes the dam- foundation interaction, the foundation's mass, flexibility and radiation damping are important in gravity dam's response.

***Keywords*—**Numerical methods**;** concrete gravity dams; finite element method; boundary condition

I. Introduction

THE operation of mega-structures such as concrete gravity dams when subjected to an earthquake can cause severe damages to the structures. Nonlinear dynamic behavior of concrete gravity dams has been the subject of many researches. To investigate seismic safety of concrete gravity dams, many researchers worked on developing numerical models.

Pal [1] analyzed concrete gravity dams using nonlinear models. He considered the Koyna dam, assuming rigid foundation and excluding the dynamic interaction effect of the reservoir. El.Aidi and Hall [3],[4] included the smeared crack model for considering the nonlinear behavior of concrete gravity dams. In their research, the reservoir interaction was considered and the foundation was modeled as a rectangular mass-less region connected to a semi-infinite visco-elastic half space. Using the size reduced strength criterion (SRS), caused that the crack profiles to be unrealistic. Vargas-Loli and Fenves [5] used the smeared crack model with the brittle fracture criterion to consider the seismic response of Pine Flat dam. The crack profiles were diffused and due to sudden release of energy in small fractured elements, numerical instability was observed. Ghaemian and Ghobarah[6] used staggered displacement method in two-dimensional space in nonlinear analysis of concrete gravity dams under dynamic loads. Guanglun et al.[7] included the smeared crack model that was concluded by Leger and Bhattacharjee. In their study a re-meshing capability in the crack tip was used such that the re-meshed elements have boundaries parallel to the crack profile. The proposed method lead to more real crack profiles. Mirzabozorg and Ghaemian[8] proposed a three-dimensional smeared crack approach to model the tensile fracture in static and dynamic analysis. Calayir and Karaton[9] investigated seismic analysis of concrete gravity dams with considering the effect of dam-reservoir interaction. In their study a co-axial rotating crack model (CRCM), which included the strain softening behavior, was used for analysis of Koyna dam.

II. Dam-reservoir interaction

The equation of motion of reservoir can be represented by Helmholtz's equation in the following form:

$$\frac{1}{C^2}\ddot{p} = \nabla^2 p \tag{1}$$

Where P and C are hydrodynamic pressure and speed of pressure wave in water, respectively.

Boundary condition at the free surface in the reservoir is written as:

$$p = 0 \tag{2}$$

The included boundary condition that could model complete absorption of propagating waves at the far-end boundary of reservoir is called Sharan[10] boundary condition and represented as follow:

$$\frac{\partial P}{\partial n} = -\frac{\pi}{2h}P - \frac{1}{V}\dot{P} \tag{3}$$

Where h is the height of reservoir and n is the vector normal to the surface.

At bottom and sides of reservoir, Helmholtz's equation is used in sediment field, assuming only vertical excitation of hydrodynamic pressure waves and the following equation is achieved:

$$\frac{\partial p}{\partial n} - q\frac{\partial p}{\partial t} = -\rho a_n^s \tag{4}$$

Where

$$q = \frac{1-k}{(1+k)C} \tag{5}$$

Where c and k are velocity of pressure wave at bottom and sides of reservoir and wave reflection coefficient, respectively.

III. The Dam-reservoir-foundation problem

The effect of dam-reservoir-foundation interaction is considered with two differential equations of the second order that can be written as follows:

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=\{f_1\}-[M]\{\ddot{u}_g\}+[Q]\{p\}=\{F_1\}+[Q]\{p\} \quad (6)$$

$$[G]\{\ddot{p}\}+[C']\{\dot{p}\}+[K']\{p\}=\{F_2\}-\rho[Q]^T\{\ddot{u}\} \quad (7)$$

Where [M], [C] and [K] are mass, damping and stiffness matrices of structure including dam and foundation and [G], [C´] and [K´] are mass, damping and stiffness matrices of the reservoir, respectively. [Q] is the coupling matrix and $\{f_1\}$ is the vector of body force and hydrostatic force. $\{F_2\}$ is the component of the force due to acceleration at the boundaries of the dam-reservoir and reservoir-foundation. {p} and {u} are the vectors of pressures and displacements. {ü} is the ground acceleration and ρ is the density of the fluid. The dot represents the time derivative.

IV. Nonlinear analysis

The smeared crack model was represented by Bhattacharjee and Leger [2], is used to evaluate the nonlinear behavior of concrete gravity dams with dam-reservoir-foundation interaction using the staggered method of solution that was used by Ghaemian and Ghobarah [6].

V. Numerical results

A. *Case study: Pine Flat Dam*

The tallest monolith of the Pine Flat Dam is selected for evaluating the results of computer code, NSAG-DRI [11] that is used to carry out the nonlinear analysis. The reason of this selection is that this dam was the subject of many experimental and theoretical studies. It 's structure has crest length of 560 m and consists of 37 monoliths 15.2 wide that the tallest of which is 122 m.(Fig.1)

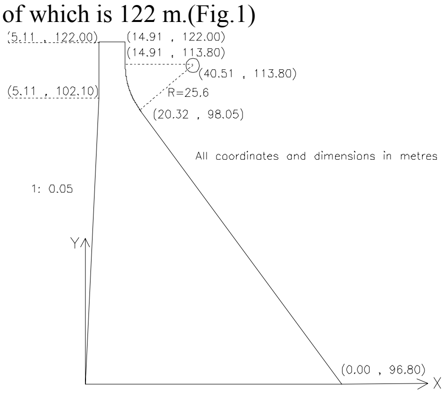

Fig.1 Dimensions of the tallest monolith of Pine Flat dam

The 4-node, quadrilateral, isoparametric finite element model of this monolith in plane stress has been illustrated in Fig. 2. The model had 5664 nodes (3768 nodes at foundation) and 5512 elements.

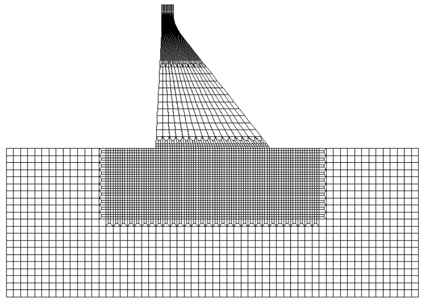

Fig. 2 Finite element model of tallest monolith of Pine Flat Dam

Basic parameters such as modulus of elasticity, unit weight and Poisson's ratio of concrete dam are chosen as 27.58 GPa , 2483 Kg/m^3 and 0.20,repectively. The modulus of elasticity, unit weight and Poisson's ratio of rock foundation are selected as 22.4 GPa, 2643 Kg/m^3 and 0.33,repectively. The tensile strength and fracture energy of concrete dam are taken to be 3.05 Mpa and 300 N/m. A dynamic magnification factor of 1.2 is considered for the tensile strength and fracture energy.

Two models are used for this research, the first of which is flexible mass-less foundation with fixed support at base and roller support for sides [12],[13] (Fig.3). Another model, flexible massed foundation that is shown in Fig 4, such as Lysmer boundary condition, there are horizontal and vertical dampers in both sides of foundation but at the base only there are rollers. It is assumed that foundation has linear behavior in two models. The length and depth of the foundation are 348 m and 126m, respectively.

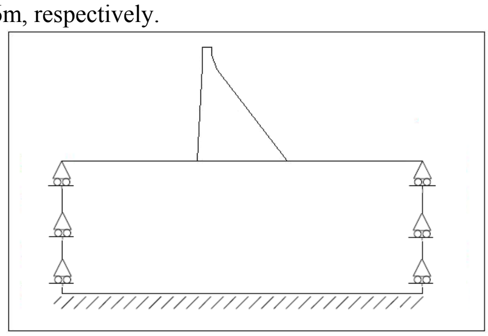

Fig. 3 Boundary conditions in massless foundation model

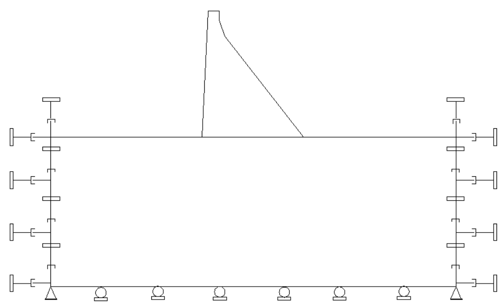

Fig.4 Boundary condition in massed foundation model

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The reservoir's length is ten times as long as the water level in reservoir and the Fig.5 shows the finite element model of reservoir. Sharan boundary condition is used for truncated far end of reservoir [10]. The velocity of pressure wave in water and wave reflection coefficient are taken 1438.66 m/sec and 0.82 respectively.

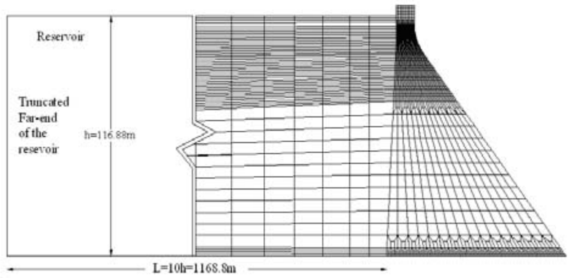

Fig.5 Finite element model of reservoir

For evaluation of the seismic response of dam, Manjil earthquake record is included.(PGA= 0.5g)[14].

B. The effect of nonlinear parameters

In this paper, sensitivity analyses were done for determining the effect of some parameters such as modulus of elasticity(E), fracture energy(G_F), tensile strength(f_t), poisson's ratio(υ) and wave reflection coefficient (α) for mass-less and massed foundation with different boundary conditions .

The results of sensitivity analyses are represented by varying modulus of elasticity(E) or ratio of (Ef/Es) for mass-less and massed boundary conditions. With considering crack profiles, it's observed that decreasing this ratio(0.922 to 0.448) ,causes the stability of structure.

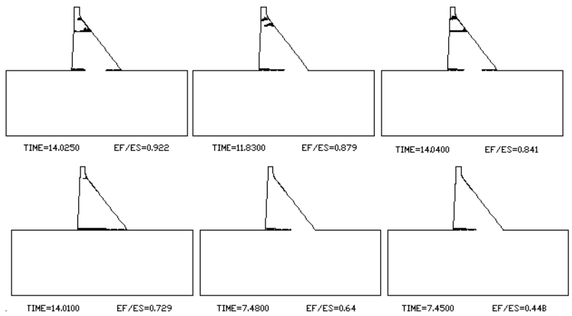

Fig. 6 Crack profiles of system , mass-less foundation, by varying E

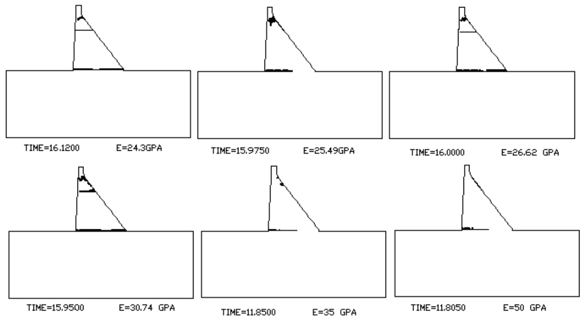

Fig.7 Crack profiles of system for massed foundation by varying E

Fracture energy of dam is increased from 175 to 1000(N/m), and the crack profiles are as following graphs.

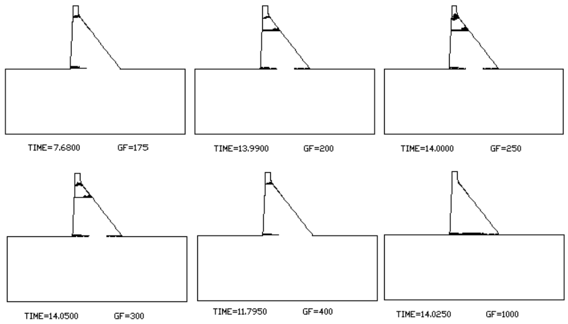

Fig. 8 Crack profiles of system,mass-less foundation, by varying G_F

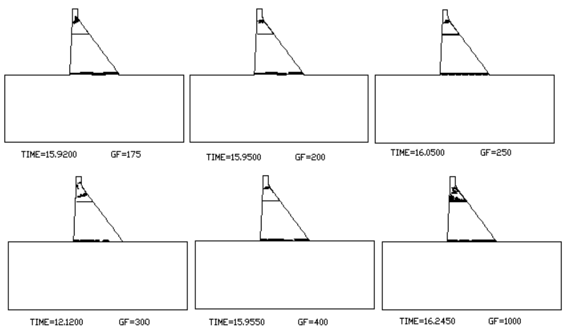

Fig. 9 Crack profiles of system , massed foundation by varying G_F

It's concluded that increasing of G_F causes more stability in mass-less system and instability in massed system unexpectantly and it can be because of nonlinear behavior of system.

Increasing f_t , from 2 to 3.95 Mpa, should cause the system more stable and this result is concluded from fig.10 for mass-less system but this result is not concluded for massed foundation. It's maybe because of nonlinear behavior of system.

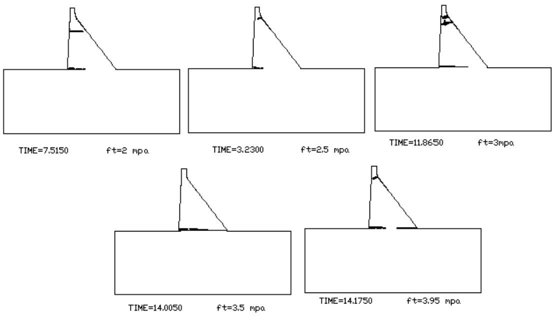

Fig. 10 Crack profiles of system,mass-less foundation,by varying f_t

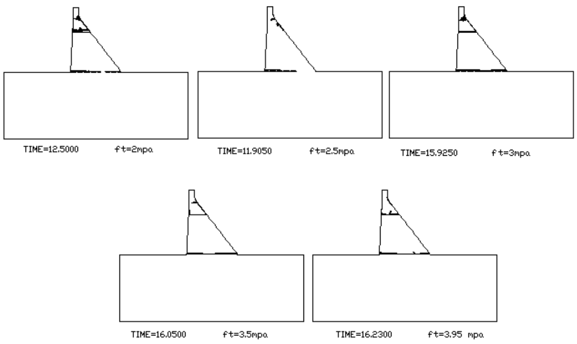

Fig. 11 Crack profiles of system massed foundation by varying f_t

VI .Conclusions

1- When the foundation's mass, flexibility and radiation damping are cared with, the gravity dam's response will be more realistic.

2-In mass-less foundation, it's considered only flexibility and structure damping, neglecting inertia and geometric damping. Then time history of displacement of dam crest increases and it's concluded that nonlinear dynamic analysis of mass-less foundation is overestimated.

3-Considering the geometric damping in nonlinear dynamic analysis of massed foundation decreases time history of displacement of dam crest then damage in system is decreased.

4- Nonlinear dynamic analysis is depended on Ef/ES. Decreasing in ratio of foundation's modulus of elasticity to dam's modulus of elasticity(Ef/ES) causes increasing in dam crest displacement.

5- In nonlinear dynamic analysis, decreasing in ratio of Ef/ES causes decreasing crack profiles.

6-The results show that because of nonlinear behavior , there is' not a special rule or model in system.

7-Increasing of G_F causes more stability in mass-less system and instability in massed system unexpectantly and it can be because of nonlinear behavior of system.

8-Increasing f_t , should cause the system to be more stable and this result is concluded for mass-less system but this result is not concluded for massed foundation. It's maybe because of nonlinear behavior of system.

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