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STATIC PUSHOVER ANALYSIS FOR KOYNA DAM

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ABSTRACT

This paper explores the static pushover (SPO) analysis of concrete gravity to determine the limit state of dam based on the crack profiles. Lateral load for concrete gravity dam that presents the range of base shear caused by seismic loading is statically applied to the dam and the coefficient loads are increased until an ultimate condition is achieved. There are two types of lateral loads which are inertial loads and hydrodynamic loads. The Koyna dam has been selected as a case study for the purpose of the analysis by assuming that no sliding and rigid foundation has been estimated. This method is able to determine three limit states of the dam. The limit states proposed in this study are yielding state, first crack initiation and ultimate state which is identified base on crack pattern perform on the structure model. The displacement of yielding state for Koyna dam is 2.83cm and 4.49cm for the ultimate state. The results are able to be used as a guideline to monitor Koyna dam under seismic loadings.

1. Introduction

Dams are one of the largest structures constructed by human to serve different purposes, such as irrigation, hydroelectric power generation, flood control, domestic and industrial water supply. Dams must be designed with a high safety factor to resist natural forces such as flooding and earthquakes. Nuss et al. (2012) reported the crack damage of the concrete dams caused by the earthquake, which have been experienced by Koyna Dam (1957), Hsinfengkiang Dam (1959), Sefid Rud Dam (1962), Techi Dam (1974) and Takou Dam (2007). In 1999, serious damage to the Shih-Kang Dam, which is located directly over the fault, caused by Chi-chi earthquake with 7.6 M have failed (Nuss et al. 2012).

The location of Koyna dam in India is in highly seismic zone and thus is vulnerable to near-field ground motions (Mohan and Ramancharla 2014). Koyna dam is located on Koyna River in the western of the Indian Peninsula. The dam experienced crack damage caused by Koyna earthquake in December 1967 with magnitude of 6.5 (Anderson et al. 1998; Chopra and Chakrabarti 1973). However, the dam was not in danger from a major failure that required repairs and permanent strengthening (Chopra and Chakrabarti 1973). The criteria of Koyna dam with Koyna earthquake have been studied worldwide as a guideline for designing a concrete gravity dam (Omidi et al. 2013).

Since limited data is available for the actual concrete dams on the field and laboratory tests, the limit state of concrete dams in light of uncertainties calculation is based on theoretical and numerical methods (Alembagheri and Seyedkazemi 2015). Static pushover (SPO) analysis is a method to determine the state of the damage by continuously increasing the lateral load until an ultimate condition is achieved. Alembagheri & Ghaemian (2012) introduced a new concept to verify the limit state of the damage in concrete dams by using incremental dynamic analysis and SPO analysis that do not only consider initial loads but also the hydrodynamic loads. These methods can be applied to obtain indexes for seismic performance evaluation and

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damage assessment (Alembagheri and Ghaemian 2012; Feyza Soysal 2014).

The limit state of the structure is the important parameters to engineers to designing the structures. The limit state of building is able to identify according to FEMA-356, (2000) based on the global collapse capacity. Meanwhile the concrete dam there are no specific code of practice to define the limit state. A few researches have established the method to determine the collapse capacity of the concrete gravity dam which is different with the building. The collapse capacity can be determine based on the cracking pattern perform on the structure. However, the researcher only focused on the specific concrete gravity dam which is Pine Flat dam and Melan dam (Alembagheri and Ghaemian 2012; Feyza Soysal 2014).

2. Methodology

2.1 Numerical Modeling

The structure of the dam has an elongated geometry with constant cross section. The structure of the dam can be determined by plane strain condition because the loading position does not differ along the trend. The depth of the reservoir for Koyna dam is 91.8m and the height of the dam is 103m. The full dimension of Koyna dam as illustrated in Figure 1. The rigid foundation has been considered for this model and the material properties for this model are tabulated in Table 1.

The present study uses the concrete damage plasticity (CDP) model to evaluate the nonlinear seismic performance of the concrete gravity dam (Mridha and Maity 2014; Oudni and Bouafia 2015). The concrete damage plasticity model is to simulate the nonlinear constitutive behaviour of concrete by presenting scalar damage variable to describe the irreversible damage during loading process (ABAQUS 2012; Lee and Fenves 1998; Sümer and Aktaş 2015; Zappitelli et al. 2014). The failure mechanisms of the concrete material, which are cracking in the tension, are considered in this study as shown in Figure 2.

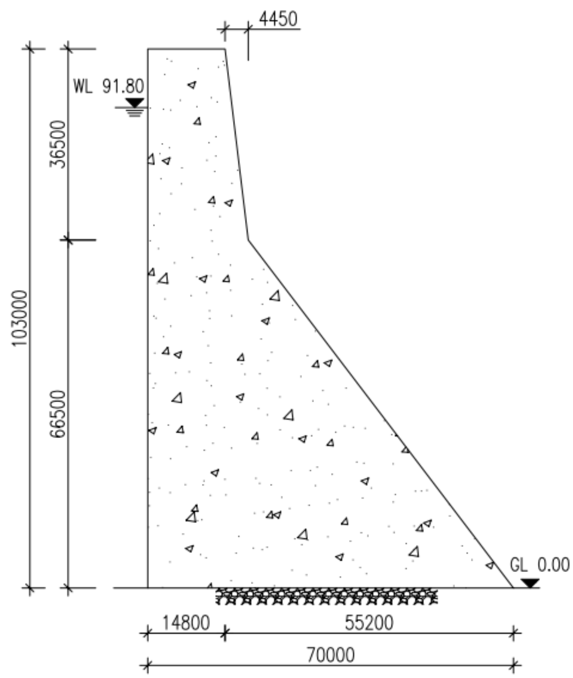

Figure 1: Dimension of Koyna Dam

Table 1: Concrete properties

Material parameter	Value
Modulus of elasticity (E)	31513 MPa
Poisson's ratio (v)	0.2
Density (ρ)	2643 kg/m^3
Dilation angle (ψ)	36.31°
Compressive initial yield stress (σ_{c0})	13.0 MPa
Compressive ultimate stress (σ_{cu})	24.1 MPa
Tensile failure stress (σ_{t0})	2.9 MPa
Damping for the first mode vibration	3%

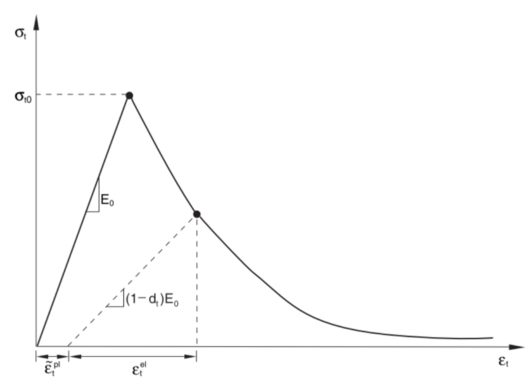

Figure 2: Concrete Damaged Plasticity (CDP) model in tension (ABAQUS 2012)

2.2 Static Pushover (SPO) Analysis

The static pushover (SPO) analysis is a method to determine the performance levels of the structures. It can be defined by applying a static lateral force distribution on the structure to estimate the seismic structural deformations (FEMA-273 1997). Pushover analysis is a method widely used for buildings with well-defined performance level.

There are two types of lateral loads that are generated by earthquakes for concrete gravity dam which is inertial loads and hydrodynamic loads that should be considered for generating the lateral load distribution. The inertial load are the seismic loading that generated respect to the dam that may move in any direction and the hydrodynamic load are created by wave pressure causes a momentary increase in the water pressure. The lateral load distribution applied on the dam increases until achieving the structure failure. The lateral load distribution is considered (Alembagheri and Ghaemian 2012) as:

$$P(y) = F(y) + H(y) \quad (1)$$

$$F(y) = \alpha \times b(y) \times \varphi_1(y) \times \rho_c \quad (2)$$

where, b is the dam width, φ_1 is the normalized first mode shape of the dam, ρ_c is the concrete density, α is the weight factor, *H(y)* is the hydrodynamic load distribution, *F(y)* is the inertial load distribution, *P(y)* is the total lateral load distribution, and y is the height measured from the base of the dam. The hydrodynamic load distribution is derived originally from Westergaard added mass distribution as follow:

$$H(y) = \frac{7}{8}\rho_w \sqrt{h_w(h_w - y)} \quad \text{for } y \le h_w \quad (3)$$

where, ρ_w is the water density and h_w is the reservoir height. The weight factor α in Equation (2) is considered as 2 for Koyna dam so that the total inertial load will be 2 times of hydrodynamic load (Alembagheri and Ghaemian 2012). The distribution of the inertial and hydrodynamic loads along the dam height and the direction of pushover load facing the downstream are shown in Figure 3.

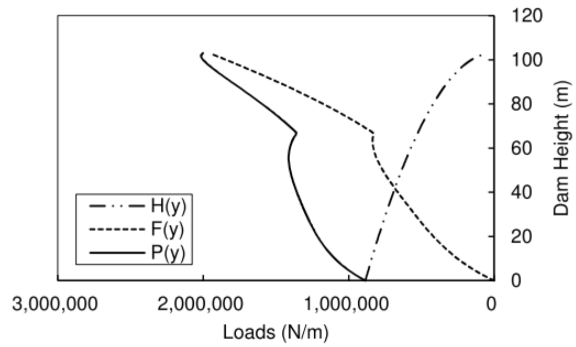

Figure 3: Input lateral distribution of pushover

3. Results and Discussion

3.1 Validation of Numerical Model

The dam has been analysed using two-dimensional plane strain formulations as shown in Figure 1. To validate the accuracy of the numerical model, the results available for the Koyna dam (Nayak and Maity 2013) are considered. The assumed material properties are as tabulated in Table 1. The comparisons of the results indicate the validity of the present numerical model based on natural frequencies (rad/sec) as presented in Table 2 which the percentage different between the current model and the authors is less than 3%. The mode shape of the model similar to the authors shows in Figure 4.

Table 2: Natural frequencies of Koyna dam

Mode	Present	Nayak and Maity (2013)	% of deviation
1	18.87	19.27	2.08
2	50.09	51.50	2.74
3	68.17	67.56	-0.90
4	98.70	99.73	1.03

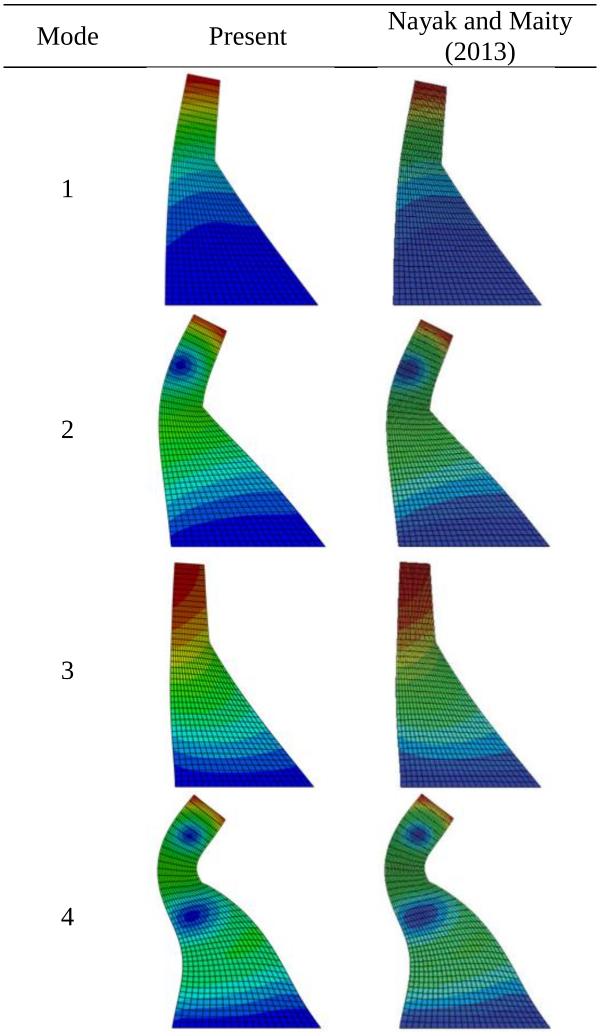

Figure 4: Modal shape of Koyna dam

3.2 Limit State of Koyna Dam

The lateral load pushover is applied statically from the upstream face of the dam to the downstream direction from zero and the coefficient of loads increased. The weight and hydrostatic loads of the dam remain during the analysis of SPO. The lateral pushover loads as illustrate in Figure 3 are using Equation (1) to (3).

The SPO curves are developed for Koyna dam as shown in Figure 5. The results show tension softening which the yielding state is initiated at the heel of the dam in the load coefficient of 0.35 lateral load with 2.83cm displacement. The first cracking appeared at the heel with 0.400 load coefficient, which is equal to 19114kN as illustrated in Figure 6(a).

Lateral load increased until 0.475, which is shown in Figure 6(b). The crack growth and unstable crack developed at the neck from the upstream face to downstream face. Thus, the dam structure loses its stiffness and deform drastically under the lateral loads. This behaviour considered as an ultimate state and the displacement is 4.49cm. Between the load coefficients 0.400 to 0.475, there is stable crack growth at the base of the dam. The summary of limit state for Koyna dam is tabulated in Table 3.

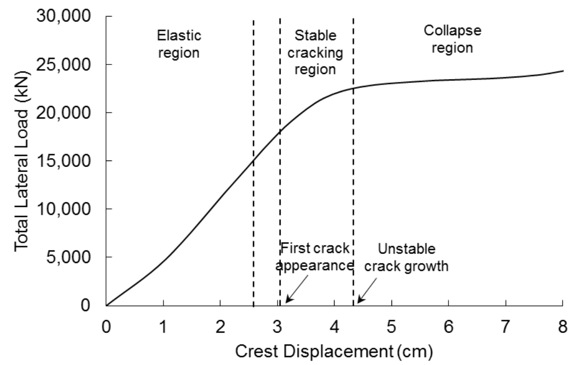

Figure 5: Pushover curves

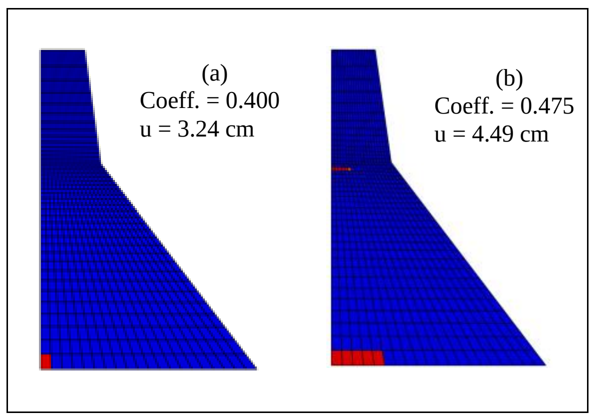

Figure 1: Crack profiles

Table 3: Model responses at three limit states

Limit	Lateral Load (kN)	Displacement (cm)
Yielding state	16725	2.83
Cracking initiation	19114	3.24
Ultimate state	22698	4.49

4. Conclusions

Static pushover (SPO) analysis is a lateral load distribution caused by seismic loading applied statically to the dam by continuously increasing the lateral load coefficient until an ultimate condition is reached. It was observed that the dam started to crack at the heel area with 3.24cm and growth until 25% from the base length of the dam. Unstable crack started to perform at the neck area from upstream face to the downstream which is considered as ultimate state or collapse region with 4.49cm displacement. The displacement of yielding state for Koyna dam is 2.83cm. The results can be developed into a guideline to monitor the Koyna dam under seismic loadings.

More researches are required to define the accurate limit state of a concrete gravity dam. Further study will have to be investigated by considering the upstream and downstream direction of lateral load pushover to identify the minimum values reached for yielding and ultimate state for concrete gravity dam.

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