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Experimental investigation on nonlinear dynamic response of concrete gravity dam-reservoir system

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ABSTRACT

The nonlinear response of concrete gravity dam-reservoir system has been investigated by conducting experiments on small scale model of Koyna dam on a horizontal shake table using sinusoidal chirp motions. Two dimensional models of non-overflow section of Koyna dam have been prepared in the laboratory with a scale ratio of 1:150. To satisfy the laws of similitude, an appropriate ratio of cement, sand, bentonite and water has been mixed to find the target properties of model dam. Dam models have been casted over a wooden base plate using a wooden mould. After setting and drying process the wooden mould has been removed and each dam model has been assembled with a reservoir model after placing them over a horizontal shake table. The interaction between dam and reservoir model has been made in such a manner, so that it can transmit the hydro dynamic force of reservoir water to the dam model without allowing any seepage of water across it. Experiments have been performed on the dam-reservoir system with empty and full reservoir water by applying horizontal sinusoidal chirp excitations to the shake table to observe the basic behaviour, crack formation, crack opening, sliding along crack planes and stability after crack formation of the dam model. The numerical analysis of the system has been carried out using ABAQUS 6.10 considering damage plasticity model. The effect of foundation has been neglected assuming a rigid dam foundation as the dam is placed on a rigid plate. The eigen frequencies of the dam model have been calculated and compared with experimental values to calibrate the analysis model. The crack propagation due to tensile damages is computed and the results are compared with the experimental results. The outcome of the response results shows the correctness of the developed experimental model of dam-reservoir system.

1. Introduction

A gravity dam is a solid structure, made of concrete or masonry, constructed across a river to create a reservoir on its upstream. The section of the gravity dam is approximately triangular in shape, with its apex at its top and maximum width at bottom. The section is so proportioned to resist the various forces acting on it by its own weight [1]. Concrete gravity dams serve electricity generation, water supply, flood control, irrigation, recreation, and other purposes. They are an integral component of the society's infrastructure system. Concerns about their safety in a seismic environment have been growing over the past few decades, partly, because earthquakes may impair their proper functioning and trigger catastrophic failure causing property damage and loss of life [2]. Though gravity dams can survive moderate earthquake motion they present difficult problem if they are built in seismically active areas as little is known about the response of the dam to severe levels of excitation. The damage caused mainly by the cracking of the concrete with subsequent opening and closing of cracks and sliding along crack planes, additional damage can be caused by high compressive stresses resulting from impacts during crack closure and from small contact zones during maximum crack opening [3]. It should be mentioned that the occurrence of cracks does not imply complete failure which is proved by the survival of the 103 m high Koyna dam during an earthquake (1967) with a magnitude of 6.5 Richter scale and with the peak ground acceleration in the stream direction of 0.49 g [1,31]. The duration of the strong shaking lasted about 4 s and the water level stood 11.278 m below the crest. After the earthquake, a major crack was noted at a level of 36.576 m below the crest, which coincides with the level of slope change on the downstream face [4–6]. The other concrete dams known to have suffered cracking as the results of earthquake is Hsinfengking Dam (China,1962), a 104.851 m high buttress dam and the Shih-Gang Dam which was also severely damaged by fault movements and ground shaking during the 1999 Chi-Chi earthquake in Taiwan [7].

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The issues of seismic safety of dams have been looked at with increased attention in various parts of the world in recent years. It has become a major factor in the planning and designing of new dams, proposed to be built in seismic regions and for safety evaluation of existing dams in these regions. To prevent the failure of a dam, it is important to assess its behaviour at any age during its lifetime [8,9], so that remedial measures can be undertaken to strengthen or perhaps decommission the dam at the right time. For the design of an earthquake resistant dam and the evaluation of the safety of an existing dam, it is important to use a rational and reliable dynamic analysis procedure. The analysis procedure should be capable of evaluating the deformations and stresses in a dam subjected to a given ground motion. Various numerical techniques have been used by number of authors to investigate the evaluation of damage in dam. However, smear crack model and discrete crack model have been used by many researchers to study the damage propagation in concrete dam such as Lotfi and Espandar [29]. Ghrib and Tinawi [10] investigated the damages in Koyna dam with an initial damage using pseudo-dynamic earthquake forces. The continuum damage model and co-axial rotating crack model (CRCM), which includes the strain softening behaviour of concrete, has been carried out by Calayir and Karaton [11] to investigate the seismic fracture response of gravity dam. Guangluna et al. [12] proposed nonlinear crack band theory for the seismic fracture behaviour of concrete gravity dams. Khaji and Ahmadi [13] used distinct element–boundary element approach for seismic analysis of cracked gravity dam-reservoir systems. Mirzabozorg and Ghaemian [14] examined the crack profile in the dam using smeared crack approach. Ftima and Leger [15] investigated the stability of cracked concrete dams under seismic excitation by means of rigid block model. A continuum damage model based on continuum damage mechanics was developed by Silva and Castro [16] to represent the nonlinear behaviour of the quasi-brittle material. Mansouri et al. [17] introduced the Bazant's non-linear fracture mechanics criteria for the seismic analysis of the concrete gravity dam. The crack propagation of concrete dams with initial cracks was studied by Zhang et al. [30] during strong earthquakes using extended finite element method.

A number of attempts have been made to mathematically model the nonlinear response of gravity dam during severe earthquake in order to determine whether a gravity dam can remain stable and retain the impounded water [18,19]. But the large amount of variation in the computed behaviour of the dam implies that nonlinear earthquake analysis of concrete gravity dam is not straightforward and is highly uncertain. This uncertainties and the absence of proper field data motivate laboratory experiments on small scale models [20,21]. Many experiments [22–24] have been carried out on small scale models of dam to investigate the dynamic response of concrete gravity dam during seismic excitation. However, the experiments considering the hydrodynamic effect of reservoir water are very rare.

The present study concentrates on evaluation dynamic response of concrete gravity dam-reservoir system by experimental and numerical analysis. Dynamic analysis of a 1/150 scale model of Koyna dam along with reservoir has been carried out in a shake table with high frequency capability. Sinusoidal loadings have been applied to the shake table and the responses of the dam reservoir system have been observed. The small scale modelling of concrete gravity dam incorporates additional demands on properties of model materials. Therefore, a similitude analysis has been carried out and material properties of the model dam have been derived using the similitude equations. A mix of cement, sand, bentonite and water has been used in the mix design of dam model. Several samples have been prepared and tested by trial and error method to find out the exact mix proportion required to arrive at the target material properties used to prepare the dam model. Dam models are casted using the selected mix and pouring it in a wooden mould. At first the casting, curing and drying process are carried out with the horizontally aligned mould. However, in this process, shrinkage cracks develops at the bottom and upper side of the model. To overcome this, the wooden mould is vertically placed and fixed on a wooden base plate using wooden channel nuts and bolts. Materials are poured through top opening and compacted accordingly to ensure no voids remains inside the model. After the setting and drying period, the dam models are de-moulded and each of the dam models along with the wooden base plate is placed on the shaking table where dam models are assembled with a reservoir model which is prepared mainly using perspex sheet. The side of the reservoir which is facing towards dam model is kept open to transfer the hydrodynamic effect of reservoir water to dam model. But the prepared dam model cannot sustain water flow as it starts getting dissolved when come in contact with water. Therefore, to protect the dam model from reservoir water a very thin polyethylene membrane is used at the open side of the reservoir-dam interface. Thus, it prevents reservoir water from seeping through it but transmits the hydrodynamic force to the dam model. Experiments are carried out using horizontal sine chirp motions to determine the natural frequencies of the system. The crack initiation, propagation and response of the structure during crack formation have been observed. A numerical modelling of dam with hydrodynamic effect of reservoir water has been done using ABAQUS 6.10 [25]. The hydrodynamic effect of reservoir has been modelled using Westergaard added mass technique [26]. The stresses at various points and path of propagation of tensile damages are computed and the numerical results are compared with the experimental results.

2. Theoretical formulation

2.1. Modelling of damage plasticity

The uniaxial tensile and compressive response of the material is characterised by damaged plasticity. The stress–strain response under uniaxial tension follows a linear elastic relationship until the value of the failure stress. Beyond the failure stress the formation of micro-cracks is represented macroscopically with a softening stress–strain response, which induces strain localization. Under uniaxial compression the response is linear until the value of initial yield. In the plastic regime the response is typically characterised by stress hardening followed by strain softening beyond the ultimate stress [25]. The uniaxial stress–strain curves can be converted into stress vs. plastic-strain curves by the following equations:

$$\sigma_t = \sigma_t(\tilde{\varepsilon}_t^{pl}, \dot{\tilde{\varepsilon}}_t^{pl}, \theta, f_i) \tag{1}$$

$$\sigma_c = \sigma_c(\tilde{\varepsilon}_c^{pl}, \dot{\tilde{\varepsilon}}_c^{pl}, \theta, f_i) \tag{2}$$

where $\tilde{\varepsilon}_t^{pl}$, $\tilde{\varepsilon}_c^{pl}$ represent the equivalent plastic strains and, $\dot{\tilde{\varepsilon}}_t^{pl}$, $\dot{\tilde{\varepsilon}}_c^{pl}$ are the plastic strain rates. θ is the temperature and f_i refers to other predefined field variables. Subscripts, t and c correspond to tension and compression, respectively.

The degradation of the elastic stiffness of the material when the specimen is unloaded from any point on the strain softening branch of the stress–strain curves, is characterised by two damage variables, d_t and d_c, which are assumed to be functions of the plastic strains, temperature, and field variables and represented as:

$$d_t = d_t(\tilde{\varepsilon}_t^{pl}, \theta, f_i) \quad 0 < d_t < 1 \tag{3}$$

$$d_c = d_c(\tilde{\varepsilon}_c^{pl}, \theta, f_i) \quad 0 < d_t < 1 \tag{4}$$

Therefore, the stress–strain relations under uniaxial tension and compression loading are defined as: