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Effects of close proximity underwater explosion on the nonlinear dynamic response of concrete gravity dams with orifices

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ABSTRACT

In order to meet the demand for power, irrigation, flood control, drinking water, etc., many orifices are usually designed on the dam body. This paper is aimed to evaluate the close proximity underwater explosion effects on the nonlinear dynamic response of concrete gravity dams with orifices. The accuracy and reliability of the coupled model is calibrated against a previous experimental test. The effects of the existing orifice on the damage processes of concrete gravity dams to close proximity underwater explosion are investigated. Damage characteristics of gravity dams with the orifice under close-in, inlet and internal underwater explosions are compared. The influence of the reinforcement and the water inside the existing orifice on the nonlinear dynamic response of concrete gravity dams is also discussed. The results show that the dam with orifice suffers more serious damage subjected to close proximity underwater explosion than the dam without orifice. Closing the gate of the orifice will significantly reduce the damage level of the dam.

1. Introduction

Many orifices are usually designed on the dam body to meet the requirements for power, irrigation, flood control, drinking water, etc. For example, Three Gorges Project deploys 23 deep orifices, 22 surface orifices, and 22 diversion bottom orifices [1]. The Jinping I consists 4 surface orifices, 5 lower level orifices and a long spillway tunnel on the right bank [2]. Xiluodu hydroelectric power station places 7 surface orifices, 8 deep orifices and 10 diversion bottom orifices in monolith 12 to monolith 19 [3]. The presence of these orifices will weaken the integrity of the dam structure, which significantly impacts the structure performance when subjected to a close proximity underwater explosion near the orifice. Although lowering the water level according to the orifices is an effective defense measure to reduce the risk of the dam failure, this also makes it possible for the bomb detonated near the inlet of the orifice and even at the inside of the orifice. Hence, it is very important to protect the monolith with orifices against close proximity underwater explosion. This enlightens the importance to gain nonlinear dynamic response and damage mechanism of dams with orifices to close proximity underwater explosion.

Open holes in the structure will inevitably cause stress concentration and weaken the strength of the structure [4, 5]. It is well known that during the service of dams, stresses around the orifices tend to be larger due to the concentration of stress, which may result in greater risk to the integral stability of the dam [6, 7]. From the seismic analysis, it was found that crest displacements of the dam with orifices are 65%~80% larger than that without orifices, and the presence of orifices attracts the stresses around them [8]. The seismic analysis also shows that dam hole-opening has more impacts on local stress rather than on integral rigidity. Considering thermal and creep effects, the bottom and roof concrete surfaces of orifices always experience large tensile stresses in excess of the

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concrete tensile strength, bringing high cracking and failure risks to the orifices in gravity dams [9]. Under overloading conditions, the orifices would harm the structural continuity of the dam and weaken the carrying capacity [10]. It can be seen from the above studies that the presence of orifices will significantly reduce the overall stability and structural safety of dams.

Concrete gravity dams are constructed as individual monoliths separated by contraction joints, generally composed of the non-overflow monolith, overflow monolith, sediment discharge bottom outlet monolith and power house monolith, etc. However, the performance evaluation of concrete gravity dams subjected to blast loadings is mainly concentrated in the non-overflow monolith. The first experiment was carried out on the non-overflow monolith of Möhne dam and further trials involving a one-fiftieth scale model demonstrated that the Möhne dam could be breached when 3000 kg of explosive was detonated near the upstream of the dam [11]. Vanadit-Ellis and Davis [12] investigated dynamic loading conditions placed on the face of the non-overflow monolith subjected to underwater explosions. Wang et al. [13, 14] observed that underwater explosion will cause significantly more damage to the dam than the same mass of explosive in air, and obtained the critical curves in the form of critical charge weigh-standoff distance relationships corresponding to the damage states for the non-overflow monolith subjected to underwater explosion. Zhang et al. [15] found that the damage to the non-overflow monolith is weakening with the increase of the dam height, and for the same charge and standoff distance, the lower level is in the reservoir, the less damage is caused to the non-overflow monolith. Lu et al. [16] studied the property of the flexible polyurethane foam as a material to protect the non-overflow monolith acting by the strong underwater shock wave. Yu [17] revealed the damage evolution process of the non-overflow monolith subjected to underwater contact explosion. Linsbauer [18, 19] discussed the dynamic response, stability and failure mechanism of the non-overflow monolith (with the initial cracks at the upstream surface) under the impact of blast loading at the bottom of the reservoir.

Despite the fact that the problem of structural safety of concrete gravity dams with orifices to blast loads has been qualitatively acknowledged, very few studies have been reported in the literature regarding the nonlinear dynamic behavior of the monolith with orifices to blast loads. To the best of the authors' knowledge, there is only one work that has considered the influence of the orifice on the accumulative damage processes of the monolith when subjected to underwater explosion [20]. Moreover, the overall safety performance of concrete gravity dams subjected to blast loads is determined by the weakest monolith. Hence, more attention should be paid to the monoliths with orifices when subjected to blast loading.

The presence of orifices will significantly impact the failure process and damage characteristic of concrete gravity dams subjected to underwater explosion. In this paper, the close proximity underwater explosion effects on damage characteristics of concrete gravity dams with orifices are studied. Fully coupled models with combined Eulerian and Lagrangian algorithm are adopted, and the accuracy and reliability are verified through comparisons between the numerical and test results. Damage characteristics of gravity dams with the orifice under close-in, inlet and internal underwater explosions are simulated and compared. The influence of the water inside the existing orifices on the nonlinear dynamic response of concrete gravity dams to close proximity underwater explosion is also discussed. In addition, the failure modes of dams after strengthening are also simulated by using the same model, and the effect of reinforcement is evaluated.

2. Description of the coupled method

2.1. A fully coupled Eulerian-Lagrangian numerical approach

With the development of the material and numerical method, numerical simulation could be a powerful method to describe the dynamic response of structures under blasting loads. In the present study, Coupling Eulerian-Lagrangian (CEL) method [21, 22] is presented to simulate the dynamic response of the concrete gravity dam with the orifice subjected to underwater explosion.

This coupled method, adopted in the present study, has been made possible in AUTODYN [23] and other hydrocodes. In the CEL method, the Eulerian material can exert pressure boundary conditions on the Lagrange element which causes displacement of the structure, and the Lagrange interface can cut through the Eulerian mesh that is fixed in space in an arbitrary manner. The Lagrangian interface, in return, provides velocity boundary conditions to Eulerian material flow and the Eulerian material cannot penetrate the Lagrange element. A typical coupled situation is shown in Fig. 1.

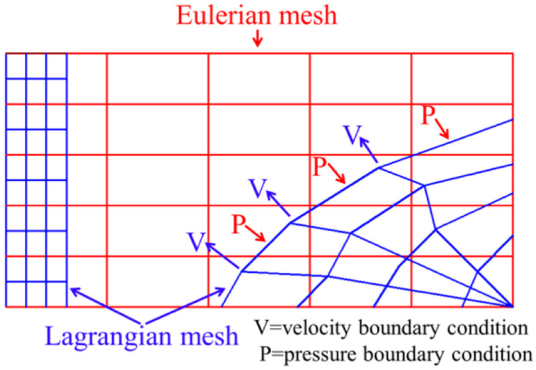

Fig. 1. Schematic of the CEL approach.