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Damage prediction of concrete gravity dams subjected to underwater explosion shock loading

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ABSTRACT

The damage prediction of concrete gravity dams under blast loads has gained importance in recent years due to the great number of accidental events and terrorist bombing attacks that affected engineering safety. It has long been known that an underwater explosion can cause significantly more damage to the targets in water than the same amount of explosive in air. While the physical processes during an underwater explosion and the subsequent response of structures are extremely complex, which involve lots of complex issues such as the explosion, shock wave propagation, shock wave-structure interaction and structural response. Hence a sophisticated numerical model for the loading and material responses would be required to enable more realistic reproduction of the underlying physical processes. In this paper, a fully coupled numerical approach with combined Lagrangian and Eulerian methods, incorporating the explosion processes, is performed. The RHT (Riedel–Hiermaier–Thoma) model including the strain rate effect is employed to model the concrete material behavior subjected to blast loading. Detailed numerical simulation and analysis of a typical concrete gravity dam subjected to underwater explosion are presented in this study. In terms of different TNT charge weights, the structural response and damage characteristics of the dam at different standoff distances are investigated. Based on the numerical results, critical curves related to different damage levels are derived.

1. Introduction

Blasting loads have come to be forefront of attention in recent years due to the great number of accidental explosions, intentional events or terrorist bombing attacks that affected the safety and stability of some important infrastructures such as government buildings, embassy buildings, bridges and high dams. The damage prediction of important infrastructures under blast loads is crucial in structural engineering, which has gained importance in recent years [1–6]. Dams are important lifeline engineering which have contributed to the development of civilization for a long time. Due to their significant political and economic benefits, they are possible targets for terrorist attacks or intentional explosions. The possible failure of dams retaining large quantities of water can cause the most undesirable impact on the downstream populated area along with a considerable amount of devastation, clearly indicating that it is essential to protect dam structures against explosions. This enlightens the importance for researchers and structural engineers to gain a better understanding of dams' response to explosive loads.

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Dam structures may undergo air blast loading due to the attack of rockets and missiles above the waterline and underwater explosion loading due to the explosion of mines, torpedoes and depth charges below the waterline. While attention may be mainly paid to shock wave propagation characteristics from underwater explosion and the subsequent response and damage of dam structures. This is because that an underwater explosion can cause significantly more damage to the targets in water than the same amount of explosive in air [7]. Although many researchers have conducted comprehensive experimental and numerical investigations to model the blast effects on civilian structures (mainly on building structures) [8–11], marine structures [12–14], bridge structures [15–18], relatively less attention has been paid to dam structures under blast loads.

Most investigations on the dynamic behavior of structures subjected to blast loadings have focused mainly on full-scale model tests, reduced scale/enhanced acceleration physical tests (as in centrifuge tests), and numerical damage predictions. In October 1940, a series of trials was firstly carried out on a scale model of the Möhne dam to see whether a big conventional bomb could destroy the dam. Further trials involving a one-fiftieth scale model of the Möhne dam and a full-size dam in mid-Wales proved that the Möhne dam could be breached if 6500ib of high explosive could be detonated against the inner wall of the dam. The Möhne dam was severely damaged by a bomb on May 16th 1943 in WW II [19]. Vanadit-Ellis and Davis [20] designed the small-scale model of a typical gravity dam to investigate the response of dams subjected to blast loads in a large centrifuge. However, evaluating the performance of concrete dams to explosive loading through full-scale tests is often beyond affordability. In addition, the experimental tests require the use of relatively large amounts of charges, involving potential risks and need careful handling, which is typically not feasible in civilian research. In the past, numerical simulation of underwater explosion was difficult to perform due to the limitation of computational capability. However, with the rapid development of computer technology and the advancement of numerical techniques, damage predictions of concrete gravity dams subjected to blast loads through computer simulation become viable. Yu [21] applied the ALE algorithm to study the dynamic response of dams through establishing a fully coupled model of underwater contact explosion. Linsbauer [22,23], through the establishment of a coupled model of reservoir water and the dam, studied the dynamic response, stability and failure mechanism of concrete gravity dams (with the initial cracks at upstream surface) under the impact of blast loading at the bottom of the reservoir. Lu et al. [24] studied the property of the flexible polyurethane foam as a material to protect the concrete gravity dams acting by strong underwater shock wave. Zhang et al. [25] discussed the possible failure modes of concrete gravity dams subjected to underwater explosion. The influence of the dam height, standoff distance and the upstream water level on the antiknock performance of the dam is also investigated.

It is of interest to understand the behavior of concrete gravity dams under blast loadings since the structural response to explosive loads is much more complicated than that under other loadings such as static and earthquake loadings. The amount of damage in the dam will depend on the weight of the charge, the standoff distance and the detonation depth. However the physical processes during an underwater explosion and the subsequent response of structures are extremely complex, which involve lots of complex issues such as the explosion, shock wave propagation, shock wave-structure interaction and structural response. Hence a sophisticated numerical model for the loading and material responses would be required to enable more realistic reproduction of the underlying physical processes. Wei et al. [2] performed a fully coupled numerical analysis, incorporating the explosion process, to predict the damage depth into rock mass induced by underground explosion. Lu et al. [8] developed a fully coupled numerical simulation approach with combined Lagrangian and Eulerian methods to characterize the structural effects for above-ground explosions. The model encompasses the charge detonation, propagation of the shock wave in air, propagation of stress wave in the ground, as well as the dynamic response of the structure. Wang et al. [26] establish a fully coupled numerical approach for analyzing the response of underground structures subjected to blast loading.

Concrete gravity dams during their service life may be subjected to explosive loads. The damage prediction of dam structures under blast loads is crucial in protecting the high dams against explosions. Studying the blast response of concrete gravity dams will help understanding and improving their blast resistance. The present study aims to predict the behavior of a typical concrete gravity dam subjected to underwater explosion of various detonation positions. A fully coupled numerical simulation approach with combined Lagrangian and Eulerian methods, which incorporate the essential explosion processes, is performed, where the explosive charge, the air and the water are modeled using an Eulerian mesh, while the solid concrete and rock are modeled using a Lagrangian mesh. In this approach, the explosive charge, water and air medium, rock and the dam structure are all incorporated into a single model system. The material models are carefully selected and validated. In terms of different TNT charge weights, various detonation positions are considered to gain a better perspective of the dam performance against blast loadings. The structural response and damage characteristics of the dam subjected to underwater explosion shock loading are characterized. The damage processes to the dam are observed and damage mechanisms are discussed. Critical curves corresponding to different damage levels for concrete gravity dams subjected to underwater explosion shock loading are derived based on the numerical results.

2. Description of the coupled model

2.1. A fully coupled Lagrangian–Eulerian numerical approach

In order to incorporate the various physical processes into a single model system, many complex phenomena should be considered such as large deformation at the vicinity of the charge, the fluid–structure interaction. and more advanced