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Failure modes and effect analysis of concrete gravity dams subjected to underwater contact explosion considering the hydrostatic pressure

Qi Li[a], Gaohui Wang[a,*], Wenbo Lu[a], Xinqiang Niu[a,b], Ming Chen[a], Peng Yan[a]

[a] State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan 430072, China
[b] Changjiang Institute of Survey, Planning, Design and Research, Changjiang Water Resources Commission, Wuhan 430010, China

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A B S T R A C T

To better understand damage characteristics of concrete gravity dams under contact explosion is a critical issue to evaluate the protective performance of dams. In this paper, a fully coupled Lagrangian-Eulerian numerical approach, incorporating the detonation process of underwater contact explosion, is performed to predict the damage propagation of a typical concrete gravity dam. In order to verify the validity of the coupled algorithm, damage profiles of a normal strength reinforced concrete (RC) slab subjected to contact explosion are predicted and compared with the published experimental results. The hydrostatic pressure of the reservoir is modeled by using the specific internal energy method. The interaction between detonation products and dam-foundation-reservoir systems is also considered. The detonation products development processes, shock wave propagation, and failure modes of the dam subjected to underwater contact explosion with and without considering the hydrostatic pressure are compared. In order to analyze the underwater contact explosion effects on failure modes and dynamic responses of the dam, three positions of the detonation point, i.e., upper blast point, middle blast point, and lower blast point, are considered in this study. The results show that the initial hydrostatic pressure has a significant influence on failure characteristics of the dam subjected to underwater contact explosion. Underwater contact explosion detonated in the lower zone will cause more serious damage to the dam heel and threaten the overall stability of the dam. Hence, more attention should be paid to the deep water contact explosion.

1. Introduction

In recent decades, with the rising of terrorism threats, increasingly more attention is drawn to structural damage under blast loads [1–6]. During the service life of some crucial infrastructures such as government buildings, subway stations, warships, bridges, and high dams, the accidental or intentional explosion is a threat to these structures with relatively low probability but disastrous consequences. High dams are usually designed for power, irrigation, flood control, and drinking water. Due to their significant political and economic benefits to society, high dams are possible targets for terrorist explosion attacks. In addition, with the rapid development of precision-guided weapons, dams are more vulnerable to bombing attacks. Blast loads will cause significant damage to high dams especially when subjected to underwater contact explosion. Therefore, it is very important to understand the damage mechanism and failure modes of dams subjected to underwater contact explosion, which is of great importance in the blast resistant

* Corresponding author.
E-mail address: wanggaohui@whu.edu.cn (G. Wang).

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design of dams.

Compared to non-contact explosions, contact explosions have higher pressures, shorter load durations, and more temperature effects [7]. Many researchers have carried out some field tests and numerical simulations about a wide variety of structures under contact explosion, such as vessels [8], concrete vehicle barriers [7], shell structures [9], concrete slabs [10,11], and beams [12]. However, few researches have focused their attention on the dynamic responses and damage characteristics of concrete gravity dams subjected to underwater contact explosions. This is likely because that the physical processes during an underwater contact explosion and the subsequent response of structures are extremely complex, which involve lots of complex issues such as detonation, high-pressure gas expansion, shock wave propagation, shock wave-structure interaction, and structural response. Hence, studies on dams subjected to underwater contact explosion are of great significance.

Due to the complicated physical phenomena involved in dam structures subjected to underwater explosion, it is very difficult to describe this problem by the analytical method. The field tests of concrete dams to explosive loading through full-scale models are often beyond affordability. However, with the development of the computer technology and numerical techniques, numerical simulation begins to attract scholars' attention and these numerical simulation results are proven to be credible [13,14]. Major developments in understanding the structural responses and failure modes of concrete dams subjected to blast loads have been made in recent years. Yu [15] employed the ALE algorithm to simulate the dynamic responses of the concrete dam subjected to underwater explosion and describe the damage evolution processes of the dam. Wang et al. [16,17] used a fully coupled numerical simulation approach to predict the damage condition of the typical concrete gravity dam subjected to underwater explosion. They also compared the damage characteristics of concrete gravity dams subjected to underwater explosion and air blast. Linsbauer [18] studied the dynamic responses, stability and failure mechanism of concrete gravity dams (with the initial cracks at the upstream surface) when the charge was detonated at the bottom of the reservoir. Zhang et al. [19] discussed the influence of dam height, standoff distance and water level on the blast resistant performance of concrete gravity dams. It should be noted that most of the aforementioned studies are focused on the responses of dams subjected to non-contact underwater explosion. However, relatively less attention has been paid to the nonlinear dynamic responses of the dam structures subjected to underwater contact explosion. Although the hydrostatic pressure is usually neglected for its trivial effect on the shock wave pressure [20], this hydrostatic loading will affect the development of detonation products, especially for contact explosion in deep water. Hence, it is of interest to understand the behavior of concrete gravity dams subjected to underwater contact explosion with considering the hydrostatic pressure.

The objective of this study is to investigate the damage characteristics of concrete gravity dams subjected to underwater contact explosion considering the hydrostatic pressure. To achieve this, a fully coupled Lagrangian-Eulerian method is presented. The computed distribution of damage profiles of a normal strength RC slab subjected to contact explosion is compared with the published experimental results to verify the validity of the coupled algorithm. The hydrostatic pressure of the reservoir water is considered by using the specific internal energy method. The influence of the hydrostatic pressure on the detonation products development processes, shock wave propagation, and failure modes of the dam subjected to underwater contact explosion is discussed. Three positions of the detonation point, i.e., upper blast point, middle blast point, and lower blast point, are considered to investigate the underwater contact explosion effects on failure modes and dynamic responses of the dam.

2. Material models

2.1. Nonlinear dynamic damage constitutive model for concrete material

The dynamic behavior of the concrete material under blast loads is a complex nonlinear and rate-dependent process. In this study, the Riedel-Hiermaier-Thoma (RHT) [21,22] constitutive model is used in the process of concrete material modeling. In the model, the

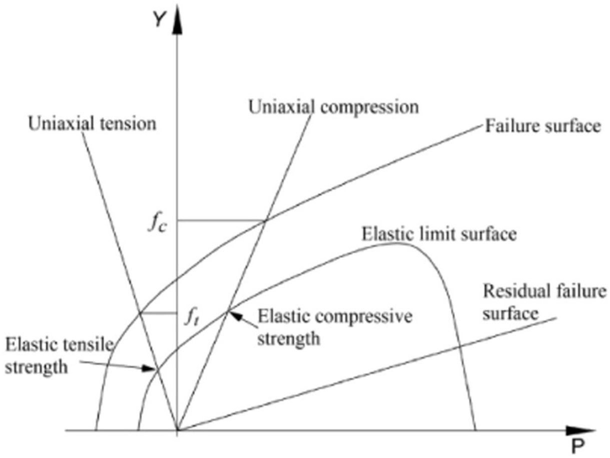

Fig. 1. Three strength surfaces of RHT constitutive model.