Engineering Failure Analysis 36 (2014) 49–64

Contents lists available at ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal

Numerical simulation of failure modes of concrete gravity dams subjected to underwater explosion

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ARTICLE INFO

Article history:
Received 1 April 2013
Received in revised form 3 October 2013
Accepted 5 October 2013
Available online 10 October 2013

Keywords:
Concrete gravity dam
Failure mode
Mesh size effect
Antiknock performance
Underwater explosion

ABSTRACT

The failure modes of concrete gravity dams under blast loading are the key problems to evaluate the antiknock safety of the dam. Dynamic failure process of structures under blast loading is much more complicated than that under other loadings such as static and earthquake loadings. Many researchers have conducted comprehensive experimental and numerical investigations of civil structures' response to blast loading. However, corresponding studies of concrete gravity dams are limited. This paper performs numerical simulation of antiknock performance and failure modes of concrete gravity dams under blast loading. Firstly, the pressure and impulse produced by underwater explosion are calculated. The numerical results are verified by comparing with analytical expressions in different scaled distances. By analyzing the effects of mesh size, some interesting conclusions regarding the mesh size for actual events are obtained. Subsequently, the possible failure modes of concrete gravity dams subjected to underwater explosion are discussed. Strain rate effect of concrete materials is also taken into consideration in establishing the fully coupled model of the gravity dam. The dynamic response of the dam subjected to underwater explosion is performed for different dam heights, varying from 30 to 142 m. The influence of the dam height, standoff distance and the upstream water level on the antiknock performance of the dam is also investigated.

1. Introduction

With the increased world tension, terrorist bombing attacks or accidental explosions are becoming a large threat to infrastructure such as the important economic, military and civilian facilities. The research on the antiknock safety of structures has increasingly attracted people's attention. In order to meet the ever increasing demand for power, irrigation and drinking water et al., the majority of high dams are being built or to be built. Considering their significant political and economic benefits, undoubtedly, high dams might be targeted by terrorists because the possible failure of dams can cause economic disaster, a large number of casualties, and garner significant media attention. Since the September 11 attacks by terrorists, there has been increasing public concern about the threat of bomb attacks on dam structures [1]. Therefore, protection of dam structures against blast loads is an important component of homeland security.

Study on the failure modes and antiknock performance of concrete gravity dams subjected to underwater explosion is crucial to evaluate their antiknock safety. While, the physical processes during an explosive detonated in water and shock wave propagation are extremely complex, and the subsequent response of the dam subjected to explosion shock loading is much more complicated than that under other loadings such as static and earthquake loadings. Many researchers have

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1350-6307/$ - see front matter
http://dx.doi.org/10.1016/j.engfailanal.2013.10.001

conducted comprehensive experimental and numerical investigations related to the blast effects on building structures [2–5], marine structures [6–8], underground structures [9–12], bridge structures [13–16], and plate structures [17–20], etc. However, the corresponding studies of concrete gravity dams subjected to blast loads are limited. This is probably because of the large size and the interactions with the reservoir and foundation which make both numerical modeling and experimental tests very costly. 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 [21]. Dam structures are possible targets of the terrorist attacks owing to their damage which can cause catastrophic consequences. This enlightens the importance for researchers and structural engineers to research the antiknock performance of the dam. In October 1940 the first in a series of trials was 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 could be breached if 6500ib of high explosive could be detonated against the inner wall of the dam [22]. On the other hand, Yu [23] has used the ALE algorithm to study the dynamic response of the dam through establishing the fully coupled model of underwater contact explosion. Linsbauer [24,25], through the establishment of coupled model of reservoir water and the dam, has 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. [26] studied the property of the flexible polyurethane foam as a material to protect the concrete gravity dams acting by strong underwater shock wave. However, few studies have focused their attention on failure modes, crack mechanism and antiknock performance of concrete gravity dams subjected to underwater explosion.

It is well known that the accuracy of numerical results is strongly dependent on the mesh size used for the analysis. On the other side, the mesh size is also limited by the dimensions of the model and the computer capacity. One of the major features in the numerical simulation of blast wave propagation in large dam-water-foundation environments is the use of an adequate mesh size. At present, some scholars have studied on the effect of mesh size in numerical simulation of explosion wave. Krauthammer and Otani [27] researched the influence of mesh size, gravity and static load in the numerical simulation of the reinforced concrete structure under the work of explosion shock loading. The study shows that the mesh size has a great influence on the structure's deformation and stress. Luccioni et al. [28] discussed the effect of mesh size when using the fluid mechanics software to simulate and predict the explosion load. They believed that if the grid size is 100 mm, the spread way of explosion load can be simulated accurately. Model with coarse mesh can be only used to simulate explosion load propagation law qualitatively in a complex environment such as in the city.

This paper presents a numerical simulation study aiming to investigate the antiknock performance and failure modes of concrete gravity dams subjected to underwater explosion. All numerical simulations are carried out based on the LS-DYNA explicit finite element code. A fully coupled numerical approach with combined Lagrangian and Eulerian methods, in which 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, is adopted to allow for the incorporation of the essential processes, namely the explosion, shock wave propagation, shock wave-structure interaction and structural response. The effect of the mesh density on the results is discussed. The explosive charge, water and air medium, rock and the dam structure are all incorporated into a single model system. The dynamic response, possible failure modes, crack mechanism, and antiknock performance of concrete gravity dams subjected to underwater explosion are studied. The influence of the dam height, standoff distance and the upstream water level on the antiknock performance and failure mode of concrete gravity dams is discussed.

2. Material models

2.1. Concrete damage model

The dynamic response of the concrete material under explosion shock loading is a complex nonlinear and rate-dependent process. At high strain rate, the strength of concrete improved significantly, compressive strength increase by 100%, tensile strength even increased to 600% [29,30]. To fully describe the concrete's dynamic effect within the impact procedure, a variety of constitutive models for the dynamic and static response of concrete have been proposed over the years. In the present study, the ''Johnson–Holmquist concrete'' material model, based on work by Holmquist et al. [31,32], is used to describe the dynamic behaviors of concrete subjected to large strain, high strain rate and hydrostatic pressure. The equivalent strength is expressed as a function of the pressure, strain rate, and damage. The pressure is expressed as a function of the volumetric strain and includes the effect of permanent crushing. The damage is accumulated as a function of the plastic volumetric strain, equivalent plastic strain and pressure A general overview of the concrete model is illustrated in Fig. 1. The equivalent strength model, accumulated damage model and the equation of state are described as follows.

2.1.1. Equivalent strength model

Fig. 1a illustrates the equivalent strength component of the model. The specific expression can be expressed in the following form:

$$\sigma^* = [A(1-D) + BP^{*N}](1 + C\ln\dot{\varepsilon}^*) \quad (1)$$