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Dynamic responses of buried arch structure subjected to subsurface localized impulsive loading: Experimental study

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ABSTRACT

A structural model experiment was carried out on a buried scaled-down reinforced-concrete arch structure subjected to underground close-in explosions. The aim of the experiment is to provide believable results of dynamic responses of large-span structures, including the dynamic loads, deflections, strains and failure modes. To achieve this objective, blast experiments were carried out under 0.6 kg, 3 kg, 6 kg and 17.4 kg TNT charges, respectively. Distribution laws of the applied dynamic loads, deflections, strains, accelerations and the failure modes of the arch were revealed. Different from the quasi-uniform distribution style subjected to far-field explosions, the dynamic loads applied on the buried arch subjected to close-in explosions have tense local effects and render a triangle-like distribution style. According to the tested deformations and strains, it can be concluded that subjected to close-in explosions, the buried arch deforms at a dominant flexural mode, companying with compression mode. Spalling, tensile cracks and shear failures of the concrete and yielding of the steel bars are the main failure modes of the blast-loaded arch. The arch will collapse after four or five plastic hinge lines formed. The experimental data are helpful for engineers and well support further theoretical analysis.

1. Introduction

Compared with aboveground protective structures, those underground are safer [1] to resist explosions. When an underground detonation occurs, the shock wave will propagate in all directions and attenuate rapidly with the increase of the distance from the charge point [2,3]. Provided a large standoff of a nuclear explosion, the stress field in the medium will be relatively uniform as suggested by Flathau [2]. From tested results, it is indicated that the response of a buried arch to a traveling airblast load can be characterized adequately with four modes: rigid body motion, uniform compression, symmetric bending, and asymmetric bending [2]. Three load conditions are recommended for design of completely buried reinforced concrete arches [2]: (a) compression mode, a static uniform radial load acting inward with an intensity equal to the peak overpressure, p_0, at the ground surface, as shown in Fig. 1(a); (b) deflection mode, a combined loading consists of a uniform radial load acting inward on the side adjacent to the blast and a uniform radial load acting inward over the entire periphery as shown in Fig. 1(b); and (c) compression-bending mode, a combined loading consisting of a uniform radial load acting inward over the entire periphery with an intensity equal to the peak overpressure at the ground surface and a uniform radial load acting inward and over the central one third of the length of the arch, p_{SL}, as shown in Fig. 1(c), with [2]

$$p_{SL} = \frac{p_0}{9\left(\frac{S}{L}\right)^2}, \tag{1}$$

where S and L denote the length and the span of the arch, respectively, as marked in Fig. 1(c). Compression-bending mode would give the critical condition for the arches, and probably would control in nearly all the cases [2].

Various methods have been applied to reveal the response of underground arch structure. Analytical method is still needed [4–10]. Most of the theoretical studies were based on single-degree-of-freedom (SDOF) models [11]. Another important method is

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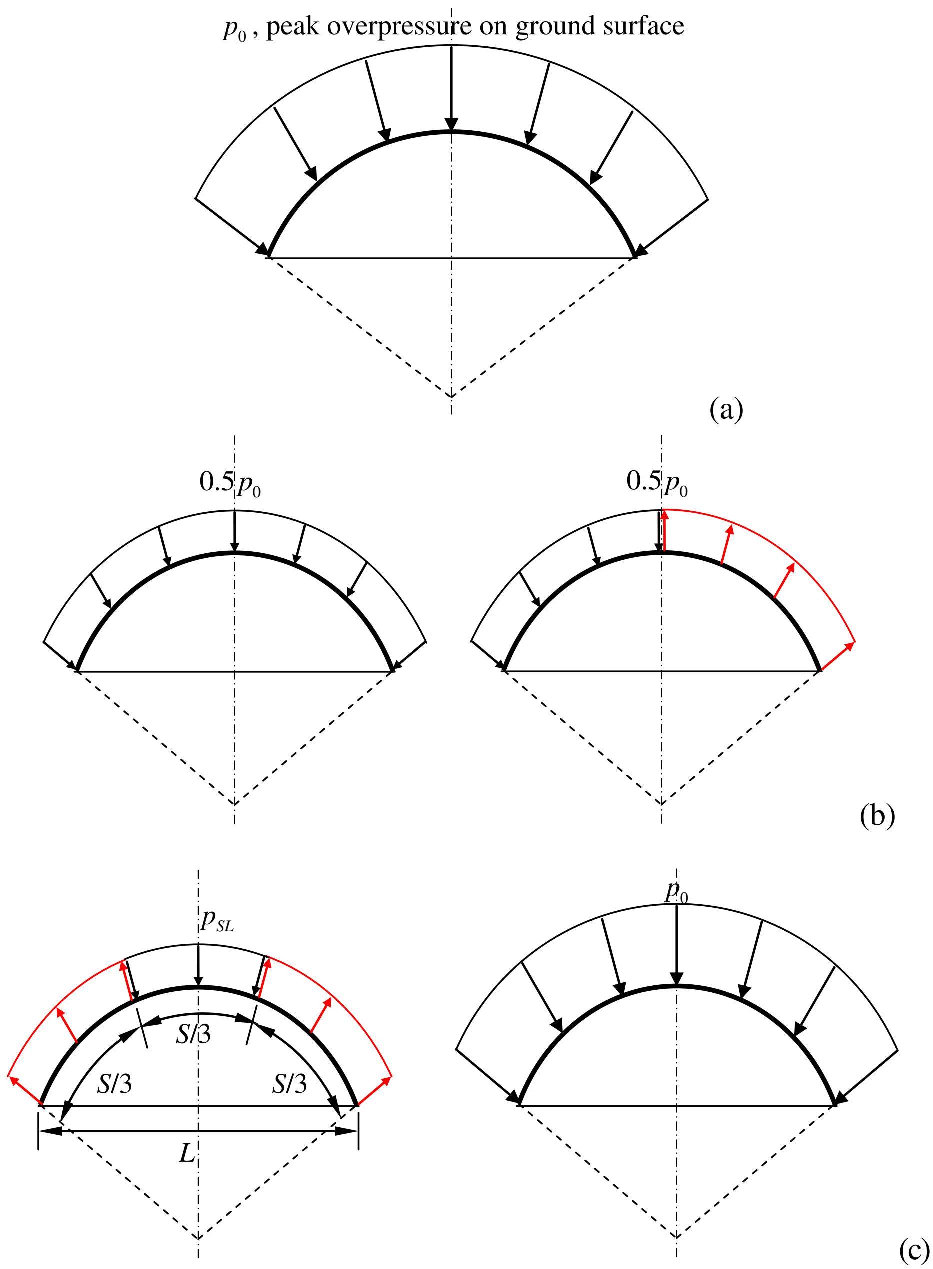

Fig. 1. Recommended idealized loadings for nuclear explosions in (a) compression mode; (b) deflection mode; and (c) compression-bending mode [2].

based on the soil-structure interaction (SSI) model. To understand the dynamic responses of buried protective arches investigators must address the governing parameters, such as the propagation of stress waves through the soil, the response modes of an arch and the dynamic interactions between the structure and the surrounding soil. A procedure was presented to analyze underground protective structures subject to conventional explosions [4,5]. The effect of SSI is incorporated into the characteristic of the structure in the form of viscous damping. This method has been adopted by Ma et al. [6] and Chen et al. in their works [3,7].

Employing numerical methods, comprehensive models can be established to represent the real detonation and response situations [12–15]. Stevens and Krauthammer [16] adopted an advanced numerical method to consider complex geometrical configurations and material properties of the arch. Boundary element method (BEM) was also employed to analyze the dynamic response of large three-dimensional underground structures [17]. With the development of meshless methods, a combined smoothed particle hydrodynamics (SPH) model was applied to study the shock response of a box-shaped underground structure subjected to a subsurface blast load [18].

Experiments are essential to obtain a more fundamental understanding of the dynamic response [19,20]. A large quantity of experiments on buried arches subjected to far-field explosions were carried out and published. Flathau et al. [2] and Grubaugh et al. [21] studied arch and dome structures by full-scale experiments subjected to nuclear detonation effects. Four underground arch structures were designed to resist kiloton-range nuclear air blast and the reinforced-concrete arch was proved to be an excellent structure type [22]. Another study was reported by McGrath [23] while Palacios and Kennedy [24] reported results from a test