Computers and Geotechnics 80 (2016) 290–300

Contents lists available at ScienceDirect

Computers and Geotechnics

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

Research Paper

Probabilistic analysis of crushed zone for rock blasting

Mahdi Shadab Far [1], Yuan Wang *,[2]

Hohai University, No. 1, Xikang Road, Nanjing, China

ARTICLE INFO

Article history:
Received 27 May 2016
Received in revised form 30 July 2016
Accepted 27 August 2016

Keywords:
Explosion load
Crushed zone radius
Exceedance probability
Reliability problem
Probabilistic prediction

ABSTRACT

Transmission of explosion waves through a rock medium causes a severe vibration that stimulates the mechanical behavior of rock mass. This stimulation imposes highly concentrated stresses on the ends of existing fine joints and depending on the toughness of the rock, causes them to propagate rapidly. Consequently, the propagation and joining of cracks form a crushed zone around the blast hole. Several studies are available in the literature to estimate the radius of crushed zone, deterministically. In this paper, however, a probabilistic approach has been adopted. This is because the initiation and propagation of cracks have a probabilistic nature, and neither the initial state of the rock nor the explosion load could be expressed in a fully deterministic way. Thus, after generating random values for involved parameters, including explosive density, detonation velocity, dynamic Young's modulus, dynamic Poisson's ratio, uniaxial compressive strength, and borehole radius, the Monte-Carlo sampling method was adopted to calculate the exceeding probability of the crushed zone radius from desired values. The results showed that the exceedance probability for the growth of cracks falls sharply by the increase in the crushed zone radius so that the probability of crushed zone radius longer than 0.5 m is less than one percent. The results of this study, compared to the deterministic models, provide advantages in that they are not only limited to a certain value for the crushed zone radius and show the probability of exceedance for any desired radius.

1. Introduction

Explosion is one of the conventional methods in tunnel and mine excavations in rock environments. The main concern with this method is the unwanted induced failures in surrounding rock media that create unanticipated adverse effects, including instability problems, the flow of water in joints, reducing the lifetime of the structure, etc. [1]. More precisely, after the explosion, the resulting pressure waves are released quickly and extremely vibrate the rock environment. The resulting vibration, which occurs very fast in a fraction of a second, will stimulate the mechanical and dynamic properties of the rock mass. This stimulation causes tensions and stresses in existing discontinuities, and depending on the toughness of rock, would start opening and propagation of the joint.

Due to the growth of fine cracks that subsequently join together, the range of discontinuities will increase, and some crushed zones that are unstable will appear. On the other hand, some of the cracks that receive greater impact from the explosion shock, go beyond the crushed zone and radially penetrate through the surrounding environment. Beyond the crushed zone and radial cracks, the explosion effect is seen in the form of ground vibration. These three parts are shown in Fig. 1.

Using the blast load in civil engineering projects has a long history, and consequently, the vibrations caused by the explosion have been studied by various researchers [2–4]. However, investigation of the different models for predicting the growth of the crushed zone under the explosion in rock started some decades ago [5,1]. Ash [6,7] was among the first researchers who tried to predict the crushed zone around the blast-hole, based on the experimental models. In his model, using the relative density of the rock mass and the relative strength of explosives, the radius of the affected area was calculated as a multiple of the blast-hole radius. After Ash, Drukovanyi et al. [8], assuming a homogeneous and elastic environment, studied the stress field characteristics and crushing intensity of the rock under the one-dimensional stress wave caused by the explosion. Szuladzinski [9], based on the hydrodynamic theory in rock, suggested a relationship to

* Corresponding author.
E-mail addresses: mahdishadabfar@yahoo.com (M. Shadab Far), wangyuan@hhu.edu.cn (Y. Wang).
[1] Ph.D. Student in Bridge and Tunnel Engineering, School of Civil and Transportation Engineering, Hohai University.
[2] Professor of Geotechnical Engineering, School of Civil and Transportation Engineering, Hohai University.

http://dx.doi.org/10.1016/j.compgeo.2016.08.025
0266-352X/

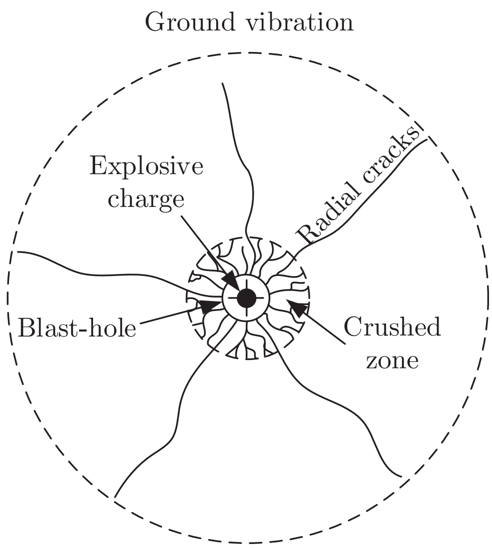

Fig. 1. Crack formation around the blast hole.

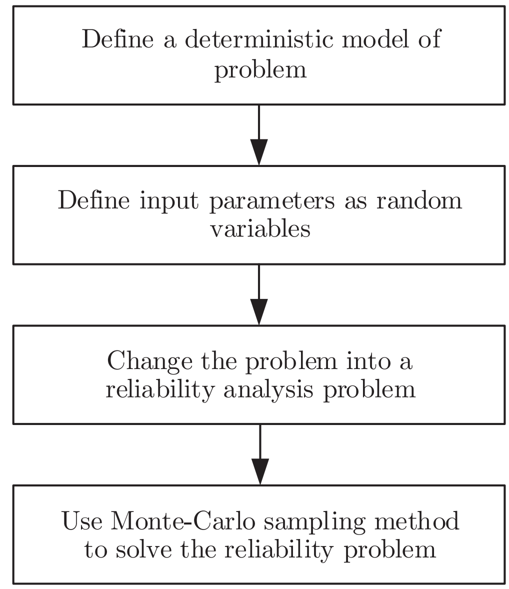

Fig. 2. Probabilistic modeling process.

predict the crushed zone radius around the blast-hole utilizing the efficient energy of the explosive material. Esen et al. [10], using several field-test explosions, developed a parameter called the Crushing Zone Index (CZI) and suggested an empirical relation for predicting the crushed zone radius. Iverson et al. [11] analytically calculated the triple areas around the blast-hole (Fig. 1) and compared the results with the field-test explosions on concrete samples. Hustrulid and Johnson [12] improved Ash's model and calculated the crushed zone radius based on the amount of explosive energy and exerted stress on the blast-hole wall.

Apart from the research listed above, there are several other research works done by analytical methods [13–15], software modeling [16–18], and laboratory tests [19,20] available in the related literature. However, as to the knowledge of the authors, few if any studies have investigated the probability of the crushed zone propagation under the explosion load. In fact, none of the explosive load and bearing capacity of the rock environment are fully known, and thus, they cannot be accounted as deterministic variables. It is, therefore, necessary to develop a method, which while considering the involved uncertainties, is able to examine the problem probabilistically. In this regard, relying on previous works done, and considering the involved parameters as random variables, this paper tried to study the exceedance probability of the crushed zone radius from any possible value.

2. Modeling

As explained in the introduction, this article focuses on the probability analysis of explosion and crushed zone growth in rock. For this purpose, we first need to set a deterministic model in which we can express the crushed zone radius by a closed-form relation. Then, defining the involved parameters as random variables, the problem can be transferred from a deterministic to a probabilistic state, and it can be established as a reliability problem. Then, using one of the available approaches for reliability problems, such as the Monte-Carlo sampling method that is adopted in this paper, the established problem can be solved, and the answer can be depicted in the form of exceeding probability versus the given radius. The above process is shown schematically in Fig. 2.

The Esen's model is chosen to be the primary deterministic model. In this model, the crushed zone radius is expressed as a function of the rock mass and explosive characteristics. This method is explained in the next section.

2.1. Esen's model

Esen et al. [10] used concrete and a combination of other synthetic materials to make 92 samples and study the mechanisms of rock breakage by explosives. According to the crushing process around the explosion point, they defined a Crushing Zone Index (CZI) as follows (Eq. (1)):

$$CZI = \frac{P_b^3}{K \times \sigma_c^2}, \tag{1}$$

where P_b is the blast-hole pressure (Pa), K is the stiffness of rock mass (Pa), and σ_c is the uniaxial compressive strength of rock (Pa). The amount of P_b and K could be calculated from Eqs. (2) and (3):

$$P_{CJ} = \frac{\rho_0 D_{CJ}^2}{4}, \tag{2a}$$

$$P_b = \frac{P_{CJ}}{2}, \tag{2b}$$

$$K = \frac{E_d}{1 + v_d}, \tag{3}$$

where P_{CJ} is the ideal blast pressure (Pa), ρ_0 is the unexploded explosive density (kg/m^3), D_{CJ} is the ideal detonation velocity (m/s), E_d is the dynamic Young's modulus of rock (Pa), and v_d is the dynamic Poisson's ratio of rock. These relations are to approximate the blast-hole pressure and stiffness. In cases that more accurate values are available through direct measurements or numerical modelings, they could be used instead of the provided relations.

After calculating the CZI, Esen et al. [10] demonstrated that there is a power relationship between this factor and the radius of the crushed zone. This relation is shown in Eq. (4):

$$\frac{r_0}{r_c} = 1.23 \times CZI^{-0.219}, \tag{4}$$

where CZI is the crushing zone index, r_c is the crushed zone radius, and r_0 is the blast-hole radius. The crushed zone radius is then calculated as follows (Eq. (5)):