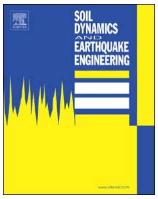
Soil Dynamics and Earthquake Engineering 105 (2018) 119–126

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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



Dynamic propagation behavior of cracks emanating from tunnel edges under impact loads

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ARTICLE INFO

Keywords:
Tunnel
Impact
TWSRC specimen
Arrest
Crack speed

ABSTRACT

In order to study crack dynamic propagation behavior of cracked tunnels under dynamic loading, a new configuration specimen of a tunnel with single radial crack (TWSRC) emanating from tunnel edge was proposed and by using these specimens, drop weight impacting experiments were conducted in this paper. The study using TWSRC specimens could be directly applied to tunnel engineering, and could guide tunnel designers to enhance tunnel stability. Sandstone was selected to make TWSRC specimens and crack propagation gauges (CPGs) and strain gauges were used to measure crack initiation and propagation time and crack speed. Numerical models were established by using the finite difference code AUTODYN to simulate crack propagation behavior and propagation path. The finite element code ABAQUS was used to calculate dynamic stress intensity factors (SIFs). For cracks propagating with a speed, the dynamic SIFs were obtained by the corresponding stationary crack SIF times a universal function. According to the initiation time and propagation time, the critical SIFs (or fracture toughness) in initiation, propagation and arrest were determined by the experimental-numerical method. The results show that (1) in the process of crack propagation, crack speeds are not a constant, and the cracks may temporarily stopped for a period, and in this study, the maximum arrest period is 227.52 μs; (2) the propagation toughness is related to crack speeds, and the arrest toughness is lower than the initiation toughness.

1. Introduction

Underground structures are often subjected to dynamic loads, such as earthquakes, blasts and impacts. For cracked tunnels under dynamic loads, the cracks may initiate and propagate, which will weaken tunnel structure stability and may even lead to large disasters, such as rockbursts. Therefore, it is essential to investigate the dynamic behavior of cracked tunnel under dynamic loads, thereby providing guidelines to improve tunnel stability. In this study, a new specimen containing a small ‘tunnel’ with single radial crack (TWSRC) emanating from the tunnel edge is proposed, and by using TWSRC specimens, drop weight impact experiments are conducted. The crack dynamic propagation behavior, including critical stress intensity factors (SIFs) and propagation time and speeds, is investigated.

There are several specimens, such as the SCDC specimen [1,2], the SCSC specimen [3,4] and VB-SCSC specimen [5] which could be applied in studying rock propagation behavior. However, these specimens are different from tunnels in configuration, and the different configuration may result in difference in crack dynamic behavior. Therefore, in this paper a tunnel configuration specimen TWSRC is applied since the study results could be directly applied to tunnel engineering, which could improve tunnel stability.

In the study of crack dynamic behavior, dynamic initiation toughness and propagation toughness have been investigated by using split Hopkinson pressure bar (SHPB) system and different specimens, such as Wang and Xing [6] used flattened Brazilian disk specimens to measure the dynamic fracture toughness K_{IC}; Nasseri and Mohanty [7] used CCNBD specimen to estimate the propagation toughness; Chen et al. [8] used NSCB specimen to estimate the propagation toughness of Laurentian rock; Wang et al. [9] used CSTFBD specimens to study mode I and mode II rock dynamic fracture toughness; Zhang and Zhao [10] used SCB specimens to carry out dynamic experiments; Gao et al. [11] used NSCB specimens to study the loading rate effect on crack behavior. More details about the dynamic experimental techniques for measuring initiation and propagation toughness have been summarized in two review papers [12,13].

For a crack propagating with a speed, the stress intensity factor (SIF) is different from those stationary cracks. Freund [14] proposed a universal function which describes the influence of crack speed on the dynamic stress intensity factors. Rose [15] pointed out that the dynamic SIF of a moving crack is the product of the universal function multiplied with the stress intensity factor of the corresponding stationary crack.

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https://doi.org/10.1016/j.soildyn.2017.12.012
Received 9 August 2017; Received in revised form 24 September 2017; Accepted 3 December 2017

This calculation method of dynamic SIFs of moving cracks has been widely applied [1–5], and it will be adopted in this study.

AUTODYN code is an explicit finite difference, finite volume and finite element code for solving a wide variety of nonlinear problems in solid, fluid and gas dynamics, which has been applied in solving a wide variety of problems characterized by both geometric non-linearities and material non-linearities, and its effectiveness has been well validated [16–22]. Therefore, in this study, AUTODYN code will be applied in the simulation of crack propagation behavior and propagation paths of TWSRC specimens under impacts.

In the study of crack dynamic propagation, several methods for determining fracture toughness have been developed. Jiang and Vecchio [12] applied strain gauges stuck near crack tips to measure crack tip displacements for calculating critical SIFs. Wang et al. [23] developed an experimental - numerical method in which dynamic SIFs are calculated through the numerical models established according to specimen dimension and the loading conditions, and then combining with experimental results, the fracture toughness is determined. Avachat and Zhou [24], Lee et al. [25] and Zhang and Zhao [26] applied the high-speed photography method to determine time-to-fracture and crack propagation speeds. Crack propagation gauges (CPGs) consist of a group of fine wires, and they can be stuck along crack propagation path. As the crack propagates, the wires will break sequentially, and the corresponding voltage signal will change, thus CPGs can be applied in measuring crack propagation speeds [2–5].

The SHPB impacting devices have been improved and the diameters of the incident and transmission bars have been enlarged [27–29]. However, the bar diameter is still not large enough and the specimen dimension by using SHPB impact system is still limited. The small size specimens could have the problem that the crack behavior is easily affected by the tensile reflected wave from the specimen free edges. The tensile wave may induce cracking failure or superpose with the compressive waves so to affect test results. Therefore, in this study, a large size tunnel specimen is applied which measures 350 mm in height, 300 mm in width and 30 mm in thickness, and accordingly a drop weight impact testing system is employed which is suitable for a large specimens. The drop weight impact test system is designed according to SHPB principle, and can be used for low & medium speed impact tests.

2. Experimental study

In order to study dynamic propagation behavior of cracks emanating from a tunnel edge, experimental study is first performed by using a drop weight impact test system and cracked tunnel specimens.

2.1. TWSRC specimens

In the study of crack dynamic propagation behavior and rock fracture toughness, three configuration specimens, i.e. the SCDC specimen [1,2], the SCSC specimen [3,4] and VB-SCSC specimen [5] have be applied. However, these specimens are different from tunnels in configuration, and the different configuration may result in differences in crack dynamic behavior. Therefore, in this paper a new configuration specimen of a ‘tunnel’ with single radial crack (TWSRC) emanating from the tunnel edge is proposed. The study results by using TWSRC specimens could be directly applied to tunnel engineering, which could guide tunnel designers to enhance tunnel stability and to prevent the disasters of tunnel fractures.

The material selected in this study is Longchang green sandstone which is compact and uniform and has been applied in the former study [30,31], and its parameters are presented in Table 1. The TWSRC specimen, as shown in Fig. 1, is a rectangular plate measuring 350 mm in height, and 300 mm in width and 30 mm in thickness with a ‘tunnel’. The tunnel height h is 35 mm; the width w is 50 mm; and the radius of circular arch R is 25 mm. The crack emanates from the symmetry axis of the circular arch of the tunnel specimen, and it is pure mode I crack. The crack length a is 50 mm, and the crack width is 1.0 mm. The crack tip was sharpened by using a diamond wire saw. P_i(t) and P_t(t) are the loads acting on the top and the bottom of the specimen from the incident plate and the transmission plate, respectively. Fifty tunnel specimens are impacted in this experimental study, which can fully avoid the influence of accidental factors on test results.

2.2. Drop weight impact test system

Drop weight impact system, as shown in Fig. 2, is applied in this experimental study. The drop weight impact system consists of an incident plate, a transmission plate, a drop weight plate, a data acquisition system and a concrete amortisseur which can transfer stress waves to the ground so to eliminate the effect of the reflected waves. In order to reduce the wave dispersion effect and the inertia effect, a piece of brass plate is chosen as wave shaper, which is stuck at the top end of the input plate. In doing so, high-frequency oscillation is reduced and a ramped wave is obtained. Different impacting speeds can be realized by adjusting the height of the drop weight plate lifted. The incident plate is made of LY12CZ aluminum alloy, and its parameters are listed in Table 1. The incident plate measures 3.0 m in height, and 0.3 m in width, and 0.03 m in thickness. The transmission plate measures 2.0 m in height, and 0.3 m in width, and 0.03 m in thickness. It is made of steel, and the steel parameters are shown in Table 1.

Three strain gauges (BX120-50AA) are stuck on the incident plate, and their distances to the top of the incident plate are 0.5 m, 1.5 m and 2.5 m, respectively. A strain gauge is stuck on the middle of the transmission plate to record the voltage signal, which can be further converted into the strains. After using ORIGIN program to de-noise, the strains can be used to calculate the forces P_i(t) acting on the top and P_t(t) acting on the bottom of the specimen by using Eq. (1) [32]

$$P_i(t) = E_i A_i [\varepsilon_i(t) + \varepsilon_r(t)]$$
$$P_t(t) = E_t A_t \varepsilon_t(t) \tag{1}$$

where E_i and E_t are the Young's modulus of the incident plate and transmission plate, respectively, A_i and A_t are the cross-sectional areas of the incident plate and transmission plate, respectively, ε_i(t) is the strain induced by stress waves travelling in the incident plate, and ε_r(t) is the strain caused by the stress waves reflected from the interface between the incident plate and the specimen, and $\varepsilon_t(t)$ is the strain obtained from the strain gauge stuck on the transmission plate.

In the experiments, the time when the stress waves just reach the top end of the specimen is set as zero for convenience. For the TWSRC specimen # 35, the curves of load versus time are presented in Fig. 3, which will be used as the loading conditions in the subsequent numerical simulations.

2.3. Crack initiation time measured by using strain gauges

Two strain gauges SG$_1$ and SG$_2$ are stuck perpendicularly to the pre-crack on TWSRC specimens, as shown in Fig. 4, SG$_1$ coincide with the crack tip, and SG$_2$ is stuck at a distance of 30 mm from SG$_1$. It can be seen that at the time $t_f = 274$ μs, the SG$_1$ was broken and the voltage signal have a jump, which means that the crack is initiated. At the time $t_p = 423$ μs, the second strain gauge SG$_2$ was broken. According to the broken time, one can obtain the crack initiation time, and according to the distance, one can calculate the average crack propagation speed which is 201.3 m/s.

Using two strain gauges, one can only measure the average speed between the two strain gauges. In order to obtain more information during the process of crack propagation, we will use crack propagation gauges (CPGs) to measure crack propagation speeds.