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Modelling of blast-induced damage in tunnels using a hybrid finite-discrete numerical approach

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ABSTRACT

This paper presents the application of a hybrid finite-discrete element method to study blast-induced damage in circular tunnels. An extensive database of field tests of underground explosions above tunnels is used for calibrating and validating the proposed numerical method; the numerical results are shown to be in good agreement with published data for large-scale physical experiments. The method is then used to investigate the influence of rock strength properties on tunnel durability to withstand blast loads. The presented analysis considers blast damage in tunnels excavated through relatively weak (sandstone) and strong (granite) rock materials. It was found that higher rock strength will increase the tunnel resistance to the load on one hand, but decrease attenuation on the other hand. Thus, under certain conditions, results for weak and strong rock masses are similar.

1. Introduction

Underground excavations in rock (e.g. civil road tunnels, mine drifts) can be subjected to blast loads associated with excavation methods, or may be even subjected to blast loads caused by external sources. Blast damage includes both cracking of the rock mass material and induced damage to structural reinforcing elements (concrete liner). Even in the case where the blast may not necessarily reduce the load capacity of the engineered excavation, there is the potential for fragments of rock material and/or structural elements to be ejected with large velocities, thus imposing a significant hazard to either humans or equipment.

Due to the complexity of the mechanisms involved, blast design in construction projects and mining largely relies on simplified empirical approaches. Most commonly, peak particle velocity (PPV) attenuation is estimated based on field tests, and compared to PPV based damage thresholds (Dowding, 1996). Different authors used numerical simulations to study the response of underground structures to blasting (e.g. Jiang and Zhou, 2012; Deng et al., 2014), and rock mass damage is defined based on the observation of the plastic zones created by the blast and/or by measuring PPV results (Wei and Zhao, 2008).

In this paper, a fracture mechanics based finite-discrete element approach (FEM-DEM) is adopted, using the proprietary code ELFEN (Rockfield, 2007). In the models, blast-induced cracking and spalling of the rock material are simulated using a Rankine rotating crack failure criterion. The hybrid FEM-DEM approach allows for an immediate and explicit simulation of the damage caused to the tunnel walls. Blast load generated by the explosive detonation is initially estimated using the ANSYS Autodyn software (ANSYS, 2013) and subsequently inserted into ELFEN.

For calibrating and validating the proposed numerical method, observations and results from extensive field tests conducted by Engineering Research Associates are used, hereafter referred to as the ERA tests (ERA, 1953). In these tests, single delay charges in the range of 145–145,000 kg of TNT were detonated above unlined tunnels with diameters of 2–10 m in sandstone and granite. All charges were buried and fully coupled to the ground. Four damage zones from total collapse to light damage were empirically defined as a function of the scaled distance of the charge to the tunnel.

The influence of rock mass strength on tunnel durability to withstand dynamic loads is debated amongst authors. For instance, Rozen et al. (1988) proposed an empirical correction factor to the empirical guidelines established in the ERA tests based on the Rock Quality Designation (RQD) (Deere and Miller, 1966) of the rock mass. They found that for lower RQDs the PPV induced by blasting increases. In contrast, Wu et al. (1998) emphasized the role of discontinuities in the rock mass on wave attenuation, implying that a weaker and heavily jointed rock mass is favourable in terms of tunnel dynamic resistance. Once the proposed method of numerical simulation is found to be consistent with the ERA tests, the method is then extended to attempt to determine the overall impact of rock mass strength on tunnel dynamic strength.

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2. The finite-discrete element method

As discussed in Hamdi et al. (2014), two main approaches are used for the numerical modelling of rock mass behavior, based on the concept that the deformation of a rock mass subjected to applied external loads can be considered to be either continuous or discontinuous. The main differences between the continuum and discontinuum analysis techniques lie in the conceptualization and modelling of the fractured rock mass and the subsequent deformation that can take place in it. A continuum model reflects mainly material deformation of the system, while a discontinuum model reflects the movement component of the system. The continuum approach may circumvent some of the difficulties associated with the discrete method, in terms of complexity of the model and impracticality of modelling every fracture in a deterministic way. However, an intrinsic limitation of the equivalent continuum approach is that the stress acting on a specific fracture is usually not the same as that deduced from the overall stress, because it depends on the stiffness of the fracture itself and on the stiffness of the fracture's surrounding matrix (Cai and Horii, 1993).

Hybrid finite-discrete element (FEM-DEM) codes combine the aspects of both finite elements and discrete elements, and also allow for the incorporation of fracture-mechanics principles to allow for the realistic simulation of brittle fracture-driven processes and a full consideration of the failure kinematics (Pine et al., 2006; Mahabadi et al., 2012; Hamdi et al., 2014). In FEM-DEM model, the finite element-based analysis of continua is merged with discrete element-based transient dynamics, contact detection, and contact interaction solutions (Munjiza, 2004). FEM-DEM based numerical analysis of fracturing processes in rock considers that such problems are often highly dynamic, with rapidly changing domain configurations, thus requiring sufficient resolution and allowing for multiphysics phenomena. Such problems are typically simulated employing time-integration schemes of an explicit nature (Owen et al., 2004). Application of dynamic explicit time-integration schemes to multifracturing solids, particularly to those involving high nonlinearity and complex contact conditions, has increased notably in recent years (e.g. Owen et al., 2004; Jaini and Feng, 2011).

There are advantages in employing a hybrid FEM-DEM approach to model blast-induced damage, including:

(1) A better description of the physical processes involved, accounting for diverse geometrical shapes and effective handling of large numbers of contact entities with specific interaction laws.

(2) The implementation of specific fracture criteria and propagation mechanisms allows the simulation of the progressive fracture process within both the finite and discrete elements.

Among the different hybrid FEM-DEM codes currently available, the code ELFEN (Rockfield, 2007) incorporates a coupled, elasto-plastic, fracture-mechanics constitutive criterion that allows realistic modelling of the transition from a continuum to a discontinuum, with the explicit generation of stress-induced cracks.

As an FEM/DEM code, ELFEN has the capability of modelling pre-existing discontinuities. In the current paper, the rock mass is modeled as an equivalent continuum. The effect of joints on wave propagation has been investigated by different authors (Cai and Zhao, 2000; Chen et al., 2000). Work is being carried out to test the proposed approach with the addition of discontinuities pre-inserted in the model.

Within the ELFEN code, the constitutive behavior used to simulate multi-fracturing of brittle materials is achieved by employing a fracture energy approach controlled by designated constitutive fracture criteria. In this paper, the rotating crack model is used to simulate crack formation under tensile conditions within the initially continuum-meshed geometry.

The Rankine rotating crack failure criterion is based on the concept of Mode I fracturing studied in fracture mechanics. Once the maximum principal stress reaches the tensile strength limit, tensile softening is initiated and the elastic modulus is degraded in the direction of the major principal stress invariant. Finally, the mesh topology is updated and when new surfaces and/or bodies are formed they interact with each other according to the discrete contact properties assigned (Rockfield, 2007). The yield surface and softening curve for the Rankine rotating crack failure criterion are shown in Fig. 1.

3. Assessment and characterization of blast load

To the authors' knowledge, there is no available software program that can model all stages of blast-induced damage (i.e. explosive detonation, wave propagation, fracturing and spalling). Therefore, it was decided to simulate the load generated by the explosive detonation using ANSYS Autodyn (ANSYS, 2013), similar to the work carried out by Chen and Zhao (1998). Autodyn is a finite-difference software, specially designed to solve a wide variety of non-linear problems including the resultant stresses emanated from explosive materials using the empirical Jones-Wilkins-Lee (JWL) equations.

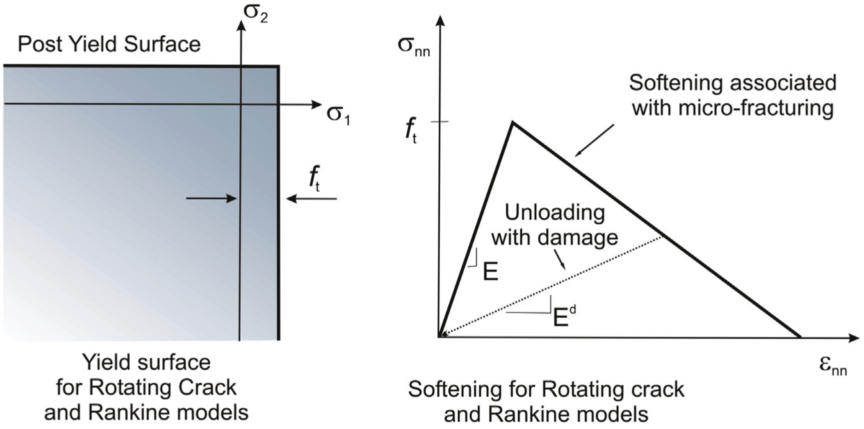

Fig. 1. Yield surface and softening curve for the Rankine rotating crack in ELFEN (from ELFEN user's manual (Rockfield, 2007)), where σ_1 and σ_2 are the tensile strengths, f_t is the elastic limit, σ_{nn} and ε_{nn} are the principal stress and strain, and E and E^d are the elastic and residual Young's moduli.