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Analysis of excessive deformations in tunnels for safety evaluation

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ABSTRACT

Tunnel construction is increasing worldwide in mining and civil engineering. There have been several accidents that resulted in delays, cost overruns, some with more severe consequences. To help minimize these accidents, it is necessary to assess and manage the risks associated with tunnel construction and exploration. A particular type of accident, or undesirable event, which can occur during tunnel construction and operation, is associated with the occurrence of excessive deformations occurring inside the tunnel. This can happen due to deficient design, construction defects, and high *in situ* stresses or due to specific swelling and squeezing grounds. Deep coal mines where large deformations can occur during and after excavations due to the soft properties of the rock and the high *in situ* stresses, are particularly vulnerable to this type of event. The associated non-linear problems are related with geomechanical behavior of the rock mass, changes in the geometry of cavities and in some cases with developing surface contacts due to large strains. In this paper, the phenomena involved in large material deformations are analyzed in detail and the basic equations for the Chen's large deformation theory are presented. The application of an FEM based method to simulate large material deformations, the Material Point Method (MPM) to the simulation of large deformation that occurs in tunnels when failure occurs, is also described. An application of MPM to the Jiahe Coal Mine, in China is presented, and the numerical results obtained with MPM compared with solutions using Chen's large deformation theory. Safety considerations about the excessive deformation scenario in tunnels are drawn and a risk assessment methodology with special use of Bayesian networks is proposed. A simplified schematic example was presented for two case scenarios.

1. Introduction

Most accidents and undesirable events are associated with uncertainties, often related to uncertainties in site ground conditions. It is important to develop risk analysis systems to avoid or to mitigate their occurrence. The associated risk has a complex nature resulting from the combination of two sets of factors, the events and their consequences, and the vulnerability factors that determine the probability of an event having certain consequences. Risk analysis illustrates the fact that decision-making must be based on a certain level of uncertainty (Einstein, 2002; Sousa, 2010).

Until relatively recently, risk assessment and risk analyses have not assumed particular relevance when evaluating underground projects and other major geotechnical projects. This situation is changing and risk analysis has been successfully implemented, for major transportation infrastructures projects in UE, USA and Switzerland, using both commercial and research software for risk analysis. Special reference can be made to the system DAT – Decision Aids for Tunneling, developed by Massachusetts Institute of Technology (MIT), USA, in co-operation with Ecole Polytechnique Fédérale de Lausanne (Einstein, 2006). DAT is an interactive program that uses probabilistic modeling to analyze the effect of geotechnical uncertainties and construction uncertainties on construction costs and time through probabilistic modeling. Recent developments were introduced in this software allowing dealing with other structures like embankments, bridges and Engineered Geothermal systems (Moret et al., 2009; Sousa et al., 2012).

A type of accident associated to tunnel construction and operation is the occurrence of excessive deformations inside the tunnel (He et al., 2012), often occurring due to particular type of ground, where swelling and squeezing happen. It is particularly important to consider the possibility of occurrence of excessive deformations in deep coal mines where large deformations may develop during

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and after excavations due to the soft properties of the rock and the high *in situ* stresses.

In China, coal resources play a leading role in the energy strategy, and represent more than 70% of the total energy consumption. Deep coal resources below 1000 m represent the majority of resources, about 70% of the total. Fig. 1 confirms this evidence in the development trend of the average mine depth of the major coal mines in China. In 2010, the planned average depth was about 700 m and in 2020 is expected to have an average of 1200 m for the referred mines (He, 2006). As coal mines went deeper and deeper, accidents and their consequences became more severe as they occurred in conditions of large deformations often associated with rockbursts, waterbursts, high temperatures and gas outbursts. In this context, some of the phenomena involved are analyzed in detail and the basic equations are presented for the classic large deformation approaches and for Chen's large deformation theory (Chen, 1979, 2000; He et al., 2012). The finite element method was applied to the different approaches for large deformation hazards, including non-linear geometrical approaches and commonly used rock mechanics constitutive models. Almost all existing commercial numerical software only include classical large deformation theories for these types of problems, in order to incorporate suitable models for geomaterials such as Mohr–Coulomb, Drucker–Prager, Hoek–Brown amongst others and supports. The paper also describes the use of the Material Point Method (MPM) to the simulation of large deformation that occurs in tunnels of deep coal mine, illustrated with a practical application to roadway tunnel in the Jiahe deep coal mine.

The depths at which this roadway tunnel is located vary between 900 m and 1032 m. The application investigates the influence of several coal seams at different depths in the large deformation behavior of the cavities for different *in situ* state of stresses. Safety considerations regarding the excessive deformation scenario in tunnels are drawn and a risk assessment methodology using Bayesian networks (BN) is proposed (Sousa, 2012). Two different scenarios of probability of occurrence of large deformations are analyzed and conclusions regarding the occurrence of large deformation scenario are drawn.

2. Excessive deformations in tunnels

2.1. General

The identification of the geotechnical risks aims to assess all causes that may lead to a hazard-inducing process. The study of

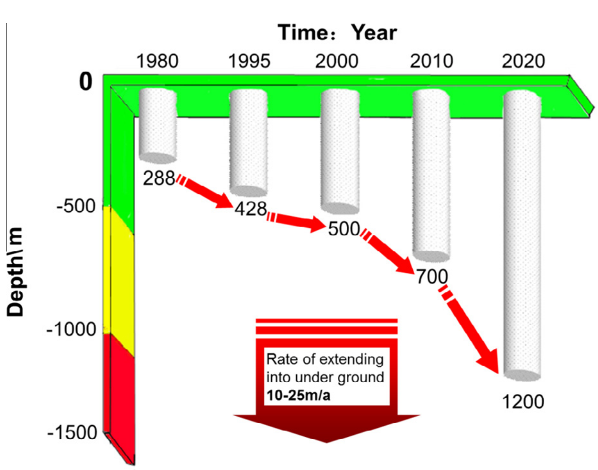

Fig. 1. Trends of average mining depth of major coal mines in China (adapted from He, 2006).

accidents in underground structures is very important in understanding the instability phenomena and mechanisms that are produced by underground construction and, as a result, allowing for the selection of the most appropriate construction methods for future projects. Even though the occurrence of accidents and incidents in underground works is not as unusual as in other geotechnical structures, their dissemination is not always common (Vlasov et al., 2001; Cost C7, 2003; Stallmann, 2005; Seidenfuβ, 2006; Sousa, 2006, 2010). In fact, there is a tendency to minimize their dissemination and causes. This fact may lead to the repetition of former errors by designers and constructors. Therefore, the number of failure reported in underground works is in comparison to those of other type of construction smaller.

An important study on cases of accidents in tunnels during construction was conducted at MIT by Sousa (2010). In this study, data on accidents were collected from the technical literature, newspapers and correspondence with experts in the tunneling domain. The data were stored in a database and analyzed, and the accidents were classified into different categories, their causes and their consequences were evaluated. The main goal of the study was to determine the major undesirable events that may occur during tunnel construction, their causes, chain of events and consequences and ultimately present mitigation measures to avoid accidents on tunnels during construction. To gather information form experts in the field, a survey was created and send to experts worldwide. The survey consisted of two sections: *Project Information* and *Accident Information*. The *Project Information* section contained information related to the project (e.g. tunnel dimensions; geological and geotechnical information, construction method, among others), as well as the location in the tunnel of the accident. The *Accident Information* section is most important and collects information that is specific to the accident itself (Sousa, 2010). In total 204 cases were registered based on questionnaires responses, literature review and private correspondence with experts from 25 countries in Europe, North and South America and Asia.

The study identified 9 types of events which were classified, as: *Rock Fall*; *Collapse*; *Daylight Collapse*; *Large Deformations*; *Waterburst and Flooding*; *Rockburst*; *Specific Locations*, such as portals and shafts; and *Other Types* that included slope failures. Fig. 2 shows the distribution undesirable events in the database. The great majority of events reported are Collapses and Daylight Collapses (36% and 28%, respectively). This does not mean that these are the great majority of events that occur during tunneling construction. They are however the most frequently reported in the literature and by the experts because most likely they are the ones with more severe consequences on the construction process, the safety of the workers and people and structures at the surface. The consequences reported ranged from loss of live, equipment damage and damage to the tunnel structure that may lead to a collapse.

One of the frequent types of accidents occurring during construction is related with excessive deformations occurring inside the tunnel or at the surface. These events can be caused, for example, by deficient design, construction defects and/or due to particular type of terrains such as swelling and squeezing ground, which had not been predicted. Fig. 3 shows large deformations of the surrounding rock located in China. The serious distortion and rupture of steel occurred at the South water storage tunnel (He et al., 2012). The location of this type of scenario is in Fig. 4.

As mentioned previously, one of the main causes of excessive deformation is crossing fault zones composed of squeezing and weak strata. Squeezing ground is characterized by excessive ground pressure that may lead to support failure and sometimes even cause collapse. It generally occurs around the whole cross section frequently involving the invert as well. The development of both rock pressure and rock deformations is time dependent.