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ScienceDirect
Mechanics Research Communications 34 (2007) 63–68
MECHANICS RESEARCH COMMUNICATIONS
www.elsevier.com/locate/mechrescom

Comparative study of rock slope stability analysis methods for hydropower projects

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Available online 27 June 2006

Abstract

This paper presents a comparative study of methods used for the analysis of the stability of rock slopes for hydropower projects. The comparison concerns the application of the limit equilibrium method, the block element method, and the finite element method on the stability analysis of two hydropower engineering projects in China. The study results show that the limit equilibrium method and the block element method give very close result, while the finite element method gives more conservative safety factor.

Keywords: Slope stability; Limit equilibrium method; Block element method; Finite element method; Safety factor

1. Introduction

Landslides present an important issue in hydropower project. Various methods have been proposed to evaluate the stability of rock slopes. The limit equilibrium method is very popular for such analysis because of its simplicity and convenience. Since the 1950s, numerical methods based on stress and strain analysis have gained popularity. However, these methods do not generally give identical results. This paper includes a comparison of three types of methods: (i) the limit equilibrium method (LEM) which involves classical mechanics and widely used in engineering practice (ii) the finite element method (FEM) which is also very popular in engineering practice and (iii) the block element method (BEM) which was developed recently within the framework of discontinuous media mechanics. Comparison is carried out on two important hydropower projects in China.

Landslides can be onset by various factors such as earthquake and heavy rainfall. Since the interest of this paper concerns a comparative study of different methods through the safety index, the calculation is carried out only for the case of natural state without the effects of earthquake and rainfall. The safety index is specified as the strength reduction safety factor K_f: if the strength parameters of the rock and slip surface are divided by K_f, the slope is at the limit equilibrium state.

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0093-6413/$ - see front matter
doi:10.1016/j.mechrescom.2006.06.004

2. Presentation of the methods used in this study

2.1. Limit equilibrium method

The limit equilibrium method (LEM) presents important advantages, mainly simplicity and practicability. As this method is adopted by various design codes for long period; it benefices from thorough practical experiences. There are various strategies to implement this method. This paper includes the use of two strategies:

(i) The Sarma method (Sarma, 1973), which considers the shear strength characteristics of slice interfaces. This method is popular in the Chinese hydropower engineering. It accounts for inclined slip surfaces, this capacity allows for a more realistic modeling of natural discontinuities.
(ii) The residual thrust method (RTM), which assumes that the reaction force between slices is parallel to the slip surface. This method has been used in the Chinese railway engineering and mining engineering for long time.

The program SA containing above two methods developed by the authors' group was used in the study.

2.2. Finite element method

The finite element method (FEM) is popular in numerical modeling of engineering structures (Griffith and Lane, 1999; Yamagami and Ueta, 1988). Since this method belongs to the continuous media mechanics system, it should be revised to deal with the discontinuities in the rock masses (Chen and Egger, 1999). The adaptive technique has been used in slope stability problem (Chen, 1998) in order to facilitate the pre-process works and to control the discretization errors.

The program ACORE of FEM developed by the authors' group is used in the study (Chen et al., 2003). The Drucker-Prager criterion is assumed for the rock, while the Mohr-Coulomb criterion is assumed for the slip surface. The slip surface is discretized with joint element (Goodman et al., 1968).

2.3. Block element method

The block element method (BEM) considers the rock mass as a discontinuous material composed of rock blocks and discontinuities (Chen et al., 2002). The set of equations governing the slope stability is established from the equilibrium condition of block elements, the compatibility condition between the block elements and the discontinuities, and the constitutive relations of the discontinuities and the block elements. The solution of the governing equations allows for the calculation of the deformation, the contact forces in the rock masses, and the safety factor of the rock slope.

The program BLOCK of BEM developed by the authors' group was used in the study (Chen et al., 2003). A rigid body is assumed for the rock and the Mohr-Coulomb criterion is assumed for the slip surface.

3. Applications on hydropower projects

3.1. Sanbanxi rock slope (Xu et al., 2004)

Preliminary evaluation showed a potential landslide at the upstream of the water intake in the Sanbanxi hydropower project (Fig. 1a). The slip body consists of clay, huge block stone and crushed stone below the elevation of 592 m. The characteristics of the slip body are: distribution range, between 375 m and 657 m in elevation; thickness, 5.0–40.0 m; total volume, 440,000 m^3; slope gradient, 32–38°. According to the geological and topographic conditions, the section (A-A) shown in Fig. 1b is analyzed. The mechanical properties were obtained through the comprehensive study by laboratory test, field test, and engineering analogy (Table 1).

The slip body was divided into 20 slices (Fig. 2a) for the limit equilibrium method (Sarma method and residual thrust method). In the block element method, the slip body was divided into 20 blocks as that used with the limit equilibrium method (Fig. 2b). The finite element mesh included 3096 elements and 3243 nodes (Fig. 2c).