Tunnelling and Underground Space Technology 51 (2016) 30–40

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Integration of three dimensional discontinuous deformation analysis (DDA) with binocular photogrammetry for stability analysis of tunnels in blocky rockmass

Hehua Zhu [a,b,c], Wei Wu [a,b,c,*], Jianqin Chen [a,b,c], Guowei Ma [d], Xingen Liu [e], Xiaoying Zhuang [a,b,c]

[a] State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai, China
[b] Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Tongji University, Shanghai, China
[c] College of Civil Engineering, Tongji University, Shanghai, China
[d] School of Civil and Resource Engineering, University of Western Australia, Australia
[e] Shanghai Tongyan Civil Engineering Technology Co. Ltd, Shanghai, China

ARTICLE INFO

Article history:
Received 24 June 2015
Received in revised form 24 September 2015
Accepted 8 October 2015
Available online 22 October 2015

Keywords:
Tunnel modeling
Three dimensional stability analysis
Discontinuous deformation analysis
Photogrammetry
Integrated system

ABSTRACT

This paper demonstrates and evaluates an integrated system coupling 3-dimensional binocular photogrammetry and discontinuous deformation analysis (DDA) for stability analysis of tunnels in blocky rockmass. 3D DDA is an effective numerical method for discontinuous and large displacement problems. In stability analysis of rockmass, especially for tunnels, one of the primary bottlenecks in 3D DDA is generating discontinuous models. For tunnel constructions requiring small interval time for blasting, traditional geotechnical data collection approaches such as hand-mapping and geologic compass are always lacking in efficiency and accuracy. 3D photogrammetry is an economical and efficient method for collecting geometric features and surface data. An integrated system connecting geometrical data acquisition and discontinuous numerical analysis automatically, is valid for improving safety in tunnel construction. This system includes photogrammetry module, modeling module and analysis module. In the photogrammetry module, binocular photogrammetry devices and image reconstruction technique are implemented for geometric data of rockmass. Then location, dip direction and dip angle of joints as well as other geometric information of tunnels are input into the modeling module to generate 3-dimensional discontinuous models. The analysis module using 3-dimensional DDA to evaluate the stability of the surrounding rock in tunnels. The integrated system is implemented in an engineering instance, Suocaopo Tunnel in Guizhou, China.

1. Introduction

For structure design and disaster prevention, superstructures are simulated with continuum-based models to enable a high accuracy analysis. However, for substructures such as tunnels, slopes and foundations, especially of which the medium is rockmass, the modeling accuracy with the finite difference method (FDM), finite element method (FEM) and other continuum-based numerical methods is relatively lower than that for superstructures. Rock mass is discontinuous medium complicated for complex geometrical and mechanical characteristics primarily resulted from discontinuity. Failures of fractured rockmass are controlled by joints in most cases and difficult to be simulated with continuum-based models. To evaluate the stability of rock mass, discontinuous methods are required in numerical modeling for engineering problems involving rockmass.

Discontinuous deformation analysis (DDA) is a discontinuum-based numerical method, especially applicable to solve large displacement and deformation problems in a blocky system (Shi, 1988; Shi and Goodman, 1989). Over the past three decades, great improvements for DDA as well as Discrete Element Method (DEM) have been made regarding neighbor searching (Williams and O'Connor, 1995; Munjiza and Andrews, 1998; Perkins and Williams, 2001; Wu et al., 2014), contact pattern identification (Jiang and Yeung, 2004; Nezami et al., 2004, 2006; Wu et al., 2005; Wu, 2008; Yeung et al., 2007; Ahn and Song, 2011; He et al., 2014), crack simulation (He and Ma, 2010; Chen et al., 2013; Cai et al., 2013a,b; Zhu et al., 2014; Nie et al., 2014; Zheng et al., 2015) and contact parameters (Doolin and Sitar, 2002; Jiang and Yeung, 2004; Yeung et al., 2007; Beyabanaki et al., 2008; Bao and Zhao, 2012; Wang et al., 2012; Jiang et al., 2013; He et al., 2013; Zhang et al., 2014).

* Corresponding author at: 1239 Siping Road, 200092 Shanghai, China.
E-mail address: 09wuwei@tongji.edu.cn (W. Wu).

http://dx.doi.org/10.1016/j.tust.2015.10.012
0886-7798/

One of the primary difficulties in implementation of discontinuous numerical methods on rock mass is generating discontinuous models. The accuracy of discontinuous numerical simulation depends on the precision of models. Because the major part of a joint is inside rock mass and usually sightless, it is difficult to obtain the joint information directly. Due to the significant influence of joint net on stability of rock mass, researchers have paid a lot of attentions to approaches of acquiring joint information with trenchless technology (Reid and Harrison, 2000; Lemy and Hadjigeorgiou, 2003; Shaffner et al., 2009; Gigli and Casagli, 2011; Liu, 2013; Wang et al., 2013; Riquelme et al., 2014).

Geological sketch is the integration of measurements by mapping, geological compass, tapeline and etc., of which the accuracy is depend on manual operation. Furthermore, for rock slopes and tunnel sections with large dimensions, information of joints beyond the reach of surveyors is difficult for collection. Geophysical prospecting for rock mass uses electromagnetic wave, seismic wave, acoustic wave and etc. to obtain geological information of rock mass (Wyatt and Temples, 1996; Zajc et al., 2014). Rockmass is a combined and solid medium with heterogeneity, nonlinearity, anisotropy and discontinuity, which have negative effects on wave propagation. Because the accuracy is difficult to be guaranteed in rock mass, geophysical prospecting is mainly implemented in qualitative forecast for geological disaster and rockmass classification. The accurate dip angle and dip direction of a joint are difficult to determine directly by reflected waves. Laser scanning uses transmitted and reflected laser signals to record geometric information of rockmass surface (Fekete and Diederichs, 2013; Lato and Diederichs, 2014). The 3-dimensional coordinates of points on rock surface with irregular shape are computed according to the reflected laser theory. But when a joint is filled with a different material, the geometric differences between feature points of the joint and other surface points are difficult to distinguish by laser scanning. Binocular photogrammetry is a voxel-based morphometric method using multiple cameras with high resolution (Richard and Andrew, 2002; Haneberg, 2008). Connections between pixel dots of two or more images are established to reconstruct geometric and topological information of the rock mass surface. The matchup of pixel dots is based on size, color, grayscale and position. Thus joints filled with different materials or joints with small width can be identified directly.

This paper demonstrates and evaluates an integrated system coupling 3-dimensional photogrammetry and discontinuous deformation analysis for modeling and stability analysis of tunnels in discontinuous rockmass. This system includes the photogrammetry module, the modeling module and the analysis module. In the photogrammetry module, binocular photogrammetry devices and image reconstruction technique are implemented for geometric data of rockmass. Then location, dip direction and dip angle of joints as well as other geometric information of tunnels are input into the modeling module to generate 3-dimensional discontinuous models. The analysis module using 3D DDA to evaluate the stability of the surrounding rock in tunnels. The 3D integrated system is implemented in a highway tunnel in Guizhou, China.

2. Three dimensional photogrammetry with binocular images reconstruction

The photogrammetry devices in this paper includes camera, holder, calibration plate and data terminal. The camera is a digital single lens reflex with high resolution. For three dimensional information acquisition of an object, at least two images from different views are required. The camera is fixed on a bearing which can move on a track on the top of the holder shown in Fig. 1(a). Thus, the camera can move to different positions to take images from different views.

After obtaining the images of rockmass, the geometric data are fetched using a reconstruction algorithm. The matrix of perspective transformation in Eq. (1) connects the 3-dimensional coordinates system and the corresponding 2D coordinate plane (Hartley and Zisserman, 2002). The transfer equation can be expressed as

(a) Camera and holder of the binocular image system

(b) Calibration plate for the binocular image system

Fig. 1. Three dimensional photogrammetry system with binocular images reconstruction.