Evaluation on Application of Numerical Software in Stability Analysis of Tunnel Engineering

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Abstract. Numerical software is widely used in stability analysis of tunnel engineering, but difference among software has always been the focus of attention. This study presents a comparison of the most commonly used numerical software in tunnel engineering calculations, including ABAQUS, ANSYS, MIDAS-GTS and FLAC3D. With the same tunnel boundary conditions, geological parameters and numerical model adopted, the calculation results of the deformation of the surrounding rock, the stress of the lining and the distribution of the yielding area with four kinds of software are compared. The results show that the deformation and its trend of the surrounding rock are basically the same, only that the results of MIDAS-GTS are slightly larger than others. The calculated lining stress and distribution differs very little from each other. FLAC3D takes into account the effect of the stress path on the plastic state, the distribution of plastic zone calculated by those shows a little larger than others. Overall, the stability of the tunnel project based on the results of software is relatively similar, all four kinds of software can be used for engineering practice.

1. Introduction

Tunnel engineering possesses strong complexity and particularity. It will be constrained by the number of statistical samples, tunnel size and rock conditions to predict the stability of surrounding rock and the stress of lining by empirical method. Theoretical method can only be applied to the circular section tunnel [1]. Numerical analysis method is increasingly valued by tunnel engineering researchers for its convenient and fast features [2].

At present, the numerical method of tunnel engineering is mainly based on finite element method and fast Lagrangian difference method. Lots of software are developed based on these two methods, and many research results have been obtained. Jia & Tang [3] analysed the mechanical failure behaviour of tunnels under different angles of jointed rock mass. Funatsu et al. [4] analysed the effect of prestressed support structure on tunnel stability. Lee & Pietruszczak [5] simulated elastic plastic analysis of soft rock wall in circular tunnel. Hejazi et al. [6] analysed the effect of constitutive model on underground engineering. Azadi & Hosseini [7] analysed the seismic performance of shallow-buried tunnels in liquefiable sites. Kamal & Das [8] analysed the effect of prestressed anchor on stratum deformation in tunnel excavation. Fernadez & Moon [9] simulated the hydraulic conductance during tunnel excavation. The research above shows that the numerical simulation method can be applied to a variety of complex geological conditions as well as shapes and sizes of the tunnel, the calculation process is convenient, while intuitive contours of stress, strain can be extracted. Therefore, numerical simulation will continue to play an important role in future study of tunnel stability.
Although numerical software has been widely used in the stability analysis of tunnel [10], there is little research about the difference of calculation results among various software. In this study, the comparative study of commonly-used numerical software in tunnel engineering is carried out, and the difference evaluation can provide a comprehensive understanding in order to grasp the reliability and accuracy. It can be important reference for selecting numerical software for tunnel engineering.

2. Characteristics of numerical software
With the development of mathematics, mechanics theory and computer technology, numerical analysis methods have been applied in engineering geology and geotechnical engineering, and widely used as an important tool to solve such engineering problems in complex media and boundary conditions.

FLAC3D is numerical modelling software for geotechnical analyses of soil, rock, groundwater, constructs, and ground support. Such analyses include engineering design, factor of safety prediction, research and testing, and back-analysis of failure. With ABAQUS users can quickly and efficiently create, edit, monitor, diagnose, and visualize advanced Abaqus analyses. The intuitive interface integrates modelling, analysis, job management, and results visualization in a consistent, easy-to-use environment that is simple to learn for new users, yet highly productive for experienced users. The ANSYS program itself has a strong 3D modelling capability, and the ANSYS GUI (graphical interface) can create complex geometric models. In addition, ANSYS provides a flexible graphical interface and date interface. MIDAS-GTS is a general finite element analysis software developed for the geotechnical field. It supports static analysis, dynamic analysis, seepage analysis, stress seepage coupling analysis, consolidation analysis, construction stage analysis, slope stability analysis and other analysis types. A variety of professional modelling assistants and databases are provided.

A study is conducted by retrieving articles for tunnel engineering stability analysis involving numerical software; The results show that the following numerical software is widely used ones: FLAC3D (27934 related papers), ABAQUS (18237), MIDAS-GTS (9266), and ANSYS (8513).

3. Numerical calculation case and model
In the four kinds of software comparative analysis, the same tunnel size, grid division of model, surrounding rock and structural support parameters, construction conditions are adopted. The tunnel is circular and its radius is 3.05 m. The excavation method is full-section excavation.

In order to make the calculation results more representative, the cases with initial support and without initial support are simulated. Each step of the construction footage is 1 m and the depth of tunnel is 250 m. In initial support conditions, the initial support lags a distance of 3 m behind excavation face. The Z axis is the direction of tunnel, the X axis is along left to right direction, and the Y axis is the vertical direction. The numerical model geometry is: X×Y×Z = 60 m×60 m × 20 m.

Numerical calculation model and data monitoring line layout are shown in Fig.1, and model grids in various software are consistent. The physical and mechanical properties of surrounding rock and support are list in Table 1.

![Figure 1. Numerical calculation model and data monitoring line layout.](image-url)
The failure criterion used in the model is a composite Mohr-Coulomb criterion with tension cut-off. The Mohr-Coulomb criterion is expressed in terms of the principal stresses $\sigma_1$, $\sigma_2$, and $\sigma_3$, which are the three components of the generalized stress vector for this model [11]. In labelling the three principal stresses so that $\sigma_1 \leq \sigma_2 \leq \sigma_3$.

This criterion may be represented in the plane $(\sigma_1, \sigma_3)$ as illustrated. The failure envelope $f(\sigma_1, \sigma_3) = 0$ is defined by the Mohr-Coulomb failure criterion $f^* = 0$ with

$$f^* = -\sigma_1 + \sigma_3 N_\varphi - 2c\sqrt{N_\varphi}$$

(1)

where $\varphi$ is the friction angle, $c$ is the cohesion, and

$$N_\varphi = \frac{1 + \sin \varphi}{1 - \sin \varphi}$$

(2)

| Material    | Modulus of elasticity/GPa | Poisson's ratio | Density kg/m$^3$ | Tensile strength/MPa | Cohesion /MPa | Friction angle/° |
|-------------|---------------------------|-----------------|------------------|---------------------|---------------|-----------------|
| Rock mass   | 1.0                       | 0.32            | 2400             | 1.0                 | 0.4           | 32              |
| Support     | 15.0                      | 0.18            | 2600             | 2.3                 | 1.5           | 45              |

### 4. Calculation results

#### 4.1. Displacement of rock mass

Surrounding convergence of tunnel is the relative displacement value of two fixed point connections in opposite direction around the tunnel, which is the most intuitive performance of the deformation caused by tunnel excavation. As shown in Fig.2, the convergence rules of tunnel in FLAC3D, ABAQUS, ANSYS and MIDAS-GTS are basically consistent.

![Figure 2](image)

**Figure 2.** Vertical displacement of tunnel surrounding rock (unit: m).

Fig.3 shows the longitudinal deformation curves of tunnel surrounding rock. At first, the surrounding rock deformation is very small. Then, the longitudinal deformation of the surrounding rock increases with the increasing distance of the excavation face. Finally, the deformation of the surrounding rock tends to be stable when the distance reaches 3 times tunnel diameter.
Comparing the surface settlement and deformation of tunnel roof, the results of the four kinds of software reflect the same deformation trend (see Fig.4). Moreover, the deformation of tunnel roof almost keeps the same.

4.2. Lining stress
The Difference of lining stress calculated by the four kinds of numerical software are small. The maximum value is 20.48 MPa by FLAC3D, the minimum value of 17.23 MPa by ANSYS, difference between the them is about 15% (Fig.5). It indicates that the calculation accuracy can meet the engineering application requirement.
4.3. Plastic zone

The plastic zone range of the tunnel and the surrounding rock of underground caverns is the important base of determining its support and design. Both local and international studies on underground tunnels have led to abundant findings. The elastic-plastic problem of the plastic zone of the surrounding rock was proposed by Kastner [12]. Fig. 6 shows the plastic zone distribution of the surrounding rock. The results of ABAQUS, ANSYS and MIDAS-GTS are consistent, and the maximum depth of plastic zone is 0.5 m-1.2 m. However, the plastic zone distribution calculated by FLAC3D is 2 times larger than that of others. All plastic models potentially involve some degree of permanent, path-dependent deformations (failure) - a consequence of the nonlinearity of the stress-strain relations. The different models are characterized by their yield function, hardening/softening functions, and flow rule. The main reason is that the criteria of plastic zone in FLAC3D not only takes the plastic yield criterion of the material into account, but also considers the influence of the stress path on the plastic state. FLAC3D divides the plastic zone into 4 types, namely Shear-n, Shear-p, Tension-n and Tension-p. While the plastic regions of other software are only one type.

![Figure 6. Distribution pattern of plastic zone in surrounding rock.](image)

4.4. Data statistics

The calculation results of tunnel surrounding rock and support are shown in Table 2. The results show that the deformation and its trend of the surrounding rock are basically the same, only that the results of MIDAS-GTS are slightly larger than others. The calculated lining stress and distribution differs very little from each other. FLAC3D takes into account the effect of the stress path on the plastic state, the distribution of plastic zone calculated by those shows a little larger than others.

*Table 2. Calculation results of tunnel surrounding rock and support.*

| Working condition | Software  | Displacement of surrounding rock /cm | Plastic zone/m | Support stress /MPa |
|-------------------|----------|-------------------------------------|----------------|---------------------|
|                   |          | Inflected arch | Side wall | Crown | Depth | Tensile | Compressive |
| With support      | FLAC3D   | 3.08     | 3.01   | 2.63  | 1.28  | -0.35   | 20.48       |
|                   | ABAQUS   | 2.57     | 2.50   | 2.11  | 0.60  | -0.45   | 19.62       |
|                   | ANSYS    | 3.00     | 2.91   | 2.52  | 0.87  | -0.39   | 17.23       |
|                   | MIDAS-GTS| 3.77     | 3.52   | 3.18  | 0.60  | -0.30   | 17.78       |
| Without support   | FLAC3D   | 4.14     | 3.93   | 3.48  | 1.27  | -       | -           |
|                   | ABAQUS   | 3.5      | 3.32   | 2.82  | 0.29  | -       | -           |
|                   | ANSYS    | 3.52     | 3.68   | 3.07  | 0.42  | -       | -           |
|                   | MIDAS-GTS| 5.22     | 4.64   | 4.39  | 0.57  | -       | -           |
5. Conclusions
Based on the case study, application of four kinds of software (ABAQUS, ANSYS, MIDAS-GTS and FLAC3D) in tunnel stability analysis is evaluated. The results show that the morphological and changing trend of the surrounding rock deformation is basically consistent, only that of MIDAS-GTS are larger. The difference of lining stress among them is small, and the distribution rule keep the same. FLAC3D takes the influence of stress path on the plastic state into account, and its calculated law in the plastic zone is different from other software. Overall, the stability of the tunnel project reflected by four kinds of software is relatively similar, all of them can be used for engineering practice.

6. References
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