Numerical analysis of pillar stability for safe mining of a combined mine based on three-dimensional solid model

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ABSTRACT: In this paper, we propose a fast and a convenient modeling technique that combines the unique advantages of ANSYS and FLAC3D in numerical calculation and those of SURPAC in 3D modeling. First, the relationships between the data structures of the model files for SURPAC, ANSYS and FLAC3D were examined, and the transformation technique of integrated 3D solid model was given via Excel. Then, the proposed method was applied for analyzing the pillar stability for sublevel open stope method in 0# upper level of the target mine. From the simulation results, heights of the upper and lower chain pillars, width of interchamber pillar for the stope were all set to 8 m, and length and height of the stope were 60 m and 50 m, respectively. Finally, we have verified the validity and feasibility of the proposed model transformation technique and the accuracy of numerical simulation could be further improved.

Keywords: Integrated 3D solid model, Numerical simulation; SURPAC, FLAC3D, model transformation.

1 INTRODUCTION

Nowadays, the numerical simulation method in the stability analysis of mining engineering is an essential tool, and it is important to ensure the accuracy and reliability of the mining engineering design to construct the numerical model used as a more realistic representation of the in situ situation.

Numerical simulation programs widely used in stability analysis for geotechnical and mining engineering structures at home and abroad are FLAC3D and ANSYS, etc. In recent years, many researchers have carried out numerical simulations of the mining area with FLAC3D to quickly obtain more realistic structural elements of the stopes and make a lot of progress in the research to apply them to production practice (Han et al. 2021). Meanwhile, some researchers carried out the stability analysis of the stopes and the openings and determined the structural elements of them, by transforming the block model of mine design software SURPAC to the FLAC3D numerical model (Lin et al. 2013 and Li et al. 2013). Besides, Liu et al. (2015) and Meng et al. (2020) obtained accurate 3D models of the underground cavities and analyzed the stability of them using 3D laser scanning technique and FLAC3D. Bock (2015) combined ANSYS and SolidWorks to construct a complex lumen constant value simulation model and then analyzed the stability of the tunnel tunneling process by programming the conversion to FLAC3D.

In this paper, we propose a new method to convert the 3D solid model into numerical model for stability analysis of geotechnical and mining structures by combining ANSYS, FLAC3D and SURPAC.

2 THE PRINCIPLE AND METHOD OF MODEL TRANSFORMATION

2.1 Data structure of model files

2.1.1 Data structure of SURFAC model file

In the SURPAC model, the base file is the string model (STR) file. The STR file contains the coordinate information for one or several points and the representation information of each point, which includes three types of points, line segments, line sequences, and open lines, closed lines and elevation points. The STR file contains coordinate information for one or several point and the representation information of each point, with three types of points, segments, segment strings, and three shapes of open lines, closed lines, and elevation points.

The data structure of the STR file is listed in Table 1.

Table 1. Data format of STR file.

Content	Remarks
file name, modification date, use, formatting file	This information is recorded on the first line.
0, Y1, X1, Z1, Y2, X2, Z2	The two endpoint coordinates of the axis line.
A, Y, X, Z	The coordinates of the point on string number A.
0, 0.000, 0.000, 0.000	Display the segments.
0, 0.000, 0.000, 0.000, END	Display the end of STR file.

SURPAC automatically generates digital elevation model (DTM) files based on the STR files. The 3D solid model (3DM) file of SURPAC consists of the DTM files, representing a 3D solid profile, e.g., orebody, tunnel, cavity, or stope.

A triangular network (i.e trisolation) is constructed with adjacent triangular faces, which are overlapped in plane projection, and in 3D space, any two triangular faces must not overlap or intersect each other.

The DTM file necessarily has one STR file, the STR file describes the wire-frame, and the DTM file describes the construction of each triangle face, i.e., “number of triangle face”, “reference point” “adjacent face”, and so on; the two files necessarily exist together.

The data structure of the DTM file is shown in Table 2.

Table 2. Data format of DTM file.

Content	Remarks
OBJECT, B	Recording of object B.
TRISOLATION, C	Recording of trisolation C.
D, Nl, N2, N3, Dl, D2, D3	Recording of triangular face D, N1 to N3 the vertex number of triangular face D, and D1 to D3 the number of the adjacent triangular face.
END	Display the end of DTM file.

2.1.2 Numerical modeling and data extraction in ANSYS

For preprocess of the APDL (ANSYS Parametric Design Language) in ANSYS, there are three kinds of commands that are needed to create a solid model.

① Reference point definition command K

Syntax: K, NPT, X, Y, Z;

where NPT is the number of key point (the default value is automatically specified by the system.) X, Y, Z is the coordinate value of the reference point in the active coordinate system (Cartesian, cylindrical or spherical coordinates).

② Face creation command A

Syntax: A, P1, P2, …, P18;

where P1, P2, ..., P18 are the number of reference points defining the face, with a minimum of 3 reference points and a maximum of 18 reference points.

③ Solid creation command VA

Syntax: VA, A1, A2, …, A10;

where A1, A2, ..., A10 are the number of the interfaces defining the solid, with a minimum of 4 faces and a maximum of 10 faces.

ANSYS has powerful management operations for nodes and elements, so it can easily extract information from the numerical model.

① Perform merging and compression of node and element numbers.

② Save the node and element information of the numerical model as NLIST.lis and ELIST.lis files, respectively.

2.1.3 Data structure of FLAC3D grid file

The FLAC3D file units includes GRIDPOINT, ZONE, and GROUP, which are represented in *.flac3d file format using number and coordinate of GRIDPOINT, element number and element node of ZONE, model classification values and elements for GROUP (Lin et al. 2013).

2.2 Transformation step from integrated 3D solid model to numerical model

Step 1: According to the data formats of SURPAC and ANSYS model files described above, the SURPAC-ANSYS model transformation file is created by Excel.

Based on the model information of the STR and DTM files, Excel creates a command flow file that conforms to the APDL format and is imported into ANSYS to complete the model import immediately.

Step 2: The detailed steps of constructing the FLAC3D numerical model using the node data file NLIST.LIS and the element data file ELIST.LIS extracted from ANSYS are as follows.

□ After importing the node and element data files of ANSYS into Excel, respectively, delete the unwanted data rows and columns and insert the grid point and element definition instructions.

□ Combine the two files into one, then define a group of zones based on the number of zones belonging to the different solid models, and then save the file with the extension *.Flac3D.

□ Start the FLAC3D program and import the *.Flac3D file using the File/Import Grid menu.

By summarizing the above, the stability simulation of geotechnical and mining structures can be performed by transforming any integrated 3D solid model to FLAC3D numerical model.

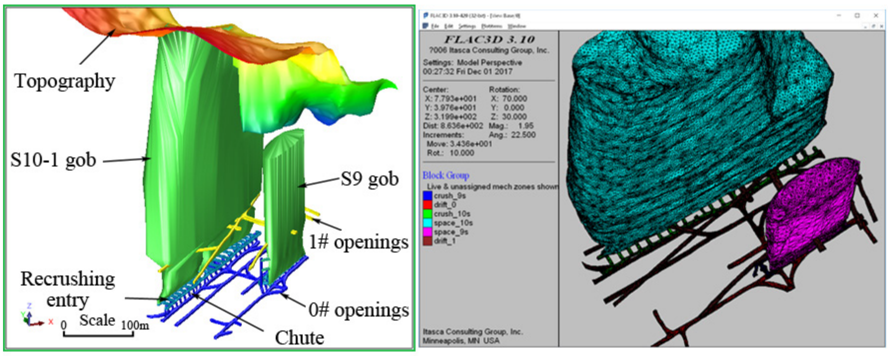
3 CASE STUDY

3.1 Engineering background

Shangnong Mine, located at the northeastern part in the Hamnam Province, is a large-scale metal mine that extracts the copper and gold ores by combined method of open pit and underground mining. This deposit can be traced over a strike length of 1.2 km with a thickness varying from 30 m to more than 100 m. The average dip of the orebody is 30° and belongs to the normal dip orebody.

Since the mining activities at surface area (above +350m) are carried out by open pit, it is of vital importance to maintain the pillar stability of the underground stopes. Also, the orebody was mined at the 0 m upper level using large-scale block method, and because of the lack of rational selection of the structural elements of the stopes, some stopes collapsed with waste ore and penetrated the surface or open pit, and there existed large mined-out spaces near the surface (see Figure 1(a)).

Currently, the main mining activity at the upper level is to mine the remnant orebodies that remain between these mined-out spaces. For this purpose, the mine is mainly applying the sublevel stopping method. Figure 1(a) shows a part of integrated 3D solid model consisting of the surface, level openings and mined-out spaces that were visualized using the SURPAC version 6.6.2.



```
FLAC3D 3.10
?006 Itasca Consulting Group, Inc.
Settings: Model Perspective
00:27:32 Fri Dec 01 2017
Center:            Rotation:
 X: 7.793e+001      X: 70.000
 Y: 3.976e+001      Y:  0.000
 Z: 3.199e+002      Z: 30.000
Dist: 8.636e+002   Mag.:    1.95
Increments:        Ang.: 22.500
  Move: 3.436e+001
  Rot.:  10.000
Block Group
 Live & unassigned mech zones shown
 crush_9s
 drift_0
 crush_10s
 space_10s
 space_9s
 drift_1
Itasca Consulting Group, Inc.
Minneapolis, MN USA
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a) b)

Figure 1. a) Integrated 3D solid model by SURPAC; b) Transformation result to FLAC3D model.

As shown in Figure 1(a), the width and length of the orebody block remaining between the present No. S10-1 gob and No. S9 gob is 35 m and 150 m, respectively, and the average height from the 0# level to the surface is 200 m. Currently, the height between 0# and 1# levels is 50 m, so the orebody block is divided into two mining panels; i.e. between 0# and 1#, and the 1# upper level, which is planned to place two or three stopes at one level. On the basis of the past mining experience, heights of the upper and lower chain pillar for the stope were set equal. Therefore, the extent of the numerical model was set to 200 m in length, 150 m in width and 200 m in height (from 150 m to 350 m above sea level).

3.2 Results and discussion of numerical simulation

3.2.1 Model transformation result

Figure 1(b) shows the results of converting the solid integration model into the FLAC3D grid model by the proposed method. The total number of elements of the numerical model is 1,232,837, the number of grid points is 219,951, and the model transformation time takes about 30 minutes on a notebook computer with Inter(R) Core(TM) i5-6200 CPU 2.30 GHz 2.40 GHz processor and 4 GB RAM.

As a result, it can be found that the model transformation time using this method was reduced by 1/50 when the block model was directly converted to the FLAC3D numerical model, and the accuracy of the numerical model was higher than 20%.

3.2.2 Design of simulation scheme for optimal stope structure

In this paper, the structural elements of sublevel stope to be optimized were selected, such as width of interchamber pillar (A), height of the upper and lower chain pillars (B), the stope height of the 1# upper level (C), and the stope length (D), considering the current status of the deposit development and the influence of the surrounding gobs.

Each factor was set at three levels, i.e. A=(6, 8, 10), B=(8, 10, 12), C=(40, 50, 60), and D=(50, 60, 70), and the simulation scheme for determining the structural elements of the stope were produced through $L_9(3^4)$ of orthogonal table.

3.2.3 Determination of mechanical properties and stress field of rock mass

In this paper, a three-dimensional elastoplastic analysis was carried out using the Mohr-Coulomb model. The physico-mechanical properties of the rock mass used in the numerical simulation are given in Table 3, based on the experimental mechanical properties of the ore and the host rock samples at the 0# upper level.

Table 3. Physico-mechanical properties of rock mass for numerical simulation.

Rock	Compressive strength σ_{cm}, MPa	Tensile strength σ_{tm}, MPa	Cohesion c_m, MPa	Internal friction angle φ_m, °	Elastic modulus E_m, MPa	Poisson's ratio v	Shear modulus G, MPa	Bulk modulus, K, MPa	Density ρ, kg/m^3
orebody	62.15	4.38	2.90	55.81	10 244.65	0.31	3 910.17	8 986.54	2 600
hanging wall	77.22	4.04	1.84	59.61	6 857.12	0.23	2 787.45	4 232.79	2 530
footwall	64.13	7.43	0.89	47.41	5 586.83	0.24	2 252.75	3 581.30	2 620

In the numerical model, the vertical (z-direction) stress was considered only gravity stress, and the x- and y-direction stresses were applied to both sides of the model considering the lateral stress coefficient of 1.2. The boundary conditions of the model include: both right and left boundaries are fixed in the x-direction; the front and back boundaries are fixed in the y-direction; while the bottom boundary is constrained on vertical displacement. The convergence criterion for the model solution was set to an average force ratio of $\varepsilon=1\times10^{-5}$, and the analysis step according to the initial stress state and the mining stage was set to 1,000 and 500 steps, respectively (Han et al. 2021).

3.2.4 Analysis of the simulation results for the plastic zone

The results of the numerical analysis according to the simulation schemes showed that the plastic zone area of the interchamber pillar is clearly more than that of the upper and lower chain pillars, mostly in the stopes on 0# level, and hardly formed in the stopes on 1# upper level.

The influence of the structural parameters for the stope on the plastic zone volume was evaluated by the range analysis method. That is, the greater the range value (R), the greater the influence of the factor on the stope stability is considered. Using the calculation results of the plastic zone volume, the range value is R_A = 3527.7, R_B = 1352.9, R_C = 2696.1 and R_D = 3308. Thus, the height of the upper and lower chain pillars has the greatest influence on the plastic zone volume size, followed by the stope length, the height of the 1# upper level, and the width of interchamber pillar. The comparison curves of the plastic zone volume after mining for each scheme are shown in Figure 2.

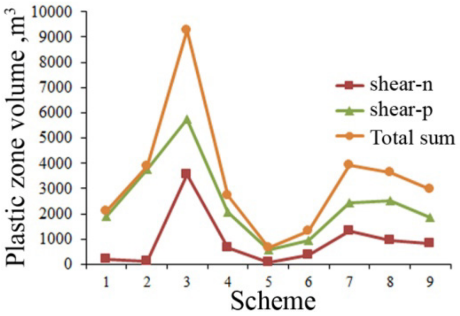

Figure 2. Comparison curves of the plastic zone volume after mining for each scheme.

In addition, it could be seen from Figure 2 that the reasonable layout scheme of the stopes in 0# upper level was Scheme 5. Conclusively, from the viewpoint of extraction rate and workload of primary mining, a reasonable stope element was set to A=B=8 m, C=50 m and D=60 m.

4 CONCLUSIONS

In this paper, the model transformation method was proposed by combining the unique advantages of ANSYS and FLAC3D in numerical calculation and those of SURPAC in 3D modeling.

With respect to a 3D solid model of the Sangnong Mine, applying the new method and conventional one by transforming the block model into the numerical model, the model transformation time can be reduced to 1/50 and the accuracy of the numerical model can be increased by more than 20%.

From the numerical simulation results of the plastic zone distribution, when the residual orebody remaining between the large mined-out spaces in the target mine is mined with sublevel stopping system, it can be seen that the height of the upper and lower chain pillars has the greatest influence on the stope stability and the width of interchamber pillar the least influence. Finally, the width of interchamber pillar, height of the upper and lower chain pillars were all set to be 8 m, the stope height of the 1# upper level to be 50 m, and the stope length to be 60 m.

The model transformation method proposed in this paper can rapidly and accurately transform the solid integration models created in any 3D mine design programs (3DMine and VULCAN, and so on) into the numerical model using EXCEL. It also provides a basis for a more realistic analysis of the underground mining process and slope stability using this method.

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REFERENCES

Bock S. 2015. New open-source ANSYS-SolidWorks-FLAC3D geometry conversion programs. *Journal of sustainable mining* 14, pp.124-132.

Han, U.C., Choe, C.S., Hong, K.U. & Han, H.I. 2021. Intelligent back analysis of geotechnical parameters for time-dependent rock mass surrounding mine openings using grey Verhulst model. *Journal of Central South University* 28(10), pp. 1−18. DOI: 10.1007/s11771-021-4822-7

Li, X., Li, D., Liu, Z., Zhao, G. & Wang, W. 2013. Determination of the minimum thickness of crown pillar for safe exploitation of a subsea gold mine based on numerical modeling. *International Journal of Rock Mechanics & Mining Sciences* 57, pp. 42–56. DOI: 10.1016/j.ijrmms.2012.08.005

Lin, H., Liu, T., Li, J. & Cao, P. 2013. A Simple Generation Technique of Complex Geotechnical Computational Model. *Mathematical Problems in Engineering* 2013, Article ID 863104, 8 pages. DOI: 10.1155/2013/863104

Liu, X., Li, X., Gong, F. & Liu, K. 2015. Safety Problem of Cavity Under Open Pit Bench. *Archives of Mining Sciences* 60 (2), pp. 565–580. DOI: 10.1515/amsc-2015-0037

Liu, X., Luo, Z., Yang, B., Lu, G., Cao, S. & Jiang, X. 2012. Visible calculation of mining index based on stope 3D surveying and block modeling. *International Journal of Mining Science and Technology* 22, pp. 139–144. DOI: 10.1016/j.ijmst.2015.07.011

Meng, Z., He, M., Tao, Z., Li, B., Zhao, G. & Xiao, M. 2020. Three-Dimensional Numerical Modeling and Roof Deformation Analysis of Yuanjue Cave Based on Point Cloud Data. *Advances in Civil Engineering* 2020, Article ID 8825015, 13 pages. DOI: 10.1155/2020/8825015