Block cutting and searching method of fractured rock mass based on topological matrix

Xingchao Lin¹*, Rongfu Guo², XinZan An³, Yanpeng Sun¹, JinHang Li¹

¹ China Institute of Water Resources and Hydropower Research (IWHR), A-1 Fuxing Road, Haidian District, 100038 Beijing; ² Xinjiang Xinhua Yeerqiang River Basin Water Conservancy and Hydropower Development Co. Ltd. Xinjiang China; ³ Fujian College of Water Conservancy and Electric Power, Fujian China.

*Corresponding author: Email: linxc@iwhr.com; ORCID: 0000-0003-3148-8793

Abstract: Aiming at the problem of block cutting and searching in fractured rock mass, a method of block cutting and searching in fractured rock mass based on topological matrix is proposed. According to the structural characteristics of fractured rock mass, the data structure of the model is established, which only contains node coordinates (vectors) and a numbering system; the line segments are divided into line segment units, which only intersect at the boundary by the algorithm of line segment intersection and discretization. The number matrix describing the topological relationship of points and lines system is constructed with the intersection and line segment as the core. According to the number matrix and geometric characteristics of spatial line segments, the number matrix for block search is obtained by cutting a non-closed polygon; without any geometric operation, only the index of the number in the matrix is used to search the blocks and form a seamless rock mass model; according to the spatial relationship between the clipped line segment and the block, the block reflecting the internal fracture is generated to form the final fractured rock mass model. Results indicate that this method can identify the distribution of complex blocks and their internal joints and fissures. It also has a great application prospect in the analysis of fractured rock mass.

1. Introduction
Rock mass is the product of a long-term geological structural movement, which contains a large number of discontinuous joints. These joints intersect one another to form a specific rock structure, which determines the engineering mechanical characteristics of rock mass. In rock engineering, such as slope and underground cavern, when a block determines its stability, deformation, and seepage, the establishment of a joint rock mass model is the premise and foundation for relevant research[1].

In recent years, many scholars have conducted research on block cutting and search methods. G. H. Shi proposed a 2D block cutting and search algorithm, which is a pre-processing method for 2D DDA and key blocks. The method establishes a clear line segment model by finding intersection points and cutting branches of line segments; it also describes the topological relationship among segments with number matrix. Only through the search number matrix can the search of 2D block be realized [2,3]. D. Heiot established a block generation algorithm for jointed rock mass, considering the random distribution of joints [4], which cannot deal with complex concave bodies. D. Lin et al. proposed a geometric recognition method of the rock block system on the basis of topology technology [5]. Jing et al. further extended this method to 2D and 3D block search [6,7]. The block search method based on topology technology is similar to that proposed by Shi. Barki et al. studied the Boolean operation method of complex spatial polygons [8,9]. Elmouttie et al. explored the grid division method of fracture rock mass...
calculation [10,11]. Zhang et al. applied block cutting technology with the practice of underground cavern, slope, and other projects [12-14]. To ensure that no ambiguity exists in the block search process, block cutting and search method based on topological relation matrix must cut the segments or polygons that cannot be used as block interface. Doing so is suitable when considering the influence of interaction among blocks and the path of connection on permeability characteristics. In addition, complex geometry (e.g., concave body) can be considered. At the same time, the accuracy and efficiency of block search are greatly improved. However, considering the gradual failure of joint rock mass, the process of fracture expansion, and the influence of non-penetrating joints on stress deformation is obviously unacceptable. In this study, based on Shi et al., a block cutting and searching method based on topological relation matrix is developed. This method retains the cut joints and forms a rock mass model, including non-through joints, which lay a foundation for the simulation of discontinuous media and joint failure process.

2. Flow of the algorithm

To realize the fast generation of 2D block system, a 2D block cutting and searching method based on topological matrix is proposed. The core of this method is to find the intersection point, discretize the line segments, and establish the relationship matrix (including only the numbers of points and lines) representing the geometric topological relationship between all points and lines. The 2D block search can be realized without repetition and omission only according to the numbered index in the relation matrix, and the 2D block model and numbering system can be generated quickly. The specific process is shown in Fig. 1.

3. Main process of the algorithm

3.1 Matrix expression of geometric boundary information

The geometric boundary information is a group of line segments and several points. Each line segment is composed of two points. The matrix expression of this stage describes the spatial topological relationship between the line segment and the endpoint. To describe a general block model, the example in Table 1 has 10 lines and 16 points. The original geometric information matrix and point and line numbering system are shown in Table 1.
### Table 1 Matrix expression of geometric boundary information

| Line number | Point number | Sketch Map |
|-------------|--------------|------------|
| 1           | 1,2          |            |
| 2           | 2,3          |            |
| 3           | 3,4          |            |
| 4           | 4,1          |            |
| 5           | 5,6          |            |
| 6           | 7,8          |            |
| 7           | 9,10         |            |
| 8           | 11,12        |            |
| 9           | 13,14        |            |
| 10          | 15,16        |            |

### 3.2 Matrix expression of the intersection of geometric boundary line segments

The intersection of all geometric boundary line segments is calculated, and the intersection points are sorted and recorded in the matrix according to the position of the line segments. The matrix expression changes of geometric information after intersection are shown in Table 2. The matrix is a matrix expression based on line, through which the geometric information matrix expression based on point can be obtained directly, as presented in Table 3.

### Table 2 Expression of geometric information matrix after intersection

| Line number | Point number | Sketch Map |
|-------------|--------------|------------|
| 1           | 1,17,18,2    |            |
| 2           | 2,19,3       |            |
| 3           | 3,21,20,4    |            |
| 4           | 4,5,1        |            |
| 5           | 5,22,17,6    |            |
| 6           | 7,20,8       |            |
| 7           | 9,23,24,18,10|            |
| 8           | 11,21,25,12  |            |
| 9           | 13,23,25,14  |            |
| 10          | 15,24,19,16  |            |

(a) Point number (b) line number (c) Nodes are sorted by position in the line segment
### Table 3 Expression of geometric information matrix based on point

| Point number | Point number | Sketch Map |
|--------------|--------------|------------|
| 1            | 17,22        |            |
| 2            | 18,19        |            |
| 3            | 19,21        |            |
| 4            | 20,22        |            |
| 5            | 22           |            |
| 6            | 17           |            |
| 7            | 20           |            |
| 8            | 20           |            |
| 9            | 23           |            |
| 10           | 18           |            |
| 11           | 21           |            |
| 12           | 25           |            |
| 13           | 23           |            |
| 14           | 25           |            |
| 15           | 24           |            |
| 16           | 19           |            |
| 17           | 1,6,22,18    |            |
| 18           | 17,10,2,24   |            |
| 19           | 2,3,24,16    |            |
| 20           | 21,4,7,8     |            |
| 21           | 3,20,11,25   |            |
| 22           | 4,1,5,17     |            |
| 23           | 9,24,13,25   |            |
| 24           | 23,18,15,19  |            |
| 25           | 23,14,21,12  |            |

#### 3.3 Matrix expression after tree cutting

If only one $i$-line exists in the matrix, then it means that the line segment passing through the point cannot form a block boundary. Thus, deleting the line segment (and deleting two directed line segments at the same time) is necessary. After the unidirectional directed line segment is deleted, there may be only one new number, which must also be deleted. The above work aims to cut the branch, and the matrix information after cutting the branch is shown in. After the branches are pruned, the information in the matrix is sorted anticlockwise according to the angle, and the data obtained are the matrix expression used to search the block.
Table 4 Matrix expression after tree cutting

| Point number | Point number | Sketch Map          |
|--------------|--------------|---------------------|
|              |              | (a) Point numbering system |
| 1            | 5,10         |                     |
| 2            | 6,7          |                     |
| 3            | 7,9          |                     |
| 4            | 8,10         |                     |
| 5            | 1,6, 10      |                     |
| 6            | 5,2,12       |                     |
| 7            | 2,3,12       |                     |
| 8            | 9,4          |                     |
| 9            | 3, 8,13      |                     |
| 10           | 4,1, 5       |                     |
| 11           | 12, 13       |                     |
| 12           | 11,6, 7      |                     |
| 13           | 11,9         |                     |

3.4 Block search
The block search process based on topological matrix is as follows:
Step 1: Traverse the position data of the directed line segment in Matrix Q1. Find the first finite line segment whose position data are not zero, that is, the starting line segment of block search: \( I \rightarrow J \), where \( I \) is the line number, and \( J \) is the number value of the midpoint of the matrix. Multiply the position data of this finite line segment by \(-1\) to indicate that the finite line segment has been used. When the position data of all dotted line segments are negative, the whole search process ends; otherwise, Step 2 is performed.
Step 2: Take point \( J \) as the origin, rotate segment \( j \rightarrow I \) clockwise, and the first directed segment is the next segment of the block. When the position data of the directed line segment are less than zero, the search process of the loop is completed, and Step 1 is executed. Otherwise, Step 3 is conducted.
Step 3: Find the point numbered \( I \) in line \( j \), and the number stored in the next position of the number is \( k \); thus, \( I = J, j = k \). \( I \rightarrow J \) is the next directed line segment found. Multiply the position data of the directed line segment by \(-1\) and execute Step 2. The search process of Example 1 is illustrated in Fig. 2.
Note: The search process listed in the figure is the loop search process based on the matrix expression realized by the program. The small gray arrow indicates the directed line segment used in the previous search loop, whereas the blue arrow refers to the directed line segment used in the current loop search.
After all the loops have been found, a solid block is identified further as follows:
(i) A loop with nodes ordered in the anticlockwise direction means a solid region, remembered as a solid loop (e.g., Loops 1, 3, 4, and 5 in Fig. 2).
(ii) A loop with nodes ordered in the clockwise direction means a hole, remembered as a hole loop.
(iii) If a hole loop is the outer part of all solid loops, then it will be the outer boundary of the solid regions (e.g., Loop 2 in Fig. 2).
(iv) If a hole loop is the inner part of a solid loop, then it will form a holed 2D block together. No holed block is illustrated in Fig. 2. Two examples, which contain holed blocks, are displayed in Fig. 3.
3.5 Line segment ownership query
The attribution of the trimmed branches can be judged by the relative relationship between the middle point and the block to form the final block. This block contains internal joints, which are important for the calculation of tip stress that must consider joint failure. The point polygon relationship fragment is displayed in Fig. 4. The final block is shown in Fig. 5.

Fig. 3 Loop searching for blocks containing holes

Fig. 4 Point polygon relation judgment

Fig. 5 The final block
4. Example verification of stress intensity factor at joint rock mass

For discontinuous medium analysis methods (e.g., DDA), the interaction among through interfaces is mainly considered, and the original block cutting and search program is fully applicable [2-3]. For the numerical manifold method (NMM), which must consider the crack propagation process of joint fissures, if the non-penetrated fissures are not considered, then the geometric length of joint fissures will be changed, resulting in inaccurate calculation results. For the NMM calculation model illustrated in Fig. 6(a), Model I does not consider non-through joints, and Model II is the result obtained by the proposed method, considering non-through joints. The stress intensity factor results calculated according to these two models and the configuration method are displayed in Fig. 6(b). The calculation results show that the stress intensity factor changes by more than 30% due to the change of joint length in the block search process. Therefore, using this method is necessary to ensure the accuracy of joint length in the analysis of discontinuous media, considering the expansion process of joint and fissure.

5. Conclusion

A method of cutting and searching fractured rock mass blocks on the basis of topological matrix is proposed and implemented. The method can quickly search fractured rock mass blocks without repetition and omission through line segment intersection, tree cutting, block search, and line segment attribution judgment. It can also retain the joint information of non-formed blocks and provide support for considering the stress state and failure process simulation of fractured rock mass.

6. Acknowledgment

This research was supported by the National Key R&D Program of China (No. 2018YFC0407000), the National Natural Science Foundation of China (No. 51809289), and the IWHR Research & Development Support Program (Nos. GE0145B462017 and GE0145B692017), including the Research Project of China Three Gorges Corporation (Contract No. JG/190551).

7. References

[1] Hudson, J.A. and S.D. Priest, Discontinuities and rock mass geometry. International Journal of Rock Mechanics & Mining Sciences & Geomechanics Abstracts, 1979. 16(6): p. 339-362.
[2] Shi, G., PRODUCING JOINT POLYGONS, CUTTING JOINT BLOCKS AND FINDING KEY BLOCKS FOR GENERAL FREE SURFACES. Chinese Journal of Rock Mechanics & Engineering, 2006. 25(11): p. 2161-2170.

[3] Shi, G.H. and R.E. Goodman, Two dimensional discontinuous deformation analysis. International Journal for Numerical & Analytical Methods in Geomechanics, 1986. 9(6): p. 541-556.

[4] Heliot, D., Generating a blocky rock mass. International Journal of Rock Mechanics & Mining Sciences & Geomechanics Abstracts, 1988. 25(3): p. 127-138.

[5] Lin, D., C. Fairhurst, and A.M. Starfield, Geometrical identification of three-dimensional rock block systems using topological techniques. International Journal of Rock Mechanics & Mining Sciences & Geomechanics Abstracts, 1987. 24(6): p. 331-338.

[6] Stephansson, L.J., Topological identification of block assemblages for jointed rock masses. International Journal of Rock Mechanics & Mining Sciences & Geomechanics Abstracts, 1994.

[7] Jing, L., Block system construction for three-dimensional discrete element models of fractured rocks. International Journal of Rock Mechanics & Mining Sciences, 2000. 37(4): p. 645-659.

[8] Barki, H., G. Guennebaud, and S. Foufou, Exact, robust, and efficient regularized Booleans on general 3D meshes. Computers & Mathematics with Applications, 2015. 70(6): p. 1235-1254.

[9] Landier, S., Boolean operations on arbitrary polygonal and polyhedral meshes. Computer-Aided Design, 2017.

[10] Elmouttie, M., G. Poropat, and G. Kr?Henbühl, Polyhedral modelling of rock mass structure. International Journal of Rock Mechanics & Mining Sciences, 2010. 47(4): p. 544-552.

[11] Zheng, Y., L. Xia, and Q. Yu, Identifying rock blocks based on exact arithmetic. International Journal of Rock Mechanics & Mining Sciences, 2016. 86: p. 80-90.

[12] Zhang, Y., M. Xiao, and J. Chen, A new methodology for block identification and its application in a large scale underground cavern complex. Tunnelling & Underground Space Technology Incorporating Trenchless Technology Research, 2010. 25(2): p. 168-180.

[13] Zhang, Q.H., Advances in three-dimensional block cutting analysis and its applications. Computers & Geotechnics, 2015. 63(jan.): p. 26–32.

[14] Zhang, Q.H., et al., Algorithm for three-dimensional curved block cutting analysis in solid modeling. Computer Methods in Applied Mechanics & Engineering, 2019. 360: p. 112721.

[15] China Academy of Aeronautics. Stress intensity factor manual. Beijing, Science Press, 1981