Geologic Model Transforming Method (GMTM) for numerical analysis modeling in geotechnical engineering

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ABSTRACT: During numerical simulation of geotechnical engineering, due to the complex engineering geological condition, the simplified geologic model is usually adopted. However, the accuracy and reliability of calculating result are directly influenced by characteristic of model. The 3D geologic model can better reflect the actual geological condition. The paper presents a new and practical modeling method (Geologic Model Transforming Method) of numerical analysis by integrating geologic model and numerical model. This method is performed with the following procedures: (1) cutting the 3D geologic model according to numerical calculation region; (2) extracting control data from cutting model to reconstruct the surface model; (3) meshing and forming the numerical model automatically by the stratum attribute; (4) importing the model into numerical analysis system. An example is given to illustrate the application of the method. The implementation of the method results in high efficiency and automaticity of modeling.

1 INTRODUCTION

With the development of the computer technology, finite element method (FEM) is widely used in geotechnical engineering and other research domains. During the solution of FEM, preprocessing, solving and the post-processing are included. The preprocessor, which involves collecting data, inputting information, meshing and defining material property, etc., is the fussiest process and spends 40~50 percent of the total time in the analysis course of FEM. That is, about half effort of FEM analysis is expended on the preprocessor (Liu et al. 2002). Therefore, preprocessing system is one of the core parts of the finite element analysis and a good preprocessor plays an important role in the success of the method.

For a practical problem of geotechnical engineering, numerous data is demanded during the modeling process because of complex geological environment, structure, construction procedure and so on. If the fussy data is inputted by manual handling, it is inefficient, and is difficult to check and modify data. Thus, the simplified geologic model is generally adopted. However, a poor model may give unreliable results that are usually misleading and may lead to incorrect conclusions. Therefore, it is necessary to develop the research on a simplified good FEM preprocessor, and the problem has received a lot of interests (Yu et al. 1999, Zhou et al. 2002, Liang et al. 2004).

The information visualization of engineering geology is an important research subject in geosciences. At present, the geology simulation has the powerful function of 3D geological modeling. 3D strata model can be established by borehole data, and part spatial analysis can also be operated, such as sectioning and cutting, etc. There are the certain similarities in modeling and spatial analysis between geologic model and numerical model. If geologic model can be transformed into numerical analysis model, its data can also be directly introduced. Thus, the preprocessor of FEM is largely simplified (Hou et al. 2002, Xia et al. 2005).

In full consideration of the characteristics of the geologic model and the numerical model, this paper presents a new modeling method of numerical analysis called the Geologic Model Transforming Method (GMTM). This method is suitable for FEM preprocessor in geotechnical engineering and simpler and more efficient than the traditional operations approach. The GMTM can be used to form finite element mesh directly from 3D geologic model. The proposed technology will give some useful references to the continuous research on this subject.
The remainder of this paper is organized as follows: in the next section the 3D geologic model is described. Section 3 introduces the implementation and the algorithm of the new method. Section 4 gives an example to illustrate the results of this method.

2 3D GEOLOGIC MODEL

2.1 Choosing data model

At present, there are more than twenty data models presented for 3D geosciences modeling. According to the form of data structure, these geologic models presented or discussed could be classified into three types as facial models, volumetric models and mixed models. The facial model emphasizes on the surface representation for terrain, strata interface, outlines of the constructions, buildings and underground engineering. The triangulated irregular network (TIN) is widely applied for the surface modeling (Baker 1989, Huang et al. 2002). The volumetric model is based on the spatial partition and the real 3D object construction. The three dimension space can be filled with regular or irregular 3D volumes, and the representative volume is irregular tetrahedron network (TEN) (Chen et al. 1994, Pilouk et al. 1994). The mixed model is the combination of facial model and volumetric model.

The small storage space of data and its fast visualization are the characteristic of the facial model, and the information of strata interface and fault could be represented in the interior of geologic surface model. The volumetric model is convenient for the description of the attributes of each volume and the storage of its related spatial location. However, due to the enormous data amount of the solid model, the efficiency of Boolean operation to strata is lower. Although the mixed model takes the advantage of facial model for fast visualization and volumetric model for spatial analysis in theory, the modeling technology is quite complicated. By contrast, the paper chooses the 3D geologic surface model as basic model.

2.2 3D strata surface modeling

The paper is concerned with the 3D geologic surface model based on TIN representation (Zhang et al. 2006). To the geological modeling, the practical implementation just requires:

1. Transaction of borehole data. The information of drill hole is extracted from database. Then every borehole is numbered with the dichotomic topologic data structure, and is blocked with the blocking rules of data. Thus, the stratum integrity can be opened out.
2. Construction of the hollow surface model. The reference TIN is constructed with the surface data of the borehole. In term of the topological relations of the formed TIN, each stratum interface is obtained by mapping the altitude and attribute of under layer borehole. For the phantom, the modeling can be established by the sliced interface rules and the interpolation of the space attribute. So the whole hollow surface model is finished.

3. Construction of the surrounding surface model. With the nearest neighbor first algorithm and Delaunay method to the scattered points in external outline of every interface, the strata surrounding surface model is constructed. Finally, the 3D strata surface model is composed of the hollow interface model and the surrounding model.

3 TRANSFORM GEOLOGIC MODEL INTO NUMERICAL ANALYSIS MODEL

The finite element mesh needs to coincide with the consistency principle and the geometrical property principle. In consideration of the difference in data structure, the geologic model can not be directly taken as the numerical model (Wang et al. 2004). To satisfy the regulation of the finite element mesh, the new modeling method presented in this paper emphasis on the process of transforming geologic model into numerical model.

3.1 Flow process

The realized procedures from geologic model to numerical model are listed in the following:

1. Calculation region cutting (section 3.2). Based on the 3D strata surface model established, the region cutting is performed along the partial research region in conformity to the request of numerical analysis.
2. Reconstruction of surface model (section 3.3). By virtue of the intersection points and the strata control points extracted from the cutting model, the strata surface model of the calculate region is reconstructed. Thus, the initial surface mesh is generated.
3. FEM surface meshing (section 3.4.1). Evaluate whether the quality of the initial surface mesh is satisfied with the request of the finite element mesh or not. If the judgment is true, the initial mesh can be acted as the calculation mesh. Otherwise, the surface mesh needs to be regenerated automatically by a new approach.
4. FEM solid meshing (section 3.4.2). Based on the generated surface mesh which satisfied with the FEM request, the relevant solid mesh is generated automatically by an efficient approach.
5. Importing into numerical analysis system (section 3.5). The topological data of the FEM mesh model is imported into the numerical analysis system in accordance with the requested data format. In the end, the modeling work is finished gradually.
In the Geologic Model Transforming Method, the key technologies include the cutting, the reconstruction and the meshing. Figure 1 shows a flowchart of the transforming process. The following sections describe the key steps in detail.

### 3.2 Calculation region cutting

According to the engineering geological condition and the survey data, the 3D strata surface model is established with the geological modeling technology. It has the advantages of better accuracy for strata attribute and larger overlying region. To a practical calculation model, the partial research region just is the region of numerical model. The conditions which determine the calculation region usually include removing the boundary effect and satisfying the calculation accuracy. So it is unnecessary to take the overlying region of the geologic model as the research region of the calculation model. To reduce the computing time and scale of the numerical analysis, the region cutting is performed in the method. By the means that choose the calculation region of the numerical analysis, the reasonable cutting boundary could also be determined, as shown in Figure 2.

To benefit the calculation, the cutting region generally is a rectangular solid. Of course, it can also be composed with many planes or polygons. The algorithm of the region cutting is a procedure that the intersection lines and the intersection points are obtained with the intersection calculation of the space planes each other. By the region cutting, the partial research region can be arbitrarily acquired on the 3D geologic model. Thus, it is unnecessary to build the calculation model again and again. At the same time, the construction process in geotechnical engineering can be simulated, such as the excavation of the foundation and the tunnel.

### 3.3 Reconstruction of surface model

The topological relations are changed when the region cutting is performed on the original strata surface model. In order to keep the same topological structure, the surface cutting model is reconstructed by the intersection lines, the intersection points and the original strata control points. The reconstruction algorithm includes two sections: the reconstruction of strata interface and the reconstruction of strata surrounding surface.

**Reconstruction of strata interface:**

1. The intersection lines, the intersection points and the original strata control points in the cutting region are classified and restored by the strata attribute.
2. To each stratum, the intersection lines are taken as the constraint boundary, and then the constraint Delaunay triangularization is applied to the scattered points in the plane region.
3. The topological structure of the formed mesh is kept invariability. The altitude of each point is mapped. Thus, the stratum interface model is obtained again.
4. Repeat step (2) and (3). Each stratum interface mesh could be reconstructed. Finally, the whole interface modeling is finished.

The illustration of the reconstruction to the strata interface is shown in Figure 3.

**Reconstruction of strata surrounding surface:**

5. The surrounding outline loop of the cutting model is constructed by the intersection points in the interface and is oriented counterclockwise.
6. To each cutting plane, the intersection lines of the plane are taken as the interior constraint lines, and
then the constraint Delaunay train-gularization is applied to the intersection points of the cutting plane.
7. The attribute of the formed mesh in the cutting planes is determined with the attribute of the intersection points.
8. Repeat step (6) and (7). The surface mesh of the closed surrounding cutting planes could be generated. Finally, the whole surrounding surface modeling is finished.

The illustration of the reconstruction to the strata surrounding surface is shown in Figure 4.

The surface model of the cutting region is the combination of the strata interface model and the surrounding surface model. The cutting model has the same geometric relation and the topological data structure. Its mesh is also taken as the initial surface mesh with the strata attribute.

3.4 Finite element meshing

At present, the algorithms of the finite element mesh generation need to be judged by the man-machine interaction way during the process of numerical modeling, such as the preconditions whether the meshing region is closed or not and whether the total redundant edge length is zero or not, etc. Thus, the automatic meshing is often not able to be performed normally. The reason of the problem does not lie in the algorithms but in the preconditions. These factors cause the modeling difficulty to be enlarged and the automaticity to be reduced. Therefore, it is necessary to research how to improve the whole modeling efficiency entirely.

3.4.1 Surface meshing

Any single irregular triangle is closed. Such the triangle region is called the Single TIN Region (STR) in the paper. The set of many STR which do not pass through each other is called the Multiple TIN Region (MTR). The surface model based on TIN representation is taken as the MTR model. So the initial surface mesh of the cutting model also is the MTR model.

By performing circularly the algorithm of the surface meshing in 3D space plane to each STR, the finite element surface mesh of MTR model could be generated automatically, as shown in Figure 5. In order to coincide with topological consistency of the nodes in shared edge, the region boundaries are discretized with fixed length partition or integer division way. The method of the surface meshing is called the MTR method.

Based on the MTR method, some man-machine interaction operations can be avoided, such as seeking manually the closed region and discretizing the boundaries one by one. The MTR method is realized easily by programming, and has the advantages of better element quality and high efficiency and automaticity.

3.4.2 Solid meshing

A single closed 3D space composed of the FEM surface mesh is called the Single Space Region (SSR). The set of many SSR which do not pass through each other is called the Multiple Space Region (MSR). The algorithm of the solid meshing needs to be performed in SSR. Generally, there are many different space regions in a calculation model. Thus, almost each SSR need to be formed with man-machine interaction. It is very inconvenient to the numerical modeling.
So, under the direction of the block thought that the surface mesh having the same stratum attribute can constitute the closed space region, a method is presented to build automatically the SSR of the different stratum. By performing circularly the algorithm of solid meshing to each SSR, the finite element solid mesh could be generated automatically, as shown in Figure 6. In consideration of the dual attributes of the interface mesh, it needs to be used two times in forming strata space region. The method is called the MSR method.

The thought of the blocking by strata attribute is applied in the MSR method. The construction for the SSR and the geometry inspection can be avoided before the solid meshing. The efficiency of the whole modeling is improved thoroughly. It is an innovation to traditional modeling method.

3.5 Importing into numerical analysis system

The topological data of the taken FEM surface mesh is imported into the numerical analysis system in accordance with the requested data format. The numerical analysis model is formed gradually and the whole modeling is finished. The finite element model generated with the GMTM is not depended on the numerical analysis system. Only changing into the demanded data format, it can be used in the different systems of the universal FEM software, such as ANSYS and Marc.

4 EXAMPLE

To illustrate the application of the GMTM, an example is presented in this section. The detailed modeling procedures are the following.

1. The information of boreholes is extracted from database. The number of boreholes and strata are 16 and 3, respectively. The total number of the strata control points is 64. The geologic surface model is constructed by the algorithm of the geologic modeling (see Fig.7). The total number of the TIN is 144, and the different stratum attribute is indicated with different colors.

2. The calculation region is determined by importing the information of the cutting surface. The paper assumes the cutting surface is composed of four vertical planes. The plane graph of the cutting region is shown in Figure 8, and the new topological relations are shown in Figure 9.

3. The cutting surface model is reconstructed according to the strata control points in cutting region. The strata interface model and the initial surface mesh are shown in Figure 10.

4. Based on the initial surface mesh, the surface meshing and the solid meshing are automatically performed by the MTR method and the MSR method respectively. The strata interface FEM mesh and the solid mesh are shown in Figure 11.
Figure 10. Surface model: (a) strata interface model; (b) initial surface mesh.

Figure 11. FEM mesh: (a) strata interface mesh; (b) solid mesh.

Figure 12. Mesh of the excavation model: (a) whole mesh; (b) part mesh.

5. The excavation process also can be simulated by the region cutting. In this example, the cutting region is taken as the foundation pit. The whole and part FEM mesh are shown in Figure 12. In the surface model, the total number of the point and the triangle element generated are 1140 and 3646 respectively. In the solid model, the total number of the point and the tetrahedron element generated are 1821 and 8838, respectively. The total time spent in the whole modeling process is about 10 minutes.

6. The topological data of the formed mesh is imported into the FEM software Marc. In order to check the element mesh quality, a simple numerical calculation is implemented. Figure 13 shows the self-weight stresses of the model before excavation and after excavation in the action of gravity.

5 CONCLUSIONS

In order to simplify the preprocessor of the numerical analysis, the paper presents a new modeling method based on the geologic model. It differs from the traditional modeling method. In our method, the numerical model is generated by the following procedures: cutting the calculation region, reconstructing the surface model, finite element automatic meshing, importing the analysis system. The characteristic of the method is generalized as:

1. The element mesh is marked by the stratum attribute, so the model further nears to the real geological condition. The partial region can be randomly extracted from the 3D strata model, and must not be established repeatedly.

2. Taking the advantage of the characteristic of the geologic model, the complex meshing algorithm is avoided. The programming of the meshing is simple and efficient. The whole modeling is highly automatic and rapid.

3. The excavation of the foundation and the tunnel can be conveniently simulated. The boundary of the excavation must not be set in advance.

4. The finite element mesh can be imported into the different analysis system to calculate. The model is applicable and flexible.

5. In a word, the GMTM realizes the dream to establish numerical model directly based on 3D geologic model. It provides a nice possibility and prospect for FEM numerical simulation. The transforming method based on other geologic model is consistent with the method presented in the paper, but the material algorithm needs to be studied further.
REFERENCES


