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3D Reconstruction and Virtual Cutting Research on Coarse Aggregate Morphology and the MicroFabric with Computed Tomography and the Visualization Toolkit

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Abstract: Three-dimensional visualization is a new research field in information processing and VTK is a visualization toolkit with strong functions. Due to the fact that most two-dimensional microfabric models of coarse-aggregate materials are not accurate, three-dimensional model is needed. This study laid its focus on the theoretical model of three-dimensional visualization and the visualization technology based on VTK to study the coarse-aggregate morphology and the microfabric. The experimental reconstruction results show that the particle morphology and inter-particle pore space are clear and can describe the morphological features of coarse-aggregate particle accurately with the assistance of suitable virtual cutting method.

Keywords: Coarse-aggregate, microfabric, morphology, surface reconstruction, three-dimensional reconstruction, virtual cutting, volume reconstruction, VTK

INTRODUCTION

Because the coarse-aggregate morphology and the microfabric is a main factor which greatly affects the engineering properties of materials made of coarse-aggregate, such as subbase and rock-fill, it is important to study the morphology and the microfabric (Tang *et al*., 2000; Qing *et al*., 2001; Andrew *et al*., 2003; Liangping, 2007). The computer processing of microfabric images is one of the key technologies used in the quantitative research of microfabric. At present, the research is mainly using two-Dimensional (2D) images of coarse-aggregate to extract the useful information, for example, DIPIX 2D image processing system is the software treating soil microstructure, including form size, void ratio, oriention and microstructure units etc. Bin *et al*. (1996). Research on consolidation traits and characteristic coefficients of 2D microstructure pictures to laterite of kunming (Kesheng, 2005). PFC~ (2D) model is proposed to build PFC2D numerical model for mesostructure of inhomogeneous geomaterial by digital image processing (Wenjie *et al*., 2007). But based on all the above methods, its three-Dimensional (3D) character cannot be completely reflected. In order to analyze the microfabric information in terms of pore structure and particle size, it is necessary to start from the original data of CT (Computer Tomography) series images and establish the 3D structure model of coarse-aggregate microfabric (Zesheng, 1999; Feichtinger *et al*., 2006; Yuan *et al*., 2008). There are two main ways to realize three-dimension visualization at present:

- Develop 3D graphics engine, which is encapsulated with hardware operations and graphics algorithms, for example, OpenGL, OpenCV, Direct X and so on Francis and Stephen (2003), Gary *et al*. (2008) and Julio and Maria (2001). The disadvantage of this kind of development is heavy workload. Besides, for some basic three-dimensional graphics algorithms, it needs to be self-developed.
- On the basis of a development kit of three-dimensional visualization, which is the most widely used in three-dimension visualization technology now. The advantage of this method is that we need not concern about basic three-Dimensional graphics algorithms and can focus more attention on the algorithm implementation for the relevant industry.

This study mainly studies the theoretical model of three-dimensional visualization and the visualization technology based on the VTK software for the coarse-aggregate morphology and the microfabric, not only realizes the whole three-dimensional reconstruction of coarse-aggregate microfabric, but also the three-dimensional particle reconstruction are realized more intuitively. The results showed that the VTK can be well applied to the analysis and measurement of coarse-aggregate morphology and the microfabric. It's also with

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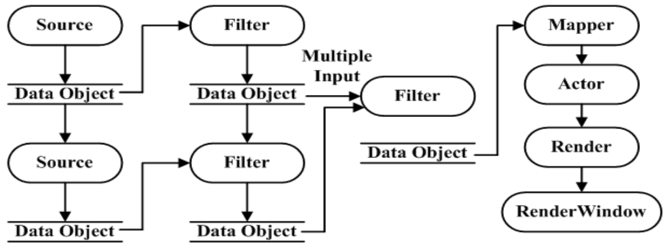


Fig. 1: VTK visualization process

much significance and would be more promising for further researches on strain softening and failure mechanism of coarse-aggregate materials.

METHODOLOGY

VTK summary: VTK is an object-oriented visual class library and three-dimensional visualization technology based on VTK has become a hotspot of research nowadays. (Kitware Inc, 2002; Schroeder *et al*., 2004; Bi *et al*., 2008). The basic process of VTK is showed as a flow diagram Fig. 1 and explained below:

Data object: Support many data types: like poly data, structure grid and structure point.
Source: Appoint the behavior and interface of source target.
Filter: Receive output data of source.
Mapper: Receive input data of filter and map it into basic unit.
Actor: Receive data attribute of mapper acted as a window entity.
Render: Final result demonstration.
Render window: Demonstrative window 3D Reconstruction of Coarse Aggregate Morphology Based on VTK

Brief introduction to reconstruction algorithm:
Surface reconstruction: Surface reconstruction is to extract interested parts in the form of Iso-surface and to generate high quality 3D image by rotation and commutativity illumination effect. This kind of method has a rapid rendering speed and can satisfy high real time requirement, but it's difficult to realize the reduction of dynamic data and can only deal with interested parts and the shape feature is not obvious (Levoy, 1988; Sabe, 1988).

Volume reconstruction: Volume reconstruction is a process which directly transforms 3D space samples into 2D image on screen and restores original 3D data file as much as possible (Kajiya and Von Herzen, 1984; Levoy, 1990). Volume reconstruction can explore internal structure of objects, with realistic reconstruction results and flexible application.

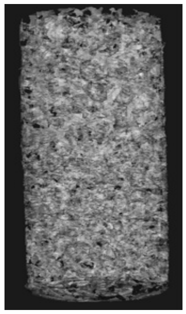
Reconstruction process and implementation: According to the above theories, this study designs and implements surface reconstruction and volume reconstruction of coarse-aggregate morphology and the micro fabric based on VTK. (Marcel *et al*., 2003; Kangping *et al*., 2008)

The data source: the CT coarse-aggregate images (the original material is subbase) are provided by Yangtze River Scientific Research Institute, Wuhan, China in 2005. The experimental images include 300 CT series images (DICOM format), the resolution is 512*512 and the space between two adjacent sections is 10 mm.

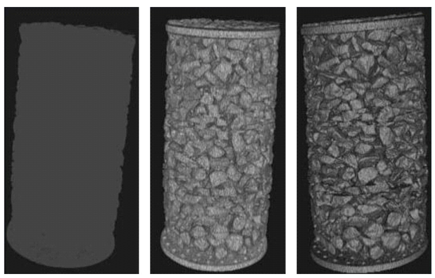
Surface reconstruction processing: Firstly, we extract contour for 300 CT series images (DICOM format). Because it has a large number of triangulated surfaces, we choose to use dough sheet curtailment function to realize real time optimization. Then smooth surface, plan image and display 3D image.

Volume reconstruction processing: The same as surface reconstruction, 300 CT series images (DICOM format) are firstly input for volume reconstruction algorithm. Then volume reconstruction needs to classify processing of volume data. Different classes endow different colors and transparency and final image effect is confirmed according to the relative position of space viewpoint and volume data.

This study is applied to realize the three-dimensional reconstruction of coarse-aggregate morphology in development platform of VC++6.0. Figure 2 denotes one surface reconstruction and three volume reconstruction results. Table 1 gives the comparison results of these four algorithms' performance.



(a) Marching cubes algorithm



(b) MIP algorithm, Composite algorithm and Iso-surface algorithm(from left to right)

Fig. 2: The surface reconstruction and three volume reconstruction results

Table 1: The comparison results of four reconstruction algorithms' performance

Reconstruction algorithm	Running time	Reconstruction results
Marching cubes algorithm	15.6 s	Fuzzy image, difficult to identify particle morphology, fast rendering speed
MIP algorithm	11.5 s	Very Fuzzy image, difficult to identify particle morphology, highest rendering speed
Composite algorithm	15.8 s	clear image and particle morphology, fast rendering speed
Iso-surface algorithm	28.4 s	Very clear image and particle morphology, slow rendering speed

3D reconstruction of coarse aggregate morphology based on VTK: In this study, a new 3D particle reconstruction algorithm is proposed for further study on the coarse-aggregate mictofabric. This study designs a new searching algorithm for the vertical boundaries and horizontal boundaries of coarse-aggregate particles. The vertical boundaries can be realized through orthogonal projection algorithm (Rafael *et al*., 2005; Pegna and Wolter, 1996); and the horizontal boundaries (two-dimensional boundaries) can be realized through region growing algorithm (Jun *et al*., 2008) from the beginning of one point in the particles. Upper and lower boundary localizations are realized respectively through upward projection and downward projection; their searching algorithms are just the same.

We can find the vertical boundaries and horizontal boundaries of coarse-aggregate particles by using the above search algorithm. Then the composite ray casting volume reconstruction algorithm based on VTK is used to realize 3D particle reconstruction. The concrete steps of 3D particle reconstruction are as follows:

- Input two-dimensional slices data of coarse-aggregate particles.
- Segment the image sequence and save images.
- Calculate the inner-particle and inter-particle microfabric elements of all the two-dimensional images.

The inner-particle microfabric elements mainly include:

Particle area and circumference: For segmented images, the particle area is the total number of white pixels included in the particle; the particle circumference is the total number of edge pixels in particle region.

Particle centroid: The particle centroid is the center position of particle plane. The centroid coordinate is expressed as the ratio between the ordinate and abscissa of all particles and the total number of particles:

$$(X,Y)=\left(\frac{\sum x_i}{S},\frac{\sum y_i}{S}\right) \tag{1}$$

where, (x_i, y_i) is the X and Y coordinate of every particle; S is the total number of particle pixels, that is particle area.

Particle shape parameter: The particle shape parameter is calculated by particle area and particle circumference:

$$S=\frac{\|B\|^2}{4\pi A} \tag{2}$$

where, $\|B\|$ is the particle circumference , A is the particle area.

Particle round parameter: The particle round parameter is defined by all the edge points in particle region:

$$C=\frac{\mu}{\sigma} \tag{3}$$

where,

$$\mu=\frac{1}{K}\sum_{k=0}^{K-1}\left\|\left(x_k,y_k\right)-\left(\bar{x},\bar{y}\right)\right\| \tag{4}$$

$$\sigma^2 = \frac{1}{K}\sum_{k=0}^{K-1}\left[\left\|\left(x_k, y_k\right) - \left(\bar{x}, \bar{y}\right)\right\| - \mu\right]^2 \tag{5}$$

μ and σ_2 denote the average distance between particle geometric center and edge points and the mean square deviation of distance, respectively. K is the total number of edge pixels, which is the particle circumference. The particle round parameter is not affected by the scale variation, translation and rotation.

Particle eccentricity: The particle eccentricity is defined as the ratio of two principal axes of the ellipse of inertia in the particle region. Set the two principal axes of the ellipse of inertia denote p and q, respectively, where, p is less than q:

$$E = \frac{p}{q} \tag{6}$$

The particle eccentricity is not affected by the scale variation, translation and rotation and describes the compact characteristic in particle region to a certain extent.

Particle long axis information (including length and direction): The particle long axis is defined as the line length of the minimum bounding-box.
The inter-particle microfabric elements mainly include:

Particle coordination number: The particle coordination number is defined as the number of adjacent particles. In this study, a description of the two adjacent particles is as follows: one is that the least distance between the two points on the edge of two particles is less than the specified threshold value; the other is that the line connecting the two particle centroids (on the premise that the line can not through any other particles) is less than a specified distance.

Particle branch vector: The particle branch vector is defined as the line connecting the two adjacent particle centroids, here, the adjacent particle is the same as the described above.

- Click one point P in the certain slice and use the above particle searching algorithm from point P. The searching results are taken as data object of 3D particle reconstruction.
- Use the Composite ray casting volume rendering algorithm to reconstruct coarse-aggregate particles.
- Three-dimensional particle display.

Figure 3 is the process of composite ray casting volume rendering algorithm. Figure 4 is some sample calculation results of inner-particle microfabric elements.

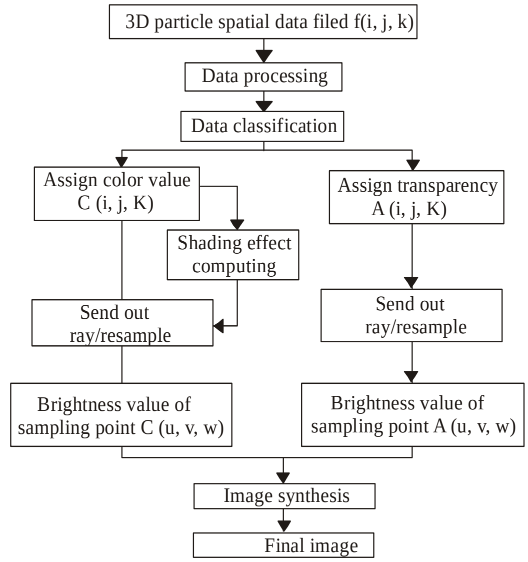


Fig. 3: The process of composite ray casting volume rendering algorithm

ParticleI	CoorX	CoorY	Area	Circle	LongAxisLen
33.bmp_33	209.6435	258.6829	533	90	40.024992192379
33.bmp_34	403.5697	267.9014	416	82	33.9558536926993
33.bmp_35	349.6025	267.8075	483	75	30.5941170815567
33.bmp_36	316.2725	274.5586	367	76	34
33.bmp_37	286.8303	282.2722	878	92	38.4707681233427
33.bmp_38	126.6169	286.7932	556	88	37.4833296279826
33.bmp_39	205.3270	299.9212	1954	172	69.8140387028282

LongAxisObli	LongAxisPointStartX	LongAxisPointStartY	LongAxisP
347.005382986419	190	250	229
256.373006442891	409	252	401
258.690068868288	354	253	348
298.072485879483	310	255	326
278.972625232718	285	263	291
279.211025162705	123	269	129
321.981056758297	175	285	230

Fig. 4: The sample calculation results of inner-particle microfabric elements

Figure 5 is the flow chart of searching algorithm for the lower boundary of coarse-aggregate particle. Figure 6 shows the results of particle segmentation and calculation of inter-particle microfabric elements. Figure 7 represents the 3D particle reconstruction results of coarse-aggregate microfabric.

The implementation process of virtual cutting: At present, there are two main methods to realize virtual cutting of volume reconstruction graphic based on VTK. The first one is cropping which uses wire-frame to realize virtual cut. The second one is clipping which uses adding cutting plane to operate virtual cutting and it can add several cutting planes and realize complex cutting effect by plane combination.

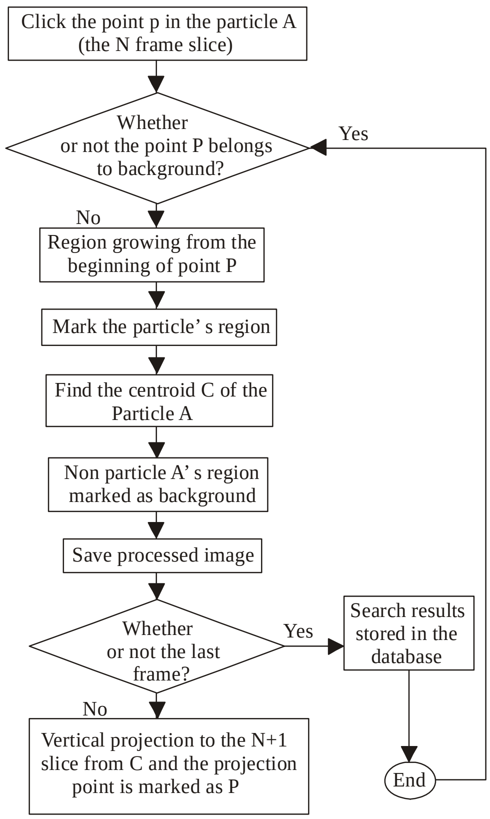


Fig. 5: The Search algorithm of the lower boundary of coarse-aggregate particle

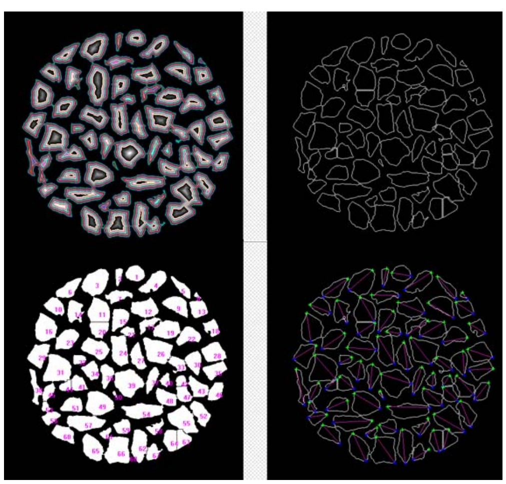


Fig. 6: The results of particle segmentation and calculation of inter-particle microfabric element

These two methods are both accurate, but lack vivacity and just realize the virtual cutting of single section every time. In this study, we use a real-time interaction method based on plane widget to realize cut volume reconstruction graphic. The presented method creates three axes planes on the screen and the virtual cutting is realized through controlling of these three planes. Thus, the users can realize the virtual cutting very directly by this method and convenient to operate.

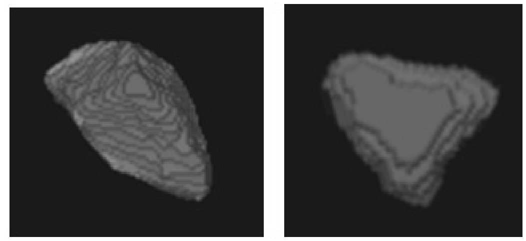
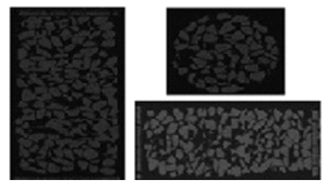
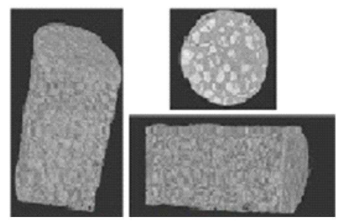


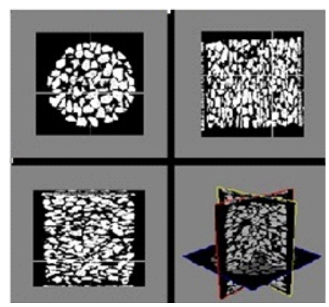
Fig. 7: The 3D particle reconstruction results of coarse-aggregate



Cropping method



Clipping method



The presented method

Fig. 8: The comparison results of virtual cutting of volume reconstruction based on cropping method, clipping method and the presented real-time interaction method based on plane widget

Figure 8 is the comparison results of virtual cutting of volume reconstruction based on cropping method, clipping method and the presented real-time interaction method based on plane widget. Table 2 gives the comparison results of these three virtual cutting methods' performance.

Table 2: The comparison results of three virtual cutting algorithms' performance

Virtual cutting method	Running time	Virtual cutting results
Cropping method	8.2 s	Clear particle morphology and the microfabric, just realize the virtual cutting of single section every time and is impossible to realize real-time interaction
Clipping method	17.6 s	Fuzzy particle morphology and the microfabric, just realize the virtual cutting of single section every time and is impossible to realize real-time interaction, slow speed
Real-time interaction method with plane widget	6.3 s	Very clear particle morphology and the microfabric, realize real-time interaction, highest speed

Experimental analysis: This study has applied the three-dimensional algorithm reconstruction based on VTK to the three-dimensional reconstruction of coarse-aggregate morphology and the microfabric of the material studied with VC++ 6.0. The original data includes 300 CT series images. According to the experimental results, we make the following conclusions.

- The 3D reconstruction of coarse-aggregate morphology results show that the composite ray casting volume reconstruction algorithm is suitable for the reconstruction of coarse-aggregate morphology.

  The effect analysis of surface reconstruction and volume reconstruction: the image and particle morphology are clear by using composite and iso-surface ray casting volume reconstruction algorithms to reconstruct coarse-aggregate morphology; and the particle morphology is difficult to be identified and the image is fuzzy by using surface reconstruction algorithm and MIP ray casting volume reconstruction algorithm .

  The running time of surface reconstruction and volume reconstruction: the reconstruction time of MIP ray casting volume reconstruction algorithm has the highest speed than other three rendering algorithms; composite ray casting volume reconstruction algorithm and surface reconstruction algorithm take the second; and iso-surface ray casting volume reconstruction algorithm has the lowest speed.

  Considering the fact, that the objective of building three-dimensional model of coarse-aggregate is to analyze the internal features of coarse-aggregate morphology, it has strict effect requirement for reconstruction, but low real-time requirement.

  Based on above analysis, composite ray casting volume reconstruction algorithm is more suitable for the reconstruction of coarse-aggregate morphology. But the algorithm efficiency is still imperfect, which needs further study.
- The 3D particle reconstruction of coarse-aggregate microfabric results shows that the proposed algorithm in this study is feasible to realize 3D particle reconstruction of coarse-aggregate microfabric and this algorithm has simple design and high efficiency.
- The virtual cutting results of volume reconstruction graphic based on real-time interaction method with plane widget can realize the virtual cutting very intuitively and the experiment effect showed that the presented method is more satisfying than cropping and clipping methods.

CONCLUSION

In this study, we first use the surface and volume reconstruction algorithm based on VTK to realize the three-dimensional reconstruction of coarse-aggregate morphology. Then, aiming to analyses the particle microfabric characteristics of coarse-aggregate more accurately, a new 3D particle reconstruction algorithm has been proposed by introducing a searching algorithm to the vertical boundaries and horizontal boundaries of coarse-aggregate particles. Finally, we realize the virtual cutting of volume reconstruction graphic based on real-time interaction method with plane widget.

The established three-dimensional model in this study can serve as the basis of mechanical analysis. It can be used in the researches on the microfabric characteristics of various materials made of coarse-aggregate and qualitative analyses of effects on the mechanical behavior of such materials. Definitely, it has a great potential future.

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