Research on an Irregular-Particle Placement Algorithm Based on a Three-Dimensional Random Aggregate Model

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Abstract

Numerical simulation of irregular particle systems is an important method for studying the mechanical behavior of granular materials, and the establishment of three-dimensional digital models and efficient placement techniques for irregular particles is of great significance for investigating the mechanical behavior of particle systems. To achieve the generation and placement of various irregular particle models, this study designed and developed irregular particle placement software based on the C# platform. First, based on the spatial polyhedral geometric attribute information of three-dimensional convex irregular particles, a particle information data structure represented by an object-oriented method was designed. Using a three-dimensional random aggregate placement generation algorithm, program software with automatic generation and placement functions for irregular particles was developed. Based on the C# platform, user interface interaction for control parameter input and irregular particle generation was implemented, and visualization operations of three-dimensional models were realized with the graphical functions of OpenGL. A 3D printing output module was designed in the software, enabling the rapid printing and generation of placed digital particles through a 3D printer, thereby providing experimental samples for experimental research on irregular particles. An output format for finite element model files of irregular particles was established in the software, which can provide preprocessing models for discrete element and finite element numerical simulations of irregular particle materials. Finally, particle packing experiments were conducted using irregular particles, and explicit finite element simulations of particle digital models were performed. The results show that the digital models and visualization technology for irregular particles implemented by the software program developed in this study can meet the needs of physical experiments and numerical simulations in the study of irregular particle problems.

Full Text

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Abstract: Numerical simulation of irregular particle systems is an important method for studying the mechanical behavior of particulate materials. The establishment of three-dimensional digital models of irregular particles and efficient particle-placement technology are of great significance for investigating the mechanical behavior of particle systems. To realize the generation and placement of various irregular particle models, this study designed and developed irregular-particle placement software based on the C# platform. First, based on the spatial polyhedral geometric attribute information of three-dimensional convex irregular particles, a particle-information data structure characterized by an object-oriented method was designed. A three-dimensional random aggregate placement-generation algorithm was applied to develop program software with automatic generation and placement functions for irregular particles. Based on the C# platform, user-interface interaction for control-parameter input and irregular-particle generation was implemented, and visualization operations for three-dimensional models were realized with the aid of OpenGL graphics functions. A 3D-printing output module was designed in the software, enabling rapid printing and fabrication of the placed digital particles by means of a 3D printer, thereby providing test specimens for experimental studies of irregular particles. An output format for finite-element model files of irregular particles was established in the software, which can provide preprocessing models for discrete-element and finite-element numerical simulations of irregular particulate materials. Finally, a particle-packing experimental study was carried out using irregular particles, and explicit finite-element simulation of the digital particle model was performed. The results show that the digital irregular-particle model and visualization technology implemented by the software program developed in this study can meet the needs of physical experiments and numerical simulations for research on irregular-particle problems.

Keywords: irregular particles; three-dimensional random aggregate placement algorithm; object-oriented technology; 3D printing; particle packing

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Irregular Particle Packaging Algorithm Based on a 3D Random Aggregate Model

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Abstract: Numerical simulation is one of the important methods to study the mechanical behavior of irregular particulate systems. Generation of three-dimensional numerical models of irregular particles and encapsulation technology are important research topics. To create a numerical model of irregular particles, a program that generates irregular particles and an intuitive interface for the program were developed by using the C# platform. First, based on the geometric property information of three-dimensional convex irregular particles, the particle information data structure characterized by object-oriented methods was designed.

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Then, the 3D random aggregate packing algorithm was applied to develop software for the automatic generation and conditioning of irregular particles. Using the C# platform, a user interface for controlling model generation and export was designed, and an interface for rendering 3D animations of particle models with the OpenGL graphics library was developed. A 3D-printing output data file was also designed in the program, enabling real particles to be generated rapidly with a 3D printer. The printed particles can be used as specimens in experiments on irregular particles. The program also provides methods for generating model-data output files for discrete-element and finite-element analysis. Finally, irregular-particle packing experiments were performed and simulated by FEM. The results show that the program developed in this study can meet the need for rapidly creating numerical models of irregular particles for use in experiments and numerical simulations.

Key words: irregular particles; 3D random aggregate packing algorithm; object-oriented technology; 3D printing; particle packing

In nature and in engineering fields, granular materials usually have irregular shapes, such as irregular rock blocks formed by rock blasting and ballast used in high-speed railway construction. To investigate the mechanical properties of irregular granular materials, scholars have conducted extensive experimental studies. For example, Xue Lihua et al. [1] carried out triaxial tests on irregular granite ballast particles. Wang Xinzhi et al. [2] conducted triaxial consolidated drained and consolidated undrained tests on calcareous soil and analyzed the influence of particle shape on shear strength. Jiang Kaifang et al. [3] studied the influence of particle shape on the compressive characteristics of sand through uniaxial compression tests. It can be seen that experiments remain the most direct and effective method for studying the mechanical behavior of granular materials, but the economic cost of such experiments is often high. With the continuous improvement of computer performance, computer simulation technology has become an important method for studying the mechanical properties of irregular granular materials.

The shape of irregular particles has a relatively significant influence on the macroscopic mechanical behavior of a particle system. This influence is mainly manifested as a type of rolling-resistance behavior when particles move relative to one another [4]. In numerical simulations, there are usually two ways to calculate the rolling resistance caused by irregular particle shapes. One is to simplify irregular particles as spherical elements and then attach a rolling friction coefficient to the spherical elements [5]. However, when this method is used, the relationship between the irregular particle shape and the equivalent rolling friction coefficient must be determined. The other method is to establish irregular particle models directly. Common approaches include combining multiple spherical elements [6–8] to describe the complex morphology of particles. This method can express the influence of particle shape, but when the number of particles is large, the computational workload is enormous and the requirements for computer performance are high. Non-spherical elements can also be established using superquadrics or extended polyhedra, which can effectively overcome the deficiency that particle elements are spherical in shape [9–12]. Three-dimensional laser scanning technology can reconstruct three-dimensional numerical models of real irregular particles [13]. This technology can accurately describe the detailed features of particles, but in use it requires a large number of scans of particles with different shapes to establish a particle model library.

The random sequential addition method generates a particle model by randomly selecting a point within the considered generation-volume range, then continues to generate particles randomly within the remaining volume, and repeats this process until completion [14–15]. In addition, a three-dimensional random aggregate algorithm [16–17] can be used to construct three-dimensional irregular particle models. This algorithm uses octahedra with random shapes and positions as aggregate bases to generate spatial aggregates, and can characterize the random probability-distribution features of the shapes of various irregular granular materials in engineering production. Through the persistent efforts of scholars, this algorithm has become relatively mature [18–19] and can be applied to the packing of irregular particle models. However, when the three-dimensional random aggregate algorithm is used to establish irregular particle models, the operation procedure is cumbersome, the model code is complex, and the program code must be debugged repeatedly, which has hindered the application and development of the three-dimensional random aggregate packing algorithm in research on irregular granular materials.

Therefore, based on the three-dimensional random aggregate algorithm, this study established an object-oriented data structure for particle geometric information. The good extensibility and reusability of this data structure were used to solve the problem of repeated debugging of program code. With the C#

platform, an irregular-particle packing software package, Agg Random Packing (ARP), was developed, enabling the rapid generation and packing of particles with various irregular shapes. At the same time, 3D-printing and finite-element modeling functions were integrated into the software. Through the 3D-printing files and finite-element model files output by the software, rapid printing of irregular particles and construction of finite-element models were realized. Finally, to verify the practicality of the software functions, packing experiments were carried out on acrylic granular materials, and finite-element packing simulations were performed.

1 Packing Algorithm

The development of irregular-particle packing software involves many technical methods, such as methods for describing irregular particle shapes, algorithms for generating and packing irregular particles, techniques for establishing object-oriented information data structures, and visualization technology.

···technologies, etc. Its core technologies are the generation and placement algorithms for irregular particles.

This study mainly designs a software program for generating and placing irregular particles based on a three-dimensional convex concrete aggregate random-placement algorithm.

1.1 Shape-Control Parameters for Irregular Particles

The three-dimensional aggregate random-placement algorithm uses a random spatial octahedron at an arbitrary position in space as the initial aggregate base. By repeatedly generating new vertices at random on the largest edges of the aggregate surface, the random growth of the aggregate is achieved. The shape of the random aggregate is mainly adjusted through the maximum edge length, the minimum edge length, the maximum control radius of the particle, and the minimum control radius of the particle.

The irregular shape of particles can be characterized at three scales: sphericity, roundness, and surface roughness [20]. Among them, sphericity and roundness mainly refer to the macroscopic and local shapes of the particle. For example, whether a particle is spherical or columnar is described as sphericity, while whether its edges and corners are sharp or smooth is described as roundness. Roundness refines the particle outline on the basis of sphericity. Since aggregates generated by the three-dimensional convex random aggregate placement algorithm all deviate from a spherical shape to varying degrees, as shown in Fig. 1, the shape variation of irregular particles generated by this algorithm can be described by a sphericity parameter in this study. Particle sphericity can be expressed in terms of surface area and volume as [21]

$$SI = \frac{4\pi}{S}\left(\frac{3V}{4\pi}\right)^{\frac{2}{3}} \tag{1}$$

where S is the particle surface area and V is the volume. Equation (1) expresses the ratio, at the same volume, of the particle surface area to the surface area of a sphere with an equivalent volume.

Fig. 1 Aggregate particles in different shapes

To reduce the number of shape-control parameters for irregular particles in the program, when designing the irregular-particle placement software, the definition of particle sphericity in Eq. (1) was referenced, and Eq. (2), used to express the irregular particle shape, was redefined as

$$\alpha = \frac{V_i}{V_b} \tag{2}$$

where V_i is the true volume of the particle; V_b is the volume of a spherical particle with the same surface area; and α is the ratio of the particle volume to the volume of a surface-area-equivalent sphere under the same surface area. Using the parameter α to characterize particle shape can not only effectively reflect the particle sphericity, but also establish the relationship between particle shape and the equivalent rolling friction coefficient, thereby providing a parameter-determination method for studying the equivalent rolling friction coefficient of irregular particles. The shape parameter α controls the particle shape by changing the three coordinate values of the vertices of the spatial octahedron. The vertex coordinates can be expressed as

$$\begin{cases} x = \alpha r + 0.2 \times (1-\alpha) + 0.8(1-\alpha)r \times \mathrm{random}(x) \\ y = \alpha r + 0.2 \times (1-\alpha) + 0.8(1-\alpha)r \times \mathrm{random}(y) \\ z = \alpha r + 0.2 \times (1-\alpha) + 0.8(1-\alpha)r \times \mathrm{random}(z) \end{cases} \tag{3}$$

where random() denotes a decimal number in the range $0 \sim 1$ generated by a random-number generator, and r denotes the particle radius. When the shape coefficient α varies from 0 to 1, the shape of the irregular particles generated by placement changes from sharp to full.

1.2 Implementation of the Irregular-Particle Placement Algorithm

The three-dimensional random aggregate placement algorithm mainly consists of an intrusion judgment criterion and an aggregate random-generation algorithm [17]. The aggregate intrusion criterion judges by calculating the value of the tetrahedral volume V_b formed by an arbitrary point P in space and the triangular element on the surface of the convex body. According to the value of V_b, the positional relationship between point P and the convex body can be divided into the following three cases.

1) When $V_b > 0$, point P is outside the spatial region Ω of the convex body.
2) When $V_b = 0$, point P is on the boundary of Ω.
3) When $V_b < 0$, point P is inside the region Ω.

In the random aggregate placement algorithm, the geometric elements constituting the aggregate model have an obvious hierarchical structure and nesting relationship. For example, the aggregate model contains three basic elements: points, lines, and surfaces. Points are connected to generate lines, lines are connected to form surfaces, and surfaces are combined with surfaces to form a body. Figure 2 shows the spatial framework of irregular particles. Object-oriented technology can directly express the complex hierarchical structure and nesting relationship of objects [22], and can realize parametric modeling of irregular particles. Therefore, when designing the irregular-particle placement software, this study treats the particle points, lines, and surfaces as objects, respectively, and then establishes an object-oriented placement algorithm for irregular particles based on the random aggregate placement algorithm.

The procedure for establishing an irregular-particle placement algorithm using object-oriented technology is as follows.

1) Generate the particle placement region according to the placement-region control parameters input by the user.
2) Determine whether particle placement has been completed according to the particle control radius and the size of the placement domain input by the user; if it has been completed, store the result.
3) Randomly place spatial octahedral aggregate bases within the generated placement region.
4) Judge whether particle intrusion occurs; if intrusion occurs, execute Step 3).
5) Search for and determine whether the maximum edge length of a particle is greater than the edge-length control parameter input by the user. If not, directly execute Step 2); if so, continue to grow the edges satisfying the growth conditions according to the growth conditions and growth mode, and then execute Step 2).
6) When the user clicks the output button, output the result file; if the user clicks the result-display button, display the generated three-dimensional irregular particle model. The detailed algorithm flowchart is shown in Fig. 3.

Figure 2. Spatial structure of irregular particles

Fig. 2 Spatial structure of irregular particles

Figure 3. Flowchart of the object-oriented algorithm for irregular particles

Fig. 3 Generation process of irregular particles based on object-oriented technology

The characteristics of this algorithm are as follows: the designed number of particles is determined, and the spatial positions of the placed particles are regularly distributed; that is, a group of randomly shaped particles with regularly arranged spatial positions is generated in a cubic space. After the center position of a particle is determined, the irregular shape and radius of a single particle are formed through a random growth method. The diameter of each particle is generally controlled by the radius-control parameter, and the contact-judgment algorithm prevents overlap and penetration between the randomly grown particle shape and adjacent particles at the later stage of growth.

2 Data Structure and Functions

2.1 Framework Design of the Placement Program

In this study, an irregular-particle placement software program was designed using the C# development platform. Figure 4 shows the software program framework. The main development idea of the software is as follows: when the program is running, it can automatically read the user' s settings in the main program···

the control parameters input on the program interface, and generates an irregular-particle model according to the user' s requirements. When the user clicks the result-output button on the program interface, two types of format files supporting 3D printing and finite-element modeling can be obtained. When the user clicks the result-display button, the three-dimensional model of the irregular particles can be displayed.

2.2 Program Software Functions

To visualize the placement results of irregular particles, this study used Open Graphics Library (OpenGL) technology. This graphics library is a powerful software graphics function library that supports low-level drawing and modeling capabilities

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. It provides functions such as three-dimensional model construction, three-dimensional scene rendering, image projection transformation, and object-surface texture mapping

24–25

. On the C# platform, the OpenGL wrapper library (CsGL.OpenGL) can be called directly through the keyword `using`.

According to the software-development concept, the software program interface designed in this study is shown in Fig. 5. The program interface mainly contains the following functional modules.

Text in Fig. 4: Program framework diagram of ARP

- Form class: `Form_MainPanel`
  - Visualization form class: OpenGL toolkit
  - User
  - Parameter input
  - Placement-region size parameter module
  - Particle control parameter module
  - Read user-input parameters
  - Result visualization (Draw Picture): `button_draw_Click()`
  - Particle generation and placement (Packing): `button_Output_Click()`
  - `.stl` file format
  - `.dat` format
- Parameter-reading class: `DomainOfPacking`
- Particle-generation class: `Agg`
  - Generate placement region: `DomainSet()`
  - Calculate number of particles, area, and volume
  - Particle random generator: `randomGenerator()`
  - Obtain center-point coordinates: `getCentCoordX()`, etc.
  - Obtain particle vertex information: `getNumberOfVertexes()`, etc.
  - Obtain particle face information: `getNumberOfFaceCells()`
  - Obtain center-point coordinates: `getCentCoordX()`, etc.
  - Obtain particle edge information: `getNumberOfSides()`, etc.
  - Find the maximum edge of a face: `getMaxSide()`
  - Set aggregate base: `setBasicAgg()`
  - Aggregate growth: `aggGrowth()`
  - Add new vertex: `addNewVertex()`
- Vertex class: `Vertex`
  - Obtain vertex coordinates and set index: `SetCoor()`, `getCoord_x()`, etc.
- Side class: `Side`
  - Set edge relationship: `setFaceCells()`
  - Set vertex relationship: `setVertexes()`
  - Obtain line normal vector: `getNormalX()`, etc.
  - Set face normal vector: `setNormal()`
  - Obtain vertex index: `getVertexI()`, etc.
  - Obtain edge index: `getSideId()`, etc.
  - Calculate edge length: `getLength()`
- Face class: `FaceCell`
  - Set face edges: `setSides()`
  - Set face vertices: `setVertexes()`
  - Obtain edge index: `getFaceCellId()`
  - Obtain vertex coordinates: `getVertexI()`, etc.

- Obtain non-adjacent vertex: `getVertexExcep()`
- Obtain non-adjacent edge: `getSideNext()`
- Set face normal vector: `setNormal()`
- Obtain line normal vector: `getNormalX()`, etc.

Figure 4 Software ARP program framework diagram

Fig. 4 Program framework diagram of ARP

1) **Placement-region size control module.** This module mainly has three control parameters, namely length, width, and depth, with the default unit being m. After the user completes the input of the control parameters, the software can automatically generate the corresponding cuboid placement region.

2) **Particle irregular-shape control module.** This module mainly contains three shape control parameters, namely: the particle shape parameter, used to

controls the fullness of the irregular particles; the particle radius R is used to control the size of the generated particles; and the maximum particle edge length L is used to control the maximum edge length of the generated particles.

Figure 5 ARP software interface
Fig. 5 Program interface of ARP

3) **Particle placement module.** After the user finishes entering the placement-region dimensions and particle-shape parameters, clicking the "Particle Placement" button on the main program interface causes the software to generate the corresponding irregular particles according to the user' s requirements and store the data. When the run ends, "Particle Placement" is displayed as "Packing finished!" , and the text box below prompts the user in Chinese that "particle generation and placement are complete."

4) **Result output module.** To meet the needs of printing irregular particles with a 3D printer and modeling them in finite elements, a "Result Output" button is provided on the program interface. When the user clicks it, ".stl files" and ".dat files" can be output. The specific organization processes for these two file types are as follows. For the `.stl` file, ".stl" is a file format used to describe three-dimensional models. The surface of the particle model placed by the software can be regarded as being formed by a large number of triangular facets. The `.stl` file is mainly composed of the geometric information of triangular facets; each triangular facet contains one normal vector (*facet normal*) and the coordinates of three vertices (*vertex*). Therefore, when organizing the `.stl` file, the normal vector of a triangle can be determined from two adjacent edges, the three vertices can then be output in a certain order, and loop statements can be used to traverse and output the entire particle model. For the `.dat` file, the software uses a file named "rock.dat" to store the point-coordinate information

and tetrahedral geometric information of the particle model. The specific organization process is as follows: first, the vertex array (`numVertex`) and face array (`numFace`) are traversed by a `for` loop, and the `sw.WriteLine` function is used to output the vertex coordinates and vertex numbers, separated by commas.

5) **Result visualization module.** When the user clicks the "Draw Picture" button in the program interface, the program pops up the three-dimensional result display interface shown in Figure 6. This interface is generated by a Form window program in C# through OpenGL functions. It has functions for resetting the position, translating, rotating, and scaling the placed irregular particles, which can be implemented with the left mouse button, the scroll wheel, and the right mouse button.

Figure 6 Three-dimensional model display interface
Fig. 6 3D model display interface

2.3 Implementation of the 3D-Printing Numerical Model and the Finite-Element Numerical Model Based on the Placement Program

2.3.1 3D-printing numerical model

In this study, the irregular particles placed by the ARP software were printed with a 3D printer through `.stl` format files. Figure 7 shows the process of printing irregular particles with a 3D printer.

(a) 3D-printing model (b) 3D printer (c) printed particles

Figure 7 Flowchart of the 3D-printing process for irregular particles
Fig. 7 3D printing procedure of irregular particles

3D printing refers to a technology that uses equipment to manufacture parts from digital models by adding material layer by layer. It can rapidly and accurately manufacture parts of arbitrary complex shapes [26–27]. This study used the Raise 3D E2 printer shown in Figure 7, which supports 3D model files in multiple formats and can print various materials such as PLA, PVA, and nylon. The printer nozzle diameter is $0.2 \sim 1.0$ mm. The internal infill rate and infill pattern of the structure can be set, effectively ensuring the surface smoothness and strength of the structure. When using the 3D printer, the result file can be directly input into the 3D printer for printing. It can be seen that, by designing the output of 3D-printing file formats in the ARP software, rapid printing and generation of the placed digital particles can be achieved.

2.3.2 Finite-element numerical model

The specific process for establishing an irregular-particle model in the finite-element software Abaqus is as follows: first, the Ansys APDL command stream is used to read the "rock.dat" file and establish the irregular-particle model.

Fig. 8 FEM model of irregular particles

Figure 1: Fig. 8 FEM model of irregular particles

Then the `Vwrite` command is used to output all node coordinates and the node numbers of the tetrahedra.

⋯, and generates the Abaqus `.inp` file. Fig. 8 shows the irregular-particle models with shape parameter α ranging from 0 to 1, established in Abaqus using the ARP software. From the modeling process described above, it can be seen that, in realizing the modeling process from the ARP software to the finite element software Abaqus, users can establish particle models with different shapes simply by changing the control parameters in the software. This greatly simplifies the process of modeling irregular particles in finite elements.

Fig. 8 Finite element model of irregular particles

Fig. 8 FEM model of irregular particles

From the processes of 3D printing irregular particles and modeling them in finite elements, it can be seen that the irregular-particle placement software ARP has the following characteristics.

1) **Simple operation.** After the user inputs the dimensions of the placement region and the shape parameters of the irregular particles in the program interface, clicking the generation button can realize particle placement and generation. Clicking the result-output button can realize one-click output of the model results, avoiding the inconvenience caused to users by complicated program code.

2) **Visualization of results.** By clicking the "draw results" button in the program interface, the user can view the placed particle model, achieving "what you see is what you get" for particle-generation results. Moreover, when the user modifies the input parameters, the software can also display the modified results in real time, greatly reducing the time required for users to modify the model.

3) **Rich output-result file formats.** When designing the result-output module, the software fully considers users' needs for irregular-particle test materials and finite element models of irregular particles, and designs two file formats, "`.stl`" and "`.dat`", which can be used for 3D printing and finite element modeling of irregular particles.

3 Case Verification

3.1 Particle Stacking Simulation

The stability and instability of particle-system stacking are closely related to particle shape. Increases in the irregularity of the particle outer contour and

Fig. 9 FEM stacking simulation procedure of irregular particles

Figure 2: Fig. 9 FEM stacking simulation procedure of irregular particles

in the interparticle sliding friction coefficient both lead to an increase in the natural angle of repose

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. To verify the practicability of the output function for the finite element model files of irregular particles established in the software, this study imported the irregular-particle model files generated by the software into the finite element software Abaqus, and simulated the process in which irregular particles form a natural accumulation body in a rectangular test trough through the movement of a single-side baffle. The stacking simulation process is shown in Fig. 9. In Fig. 9, the particle shape coefficient is set to 0.5, the particle radius is 0.1 m, the edge control size is 0.1 m, the number of generated particles is 1,050, and the volume is 0.84 m^3.

(a) Rectangular trough

(b) Particle placement

(c) Particle falling

(d) Stacking completed

Fig. 9 Finite element stacking simulation of irregular particles

Fig. 9 FEM stacking simulation procedure of irregular particles

In the numerical simulation, the length, width, and height of the rectangular trough are 6 m, 1 m, and 1 m, respectively. The movable baffle is located at the middle of the rectangular body and can move toward the opening direction of the rectangular trough during the stacking process. The stacking process mainly consists of two stages.

1) **Irregular-particle placement process.** The randomly generated irregular particles are placed in the rectangular region, and the sliding friction coefficient is set on the particle surfaces in the form of a penalty function. Then, under the action of gravitational loading, the particles freely fall and reach a naturally dense state.

2) **Baffle-movement stage.** After the particles have completed free fall, the baffle is moved slowly and uniformly to the left, and the particles spread accordingly and gradually form a stable slope surface.

Because the slope surface of the particle accumulation body obtained from the simulation is a concave–convex irregular contour line, the error in the stacking angle obtained directly by picking particle-node coordinates is relatively large.

To accurately measure the stacking angle of repose, the image-processing techniques of Photoshop and MATLAB were used to process the simulation results. The processing procedure was "image cropping → grayscale processing → binarization processing → edge detection → linear fitting of the edge contour → stacking-angle calculation," and the detailed process is shown in Fig. 10.

In the stacking simulation, the sliding friction coefficient has a relatively large influence on the particle stacking results

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. To express more clearly the influence trend of the sliding friction coefficient on the stacking stability of irregular particles, working conditions with the sliding friction coefficient in the range of 0–0.3 were added. In designing the working conditions, the selected values of the shape parameter α were 1.0, 0.9, 0.8, 0.7, and 0.6, respectively; the values of the sliding friction coefficient μ_s were 0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, and 1.0, for a total of 65 working conditions.

Fig. 10 Angle-of-repose measurement procedure in FEM simulation

Subfigure labels and in-figure annotations: (a), (b), (c), (d); grayscale processing; binarization; edge detection.

Fig. 11 shows the particle-piling simulation results. It can be seen that, under the same sliding-friction-coefficient condition, the irregular particles with $\alpha = 1.0$ have the smallest angle of repose, while those with $\alpha = 0.46$ have the largest angle of repose; the angles of repose of the remaining particles lie between these two. When the sliding friction coefficient μ_s is 0.05, there is no obvious difference in the angles of repose of the five particle shapes. However, when μ_s is in the range of 0.1–0.5, the differences in the angles of repose are relatively pronounced. When the sliding friction coefficient is greater than 0.5, the differences among the angles of repose of particles with different shapes are relatively small, and the growth rate of the curves approaches 0, which is consistent with the results in Ref. [29]. The final stable angle of repose formed in the piling simulation is 31.8°, consistent with the internal friction angle $\theta = 31°$ of the soil sample in a stable state reported in Ref. [20].

Fig. 11 Variation curves of the simulated angle of repose of irregular particles in FEM

Axes and legend: vertical axis, angle of repose / (°); horizontal axis, sliding friction coefficient μ_s; $\alpha = 1.00$, $\alpha = 0.90$, $\alpha = 0.78$, $\alpha = 0.60$, $\alpha = 0.46$, Ref. [23].

3.2 Particle Piling Experiment

To further verify the validity of the numerical simulation results, two types of irregular acrylic particles were selected for piling experiments. The particle materials used are shown in Fig. 12; the circumscribed-sphere diameters of the two particle types are 10 mm and 12.5 mm, respectively. To determine the shape parameter α of these two particle shapes, each type of particle was first weighed multiple times to obtain the mean mass; the volume V_i was then obtained from the density; finally, the shape parameter α was calculated according to Eq. (1). The results are shown in Table 1. The rolling friction coefficient and sliding friction coefficient in the table can be determined from the particle shape parameter by referring to the formula proposed in Ref. [5].

Subfigure labels: (a) $\alpha = 0.745\,4$; (b) $\alpha = 0.476\,8$.

Fig. 12 Irregular particle samples in the experiment

Tab. 1 The parameters of irregular particle samples

Parameter	Particle 1	Particle 2
Mean mass of a single particle / g	0.468 4	0.560 6
Mass standard deviation	0.009 7	0.002 0
Density / $(\mathrm{kg} \cdot \mathrm{m}^{-3})$	1 200	1 200
Single-particle volume / mm^3	390.3	467.2
Shape parameter	0.745 4	0.476 8
Sliding friction coefficient μ_s	0.24	0.24
Rolling friction coefficient μ_r	0.042 5	0.085 4

The particle piling experimental procedure was basically consistent with the finite-element simulation procedure. The test particles were placed into the test trough, and the height-to-width ratio of the formed particle assembly was kept consistent with that of the numerical model, namely $1:3$. The baffle was then slowly pulled away. After the particle pile reached a stable state, the pile height h and the spreading width l were recorded. The piling results are shown in Fig. 13. The angle of repose of the particle pile was likewise measured using image-processing techniques.

Subfigure labels: (a) $\alpha = 0.745\,4$; (b) $\alpha = 0.476\,8$.

Fig. 13 Experimental results of the angle of repose

Finite-element numerical simulations of the particle piling experiments were performed according to the experimentally calibrated particle shape coefficients. The numerical simulation parameter values were consistent with those in the experiments, and the simulation results are shown in Table 2.

Tab. 2 Comparison of the angle of repose between experimental results and FEM results

Parameter	Particle 1	Particle 2
Experimental angle of repose $\theta_1/(^\circ)$	25.29	29.70

Parameter	Particle 1	Particle 2
Simulated angle of repose $\theta_2/(^{\circ})$	24.67	29.01
Error / %	2.51	2.38

It can be seen that the experimental angle of repose and the finite-element numerical simulated angle of repose

The angles of repose are relatively close, with the error within 5%, indicating that it is feasible to use the particle model file output by the ARP software to simulate the accumulation of irregular particles.

4 Conclusions

The construction of irregular particle models is the key to studying the macroscopic mechanical properties of irregular particle systems. Therefore, based on a three-dimensional concave random aggregate placement algorithm, this study used object-oriented technology and OpenGL visualization technology to develop the irregular particle generation and placement software ARP. Finite-element accumulation simulations and accumulation tests were then conducted to verify the irregular particle models placed by the software, leading to the following conclusions.

1) The software developed in this study can rapidly generate particles of various irregular shapes by using only a small number of control parameters, realizing parametric modeling of irregular particles and effectively reducing the difficulty for users in operating program code. In addition, after irregular particle placement is completed, users can view the three-dimensional particle model in real time through buttons on the main program interface, enabling real-time interaction between the user and the software.

2) The software is designed with functions for outputting 3D printing files and finite-element model files, enabling rapid 3D printing and finite-element modeling of irregular particles, and providing experimental materials and finite-element models for mechanical research on irregular-particle materials.

3) Comparison between finite-element accumulation simulations and accumulation tests shows that the irregular particle models generated by the ARP software can accurately simulate the experimental accumulation process, verifying the high practicality of the software.

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Note: Figure translations are in progress. See original paper for figures.