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Aggregated Structure and Forming of Controlled Star-shaped Particles

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Abstract

This paper explores the controlled packing of granular materials, investigating free-fall stacking and manual placement techniques. Through computational simulations and physical experiments, it examines the influence of particle geometry on packing patterns and explores the interaction of construction methodologies. The study establishes a methodology for shaping architectural structures using granular materials, aiming to find ways to control the construction of aggregate structures. By leveraging digital simulations, the research explores interlocking patterns and probabilities, providing insights into stacking possibilities. The experimental results reveal the influence of particle geometry on stacking structures, showing the possibilities for future architectural design. Overall, this research contributes to the development of controlled granular packing methodologies with implications for innovative architectural applications.

Keywords: granular packing methods, star-shaped particle geometry, aggregate structure, granular assemblies.

1. Introduction

Natural granular matter, such as soil, ice, and snow, forms unique accumulation patterns. In the biosphere, some animals exhibit granular material stacking behavior. For example, otters gather branches to stack and build dams, and pufferfish sway their fins to stack sand and gravel into a pile. There are also many examples of using granular materials to construct artificial structures. The aggregation of granular materials, i.e., aggregate structure, offers a radically different model for both construction and constructional changes in architecture [1].

1.1. Artificial aggregate architectures

Building upon Karola Dierichs and Achim Menges' [2] studies of granular materials morphology, this paper extends the understanding of how particle geometry influences packing patterns. Zhao et al. [3] delves into the interactions of material properties, interparticle friction, packing configurations, and construction methodologies. Dierichs & Menges [4] utilizes Discrete Element Method (DEM) simulations to offer a global perspective on the stacking state of granular materials, aiming to transform these aggregates into programmable materials.

The current discussion on aggregate structure and granular material is focused on the study of free-fall stacking. The fundamental requirement for these studies is the need for a framework to shape these particle piles or to allow for free interlocking, following the inherent repose angle of the material to shape the overall structure. In Figure 1, we have summarized that the current cases of aggregate structure can generally be classified into two types of granular materials and forms: asterisk and grain. The stacking process can be categorized into three types, from uncontrolled to controlled: free-fall stacking, framework-assisted shaping, and placement. Taking Cairns stones as an example, they are structures built by early humans for burial or commemoration, consisting of stacked random stones forming specific shapes. The experiment conducted by Dierichs and Menges [4] was aimed at preparing the pouring paths and patterns of many particles using a six-axis industrial robot. These construction methods involve free-fall stacking. However, the latter uses robotic arms to control the falling path, which doesn't quite qualify as an uncontrolled stacking method.

In addition, another experiment Dierichs and Menges [5] conducted was about full-scale arches that were constructed mainly using the clogging phenomenon on a tank. A large-scale tank with an outflow at the bottom has been constructed and is filled with non-convex granules. If the bottom plate is removed, unloaded material will flow out. The ICD Aggregate Pavilion 2018 [6] uses two types of designed particles with different behaviors: The assembly consists of interlocking non-convex hexapods and decapods, along with flowing convex spheres serving as the framework. These cases use the asterisk as the granular material. The Rock Print Pavilion constructs by Aejmelaeus-Lindström et al. [7] is a house made from loose aggregates and twine, built by a mobile robot in the center of Winterthur. In this case, grain is used as the granular material, while twine serves as a framework to shape the overall form. Gabions, on the other hand, are cages filled with rock granules and used in civil engineering [8]. In our classification, both dolosse and dry-stone structures [9] belong to controlled aggregate structures. The construction of these two structures requires arrangement and analysis. Each granular material has its designated position. Therefore, this research probes critical questions: How can we construct aggregate structures in a controlled method and understand how the geometry of granular materials affects the overall structural behavior?

Figure 1: Classification of aggregate structures

particle / granular material	material	uncontrolled ←→ controlled			characteristic
		free-fall stacking	framework	placement	
asterisk non-convex	injection -molded granulates	 robotic controlled free drop	 Convex particles were filled in as a formwork in the core of the structure.  An arch of 3000 mm span has been cast from non-convex granules.	 dolosse	easy to disassemble, reshape and arrange, but less stable
grain convex	gravel / stone	 stone cairns	 adding a layer of string between each gravel level  gabion wall	 dry stone	heavy and difficult to construct, but more stable

The paper investigates the probability of the free-fall stacking forming and the feasibility of manual placement for shaping the overall structure. We attempt to analyze the difference between controlled and uncontrolled stacking in terms of how aggregate structures are constructed and explore the rules involved. In contrast to emphasizing free-fall stacking and framework forming, we focus on studying the outcomes of controlled stacking methods, exploring whether specific forms of human intervention can enhance the potential for shaping.

2. Mothodology

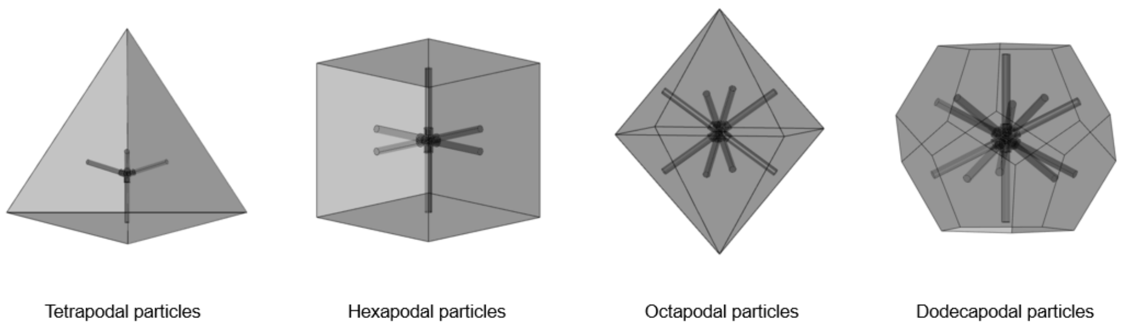
This study establishes a controlled granular material packing methodology, which incorporates two distinct stacking techniques, namely free-fall stacking and manual placement, alternately utilized for construction. This approach facilitates the development of a replicable research framework for future investigations into controlled granular stacking or assembly. Regardless of the geometric form or material composition of the granules, this methodology can be universally referenced.

- Phase 1: Establishing custom granular material formation rules. we utilize non-convex polyhedral formed by four types of regular polyhedral as the stacking granular material.
- Phase 2: Building digital models in Blender for stacking simulation, aiming to identify stacking configurations and probabilities between single or multiple particles to understand the formation rules of free-fall stacks. Concurrently, basic physical stacking experiments will be performed to validate the accuracy of the digital simulations.
- Phase 3: The manual placement method is employed for granular stacking, further subdivided into Basic type combination and Granular material packing comparison, aiming to establish fundamental properties of both single-grain and bulk granular stacking.
- Phase 4: The designs constructed based on the rules include wall, column, arch, and cantilever structures. Through the four phases described above, basic controlled stacking experiments can be conducted, allowing for an understanding of the fundamental patterns of structure formed by different geometric particles.

3. Particle geometry

We leverage the Controlled Granular Packing method to investigate the transformation of non-convex granular material, or star-shaped particles, derived from Platonic solids interlock from a collection of loose and unbound particles into a highly packed and rigid aggregation. The generation of non-convex polyhedral involves connecting the incenter of the polyhedral to each plane with vertical lines and converting these lines into solid shapes. These non-convex polyhedrals are derived respectively from tetrahedral, hexahedral, octahedral, and dodecahedral, forming shapes resembling 3D asterisks. (Figure 2) We abbreviate the four types of granular materials as Tetrapod, Hexapod, Octapod, and Dodecapod. The asterisks, or star-shaped particle models, are fabricated by 3D printing the central part and embedding bamboo sticks.

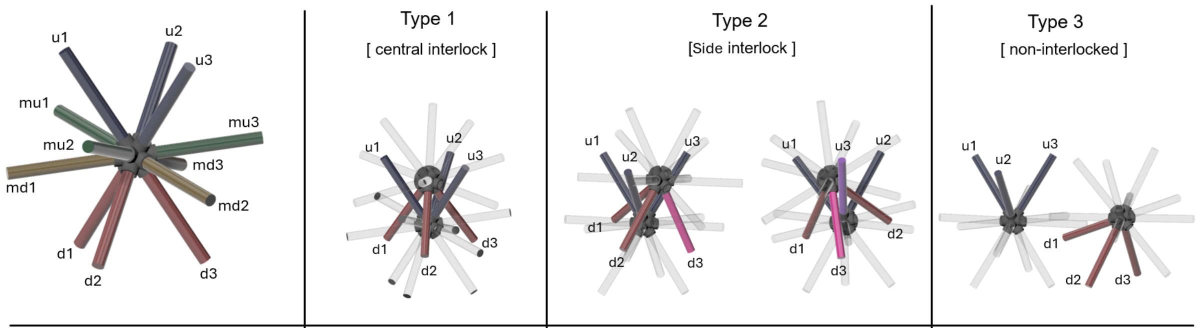
Figure 2: Star-shaped particles



4. Controlled free-fall stacking physical experiments and simulation

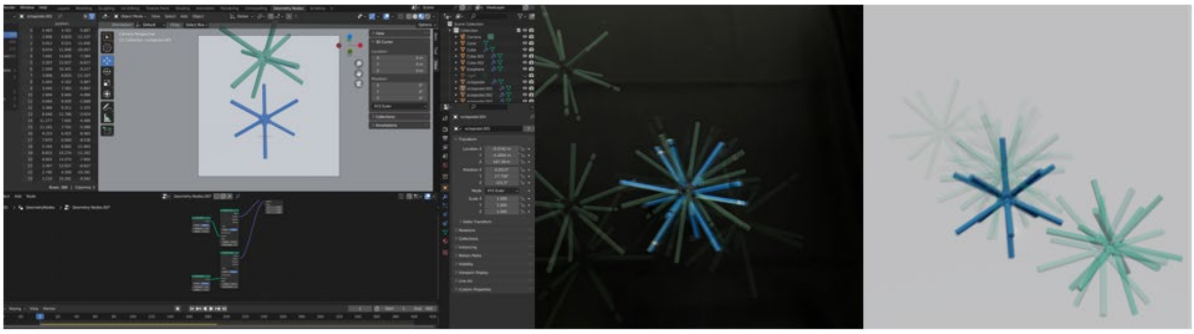
This chapter discusses controlled free-fall stacking, which differs from the previously classified free-fall stacking. Given the numerous variables in stacking many particles, we initially seek to understand the stacking behavior between individual particles. We build digital models in Blender for stacking simulation, aiming to identify stacking configurations and probabilities between single particles to understand the formation rules of free-fall stacking. Additionally, physical stacking experiments are conducted simultaneously to validate the accuracy of the digital simulations. The experiment was conducted using Dodecapods as the manipulated granular material, and they fell at random angles from twice the height of a particle. The interlocking behavior between the falling granular material and the one on the base can be observed by the operation. These observed interlocking behaviors are categorized into three types: (1) Central interlock: characterized by vertical stacking between two particles, where u1 to u3 rods and d1 to d3 rods are interlocked. (2) Side-interlock: any configuration where the u-bar and the d-bar exhibit a two-to-two or three-to-two interlocking arrangement. (3) Non-interlocked states encompass connections without interlocking or entirely disconnected states. (Figure 3)

Figure 3: The combined state of dodecapodal particles in controlled free-fall stacking



	Type 1 [central interlock]	Type 2 [Side interlock]	Type 3 [non-interlocked]
Controlled free-fall stacking (manual)	15 times	33 times	12 times
Simulations	16 times	29 times	15 times
Interlock / Non-interlock (Probability)	3/4		1/4

Figure 4: Controlled free-fall stacking physical experiments and simulation



The results of physical stacking experiments revealed that central interlock occurred 15 times, side interlock 33 times, and non-interlocked 12 times out of 60 free-fall stacking trials. Conversely, in the digital simulation, central interlock was observed 16 times, side interlock 29 times, and non-interlocked 15 times. According to the data obtained from the two experiments, the three types of interlocking behaviors respectively occurred in the ratios of 1/4, 1/2, and 1/4. After this experiment, the probability of interlocking under a stack of two particles is 3/4. If we take into consideration many stacked particles, the Side-interlock may result in interlocking with the neighboring particles. Non-interlocked particles may interlock with other particles that are not adjacent to the target particle, or they may not interlock with any particles. This result can be extrapolated to the case of multi-particle stacking. (Figure 4)

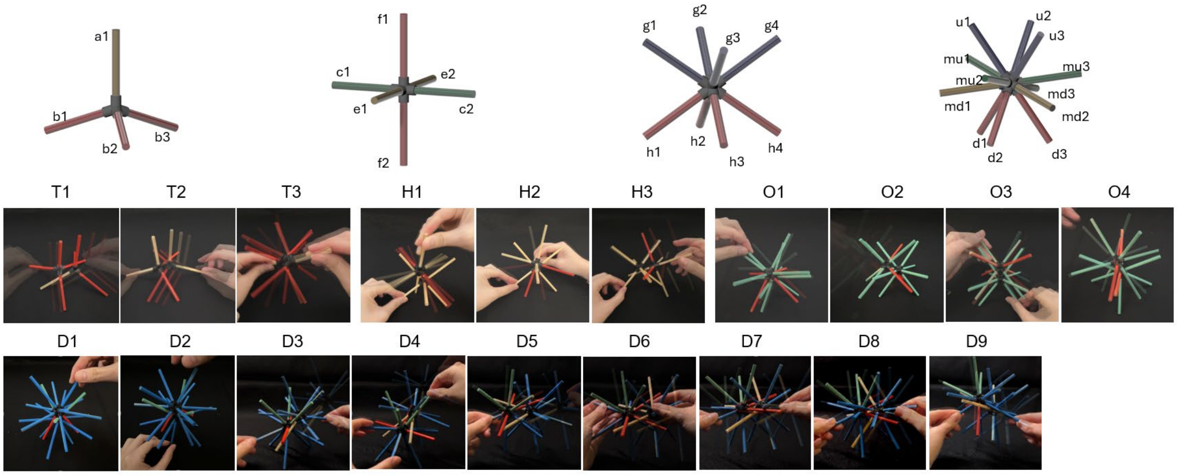
5. Manual placement

The Controlled Granular Stacking Methodology includes controlled free-fall stacking and manual placement. Considering that some interlocking configurations and orientations cannot be achieved through controlled free-fall stacking, this section includes experiments on manual placement. This research will be divided into two categories: basic type combination (interlocking 2 particles) and Granular material packing comparison (multi-particles). These experiments indicate the influence of various star-shaped particle geometries on the overall stacking structure. Therefore, the stacking rules summarized from the experimental results can be applied in the design of architectural structures.

5.1. Basic type combination

The basic type combination explores the possible combinations between two basic particles to determine the basic placement methods. The possible combinations include Tetrapods (T1 to T3); Hexapod (H1 to H3); Octapod (O1 to O4); and Dodecapod (D1 to D9). Here, Tetrapods are used as an example: T1 involves inserting one of the three rods of a tetrapod between the rods of another tetrapod. T2 is to interlock the two rods of one tetrapod with the two rods of another Tetrapod. T3 involves aligning the centers of two Tetrapods for interlocking, but since the angle between the rods of the Tetrapod is less than 90 degrees, this method cannot tightly interlock together. The interlocking mechanisms of other particles follow a similar logic. H1 and H2 are inserted into another particle in vertical and horizontal directions. H3 is inserted sideways. O1 is to interlock two particles together at the center. O2 is the interlock between the three rods. O4 is to interlock two horizontal rods in the same direction. D1~D6 are angularly decreasing from directly above to the horizontal direction, and then D7~D9 are interlocking from bottom to top. (Figure 5)

Figure 5: Manual placement



5.2. Granular material packing comparison

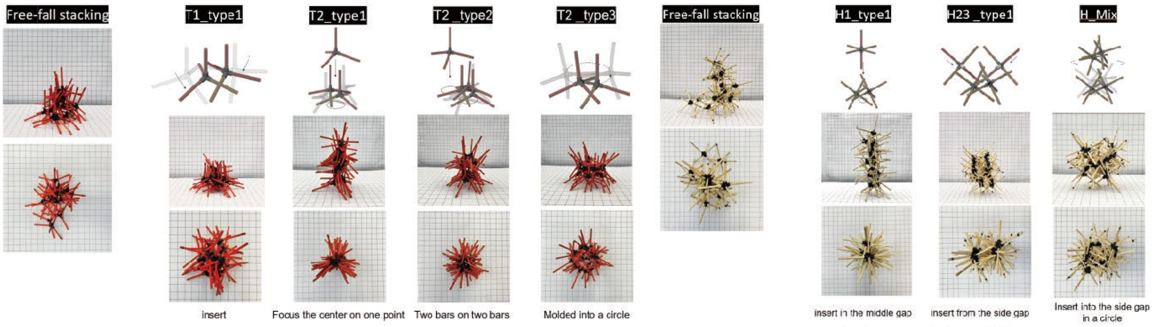
The Granular Material Packing comparison is based on the results obtained from the above-mentioned Basic Type Combination, which is stacked into a pile to understand the type of structure the stacked particles will form. Subsequently, free-fall stacking is conducted to compare the morphological differences between piles stacked in different ways (Figure 6).

- Tetrapod: T1-type1 involves inserting b-rods into each other, resulting in a more tightly packed structure. T2-type1 involves stacking with three b-rods facing downward, resulting in a taller and finer model when the particles are focused on one point but with a less stable base. Stacking in a circular manner provides a more stable base (T2-type3). Free-fall stacking results in a looser structure but is like the results obtained with T1-type1.

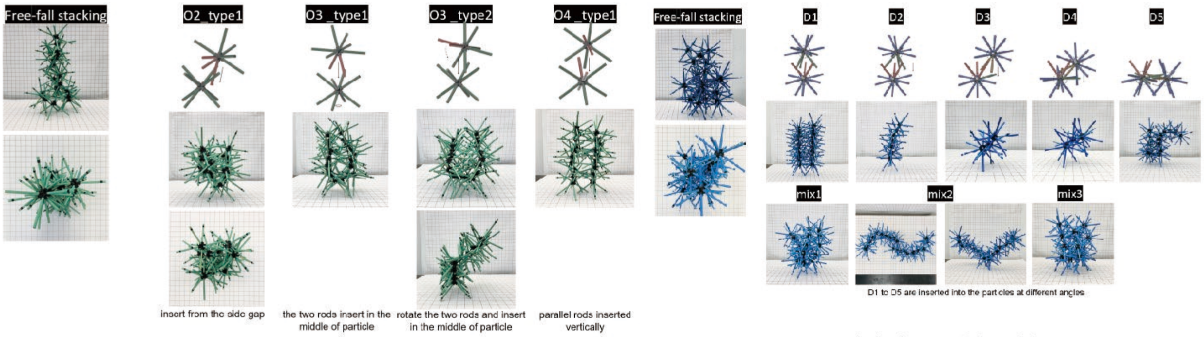
- Hexapod: H1-type1 entails inserting f-rods into the central gap, resulting in a taller and more refined model. Depending on the insertion positions, the mixed stacking of H2 and H3 can generate models with either parallel arrangements or helical structures. The outcome of free-fall stacking exhibits a disorderly and irregular pattern.
- Octapod: O1 involves stacking particles towards the center of each other with g-rods and h-rods, resulting in models that cannot securely interlock. The overall model forms an inverted triangular shape with one particle as the base. O3-type1 involves inserting two h-rods into g-rods from the center. Depending on the insertion angle, it can create U-shaped models with different inclinations, presenting a cantilevered state (O3-type2). O4 involves the connected g-rods and h-rods being inserted into opposite g-rods, forming a column.
- Dodecapod: The difference from D1 to D5 involves lines connecting with central points of two particles, starting as vertical lines and the slope gradually decreasing until they become horizontal lines. D6 to D9, on the other hand, exhibit negative slopes. In D1, vertical insertion creates a columnar shape, whereas in D5, horizontal insertion forms a cantilever. Mix1 to mix3 involves combining rules to stack into various forms.

Overall, the stack of Tetrapods provides a more stable base. The Dodecapod is the easiest to interlock. A Hexapod with perpendicular rods can maintain a certain orientation. An Octapod with symmetry can facilitate even the interlocking of particles. In the experiment, it was observed that an angle less than 90 degrees between the rods was required for downward interlocking. The most stable configuration arises when at least three rods interlock with three rods between two particles.

Figure 6: Granular material packing comparison



(a) tetrapodal particles (b) hexapodal particles

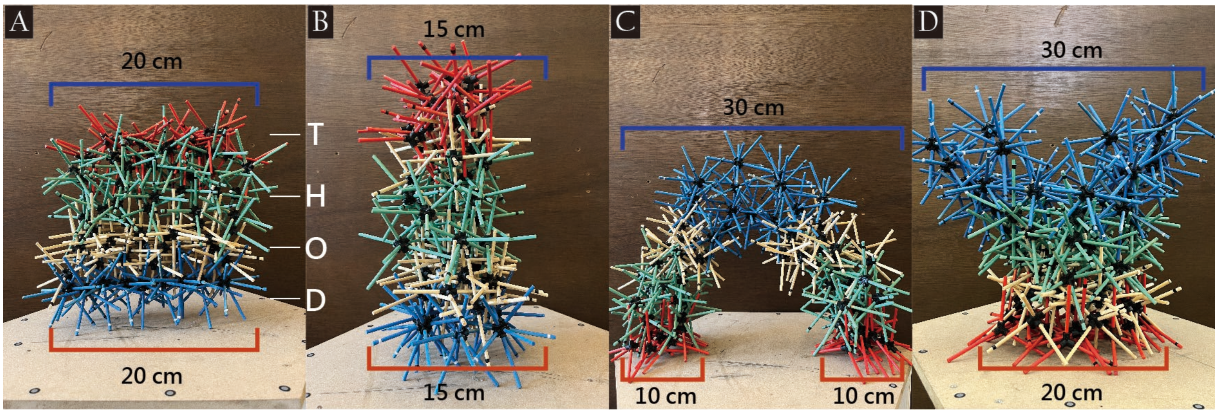


(c) octapodal particles (d) dodecapodal particles

6. Designed architecture structure

We then stack designed architectural structures using controlled free-fall stacking and manual placement methods. These structures include walls, columns, arches, and cantilevers (Figure 7). Model-A and Model-B: The first step is to interlock the Dodecapod to each other using the D5 method to form the base. Because the base width of both the wall and column matches the overall width of the structure, it is determined that the cohesion provided by the Dodecapod base is sufficient, and there is no need to use Tetrapods to increase the stability of the base. Next, insert the Hexapod into the base using the H1 method to make the rods vertical. Interlock the Octapod using free-fall stacking and complete the construction with Tetrapodal. Then, utilize the aforementioned methods to create the wall and column. Model-C: Due to the horizontal forces acting upon the arch, a more stable base is required; the Tetrapod is used for enhanced stability. The width of a single base is 10 centimeters, and the width of the overall model is centimeters. The Octapod is inserted into the second layer using the O2 method to gradually form the cantilever. The cantilever's direction is stabilized using Hexapod's H2 and H3 methods. Finally, the arch's apex is secured by interlocking Dodecapod elements from method D2 to D5, completing the arch structure. Model-D: It is created in the same way as an arch, and the cantilever parts must be interlocked by Dodecapods to be stable enough. The width of the base is 20 centimeters, and the overall width is 30 centimeters. The research findings suggest that controlled free-fall stacking can be used for rapid stacking in the horizontal direction, while manual placement is more suitable for creating stable bases or achieving angled transitions.

Figure 7: designed architecture structure. (T- Tetrapod, H- Hexapod, O- Octapod, D- Dodecapod)



7. Summary and Limitation

We attempt to analyze the difference between controlled and uncontrolled stacking regarding how aggregate structures are constructed and explore the rules involved. In contrast to emphasizing free-fall stacking and framework forming, this paper studies the outcomes of controlled free-fall stacking methods, exploring whether specific forms of human intervention can enhance the potential for shaping. This study proposes a process for controlling star-shaped particles, providing a reference for future research on the behavior of granular materials. Stacking the particles creates gaps, which can be inserted using manual placement to control the overall shape of the mold. This condition is less likely to occur in free-fall stacking. Additionally, digital simulations are employed to derive potential interlocking patterns resulting from controlled free-fall stacking. By determining the probability of occurrence for each pattern, it becomes possible to understand and control the stacking possibilities, thereby enhancing the predictability and control of the free-fall stacking method. The geometry of different particles can be understood through manual placement experiments. A single particle's geometry can influence the entire structure's deformation. Therefore, this paper integrates digital simulations to predict the potential stacked patterns resulting from controlled free-fall stacking while incorporating intervention through placement. This approach aims to develop a controlled method for creating aggregated structures. Here's a summary of the key points and findings of the paper:

- The stack of Tetrapods provides a more stable base. The Dodecapod is the easiest to interlock (Cohesive). A Hexapod with perpendicular rods can maintain a certain orientation. An Octapod with symmetry can facilitate even interlocking of particles.
- Controlled free-fall stacking can be used for rapid stacking in the horizontal direction, while manual placement is more suitable for creating stable bases or achieving angled transitions.
- Interlocking between rods is only feasible when their angle exceeds 90 degrees.

- The most stable interlocking scenario occurs when at least three rods from one particle interlock with three rods from another.

Since the base width matches the overall width, cohesive Dodecapods are used for the base when stacking walls or columns. And since the base is relatively smaller than the overall width for arches or cantilevers, more stable Tetrapods are required as the base. Additionally, interlocking with Dodecapods is necessary for cantilevers to achieve a stable interlocking state.

These findings establish a controllable methodology for form-stacking processes using varied granular packing techniques, which hold significant potential for innovative architectural applications.

This study is currently in the stage of stacking behavior and has not yet undergone actual-scale model testing. There is also a broader research scope in the selection of construction materials. The current research methodology involves practical experimental methods for formal and experiential assessments. However, through simple stacking tests and the stacking of basic architectural elements, although the scale differs from actual structures, it can be observed that these granular materials have the potential for forming.

8. Future research

This paper presents a method for controlling the stacking of granular materials, enabling the stacking process to be predicted and manipulated. The key difference between this aggregate structure and other architectural structures is how the granular particles behave. If the particles exhibit an unstable state, they demonstrate fluid-like behavior, allowing for reshaping and rearrangement. However, when stable, their behavior resembles a solid, possessing a certain degree of structural integrity, argues by Dierichs & Menges [10]. Therefore, this type of structure is particularly suitable for temporary structures. Unlike common temporary structures, this is a hollow and porous structure, resembling materials formed by foaming processes, exhibiting certain similarities. These granular materials with slidable porosity possess compressibility, allowing for achieving suitable structures through dynamic equilibrium, thus adding an additional degree of freedom in form. This construction method assembles scattered particles into rigid aggregates. Such structures are reversible, allowing for the repeated use of materials, thus reducing resource waste. At the same time, it resembles the structure of bird bones, where long bones are hollow tubes. Unlike solid bones filled with marrow in terrestrial animals, the strength of these tubes is sufficient while significantly reducing weight [11]. If this concept were applied to composite structures like reinforced concrete, with the aggregate structure serving as the reinforcement system and an outer layer enveloping it made of elastic or dynamically balanced materials, it could potentially offer a new perspective on architectural structures.

This paper's research on controlled aggregate structure is only in its initial exploration phase. The current stacking method involves horizontally layering different particles. In the future, we can explore stacking particles in different orientations and study the mixed geometry of different types of particles, which serve as the foundation for constructing actual scale granular material structures. Furthermore, exploring the influence of various geometric shapes of particles on overall morphology and developing digital simulation systems for simulating controlled granular materials more conveniently. Additionally, experimenting with a wider range of granular materials, transitioning from single-material systems to multi-layered composite material systems, could expand the possibilities for architectural structures.

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