



Simulation Algorithm Based on Weathered Rock Morphology and Optimization Algorithm for Design Applications

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Abstract. The rich organic pore spaces of weathered rocks bring inspiration to architectural design. Based on the existing research on the natural formation mechanism of weathered rocks, this paper proposes two algorithms that achieve natural formation mechanism simulation and morphology simulation. Firstly, this study deeply explores the intrinsic characteristics of weathered rocks; secondly, the basic framework of iterative cyclic calculation by multiple weathering forces is built to make the calculation results of 3D point cloud close to the real morphology of weathered rocks; subsequently, this study innovatively introduces a 2D stacked layer algorithm for optimization while maintaining the morphological characteristics; finally, the architecture design application of the optimization algorithm is verified. Compared with the 3D point cloud simulation algorithm, the 2D layered algorithm can greatly reduce the computational time complexity and control the generated space's utilization.

Keywords: Weathered rock · Natural form simulation algorithm · Algorithm-based design

1 Introduction

With the application of new technologies in the field of architectural design, computer algorithms can create a large number of architectural forms with similar features in a short time, and change the detailed shape according to the actual needs under the control of some parameters. Computational design methods assist designers to generate buildings that mimic natural forms. There are generally two ways to develop the natural form simulation algorithm: one is to summarize the intuitive characteristics of natural form and directly simulate it; the other is to study the laws of how it is formed and use the mathematical formula to develop algorithms [13]. The former focuses on the external shape, while the latter focuses on internal reasoning.

The natural form selected in this study, tafoni, is composed of countless non-Euclidean surfaces at the microscopic level, which would be a huge workload for human modelling alone and difficult to restore its natural morphological characteristics through manual control. The introduction of the algorithm can be interpreted as a “natural hand”

to restore the organic form and maintain the characteristic elements of tafoni from the beginning to the end.

Different methods have been used in the previous study on morphological simulation algorithms of natural shape. Xu Weiguo et al. took the example of mutualistic leaf order morphology and described the whole process from the analysis of biological mechanism to the simulation algorithm and architectural design application [14]. Z. Feng et al. introduced a generative design method that integrates two techniques of computational fluid dynamics (CFD) simulation and bidirectional progressive structural optimization (BESO) based on the steady-state effect of Taihu stone [4].

This paper first explores the intrinsic characteristics of weathered rocks and reclassifies them based on architectural geometric elements, then proposes two algorithms that achieve natural formation mechanism simulation and morphology simulation. The algorithm can simulate the natural form and has great application value on architecture design.

2 Study of the Natural Morphology

The study of this paper is focused on mining the morphological characteristics of tafoni and applying them in architectural design. The point, line, and plane are the basic geometric elements to express space and entity. Therefore, this study classifies the morphology of tafoni into three types: point base, line base, plane base. The natural pictures and form description diagrams are shown in Fig. 1.

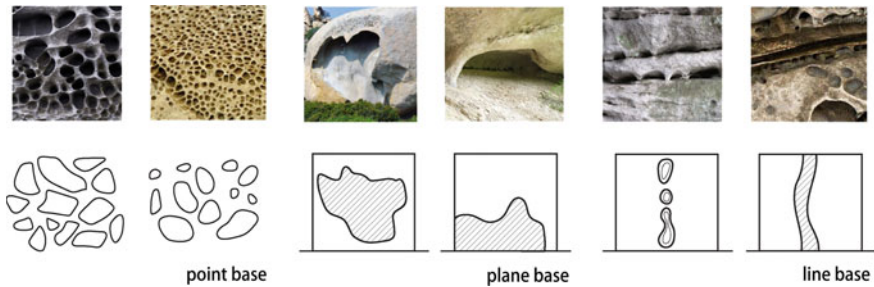


Fig. 1. Natural forms of weathered rocks and Forms description diagrams.

2.1 Literature Review

Weathered rocks were studied and classified as early as the nineteenth century, and the first such honeycomb cavities larger than 0.5 m in diameter were called tafoni [12]. Paradise defined tafoni as “lace-like, honeycomb, bowl, or pan-shaped cavities occurring in a variety of rock types that show a commonly unique assemblage and morphology” [11]. Previous studies have proposed classifications such as alveoli, stone lace, honeycombing, caverns, pitting, and other terms based on the different characteristics of weathered pore morphology in terms of size, morphology, and distribution [6]. The classification of this study is from the perspective of design.

2.2 Morphological Classification

Point base tafoni has irregularly concave holes of different sizes and organic shapes, with the inconsistent depth of the concave surface.

Line base tafoni has irregular holes of different sizes and are fused together, and different holes meet in the form of grooves, the whole is of different lengths, uneven thickness, bifurcation, irregularly curved strip-like grooves, and the depth of the grooves is not uniform.

Plane base tafoni has hook-like sides, concave in the middle and lower parts, rounded and smooth inner walls, and protruding like a cap tongue at the top.

3 Simulation Algorithm of Weathering Process

Earlier studies on tafoni indicate that tafoni develop in different types of bedrock, most commonly in granitic rocks [12]. Granitic weathering cavities are essentially the product of differential weathering and are closely related to the granular structure, homogeneity, weak permeability, and ease of disintegration of granites [9]. Burridge et al. propose a model for the formation of craters produced by corrosive gases that can be analogous to the weathering process: all solid sites are given an intensity value. If a corrosive particle occupies a site near the surface and its next randomly chosen step will bring it to the surface, the particle has the probability to decay [2].

Collectively, the main factors that control and influence tafoni development are microclimatic changes, salt weathering, and valley wind erosion [7]. Valley wind erosion is a physical weathering and salt weathering is a chemical weathering. In this study, these two weathering processes were simulated separately using algorithms.

3.1 Methodology

Based on the fact that the bedrock of tafoni is generally granular in structure [12] and homogeneous [9], this study chose to use Orthogonal 3D point cloud to simulate the weathering process of tafoni.

3.2 Physical Weathering

Physical weathering is accomplished by valley wind erosion [7]. Physical weathering is the same process in three types: point, line, and surface. An iterative mathematical model of physical weathering is established. The study classifies the forces applied to the 3D point cloud into three forces: inter-particle force, wind force, and gravity. The combined force on each point is calculated. Under the action of external force (wind force), the points with the smallest combined force in the point cloud are eliminated after each iteration. The vector value of the wind changes randomly in each iteration. The iteration will continue until all points disappear. This process simulates the actual process of physical weathering. The particle force analysis is shown in Fig. 2.

The plausibility of the physical weathering forces discussed in this paragraph has been verified and implemented in the ESO and BESO algorithms, and the benefits of the optimized structure are retained by removing ineffective or inefficient materials [15].

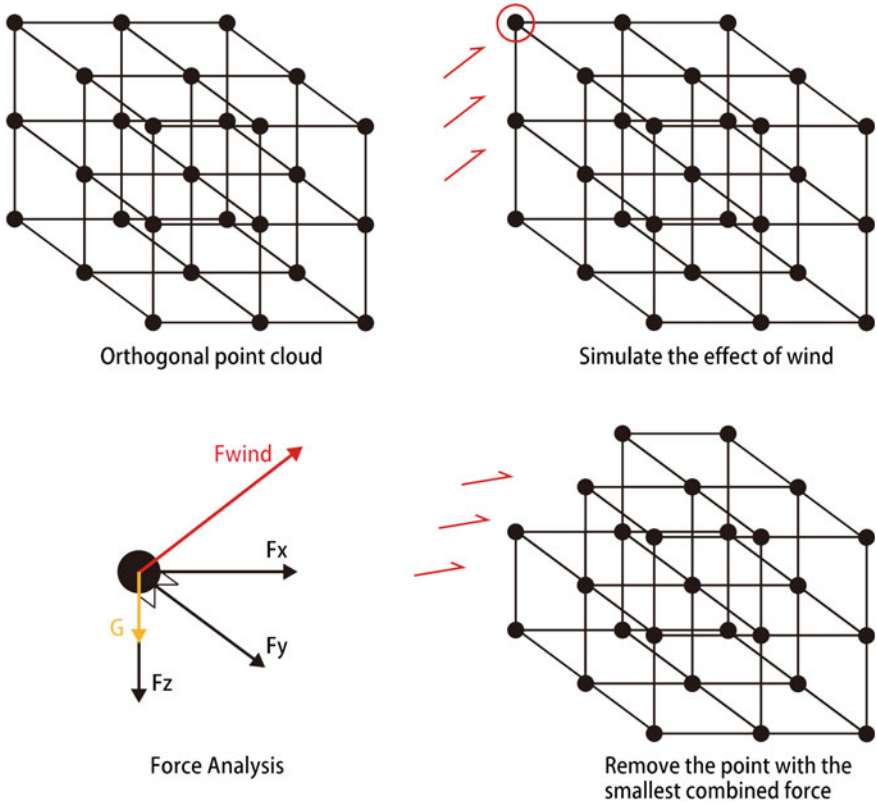


Fig. 2. Force analysis model

3.3 Chemical Weathering

Brandmeier's study showed that chemical weathering rates were found to be related to differences in lithology, microfracture, alteration, and cementation [1]. In which alteration and cementation are chemical weathering, so our simulations are focused on these two processes. A mathematical model of chemical weathering is built basically based on the two steps of chemical weathering: the decay of internal particles due to humidity changes and enhancement of external particles due to gelation [8]. The two steps are corresponding to alteration and cementation.

For point base tafoni, first input the original mesh, generate the orthogonal point cloud inside the original mesh and assign a value x to each point, when x is less than or equal to zero, remove this point. Secondly, randomly reduce some points from the point cloud. Thirdly use the two evolutionary rules according to the two steps of chemical weathering to calculate:

- (i) *the values of the neighboring points A in the vanishing particles decay*
- (ii) *the values of the surface layer(exposed) points S increase.*

For point A,

$$x_a = x - N \quad (1)$$

For point S,

$$x_s = x + \alpha N \quad (0 < \alpha < 1) \quad (2)$$

For a point X in point cloud,

if $x < 0$, remove point X from point cloud

(N is the decay integer constant, α is the enhancement ratio constant.)

For plane base tafoni, the basic process of chemical weathering is similar to point base tafoni. Due to the large surface area of each cavity of the faceted weathering cavity, the temperature and humidity at different locations where its surface is located also vary [10], and the different temperatures and humidity have a greater influence on the chemical weathering. Most chemical weathering occurs on the more obscure surfaces of the rock where the drying rate is lower. The upper part of the tafoni is not exposed to direct sunlight and has a much lower drying rate than the lower part, so the weathering is more pronounced. Therefore, compared with the point-like evolution rule (i) and rule (ii), rule (iii) is added:

(iii) *decay degree of upper points $a_1 > \text{lateral points } a_2 > \text{lower points } a_3$*

For point a_1 point a_2 point a_3 ,

$$x_{a1} = x - N \quad (3)$$

$$x_{a2} = x - \beta N \quad (4)$$

$$x_{a3} = x - \gamma N \quad (0 < \gamma < \beta < 1) \quad (5)$$

For point S,

$$x_s = x + \alpha N \quad (0 < \alpha < 1) \quad (6)$$

For a point X in point cloud,

if $X < 0$, remove point X from point cloud

(N is the decay integer constant, β and γ is the decay ratio constant, α is the enhancement ratio constant.)

For line base, the chemical weathering process is different due to stress [5]. The process of linear type weathering is affected by stress, and no decay occurs for particles with higher stress and decay occurs for particles with lower stress. Therefore, the linear chemical weathering process needs to extend a straight line on the surface of the point set to randomly delete points, which are less stressful points. After the evolution rule (i), add rule (iv):

- (iv) When there is no connection point on both sides of a point, set the point and all the points on its z-axis (stress points) as non-attenuating points.

Set the set of stress points as δ

For point A,

$$x_a = x - N \quad (7)$$

For a point X in point cloud,

if $X < 0$, remove point X from point cloud

if $x \in \delta$, do not remove point X from point cloud

The mathematical model of the above algorithm is shown graphically in Fig. 3. The constants used in calculation can be adjusted according to the specific weathered rock characteristics.

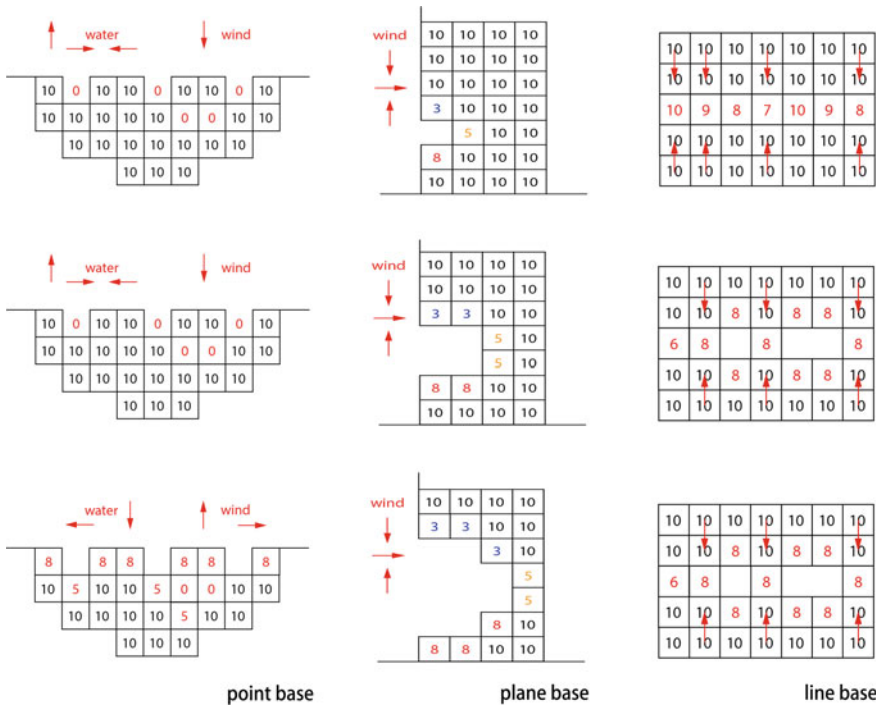


Fig. 3. Chemical weathering

3.4 Combination of Physical Weathering and Chemical Weathering

In order to better simulate the natural weathering process of tafoni, this study needs to develop the summative algorithm combining physical and chemical weathering. After

studying physical weathering and chemical weathering processes separately, it can be seen that shaping the different forms of weathered rocks (point base tafoni, line base tafoni, plane base tafoni) mainly relies on chemical weathering. In the simulation of physical weathering, the angle of the external wind is constantly changing due to the valley wind erosion process over a long period of time. So, the role of physical weathering is more to soften the cavities. In order to weaken the effects of physical weathering in the combination, the physical weathering process is simplified as a rock surface softening process. *Iso-surface* is a smooth surface through all points between voxels, and the algorithm is easy to apply, so *iso-surface* algorithm is used to simulate physical weathering effect in this study. The process combining chemical weathering and physical weathering is to first calculate the chemical weathering for the point cloud-first, and then apply *iso-surface* to simulate the physical weathering. The tafoni simulation algorithm flowchart is shown in Fig. 4. The results of the simulation for the three types are shown in Fig. 5.

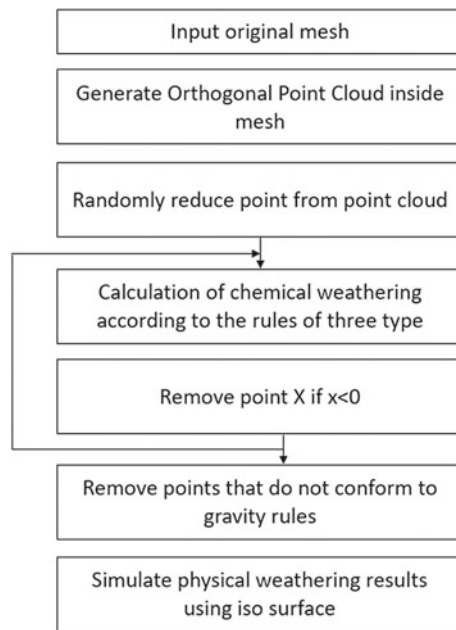


Fig. 4. Algorithm

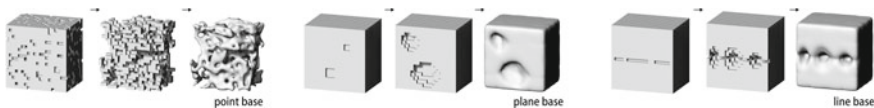


Fig. 5. Chemical weathering mathematical model

4 Optimization Algorithm

The tafoni simulation algorithm developed above is calculated iteratively to simulate the evolution of tafoni. However, the algorithm has high computational time complexity. For the input mesh volume, when the point cloud density ρ is low, this simulation algorithm can be easily calculated, but when a high-precision simulation is required, the point cloud density increases and the computation time will greatly increase. The previous algorithm is not feasible to be applied to practical design. For the purpose of applying the algorithm to architectural design, the algorithm needs to be simpler and more operable.

This study optimizes the algorithm by reducing 3D computations to 2D computations and then layering them to form point sets.

4.1 2D Stacked Layer Algorithm

The 2D stacked layer algorithm steps are as follows. The algorithm process is shown in Fig. 6 with diagrams.

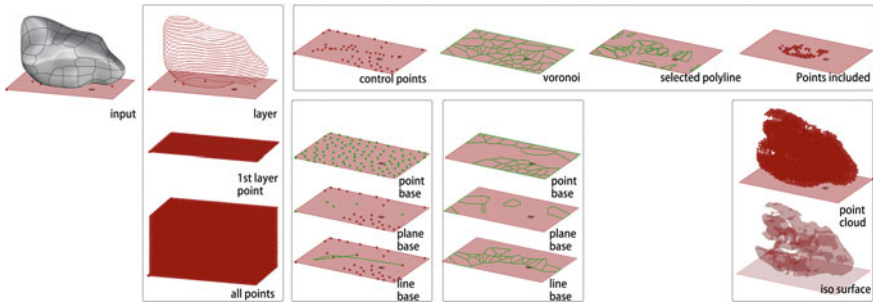


Fig. 6. Optimized algorithm process

1. Input the initial volume mesh of the rock to be weathered;
2. input the number of layers x , the number of layers can be converted into point cloud density parameters (because the point cloud for XYZ direction equally spaced orthogonal point set, so the initial volume of the number of layers to convert the overall point density in the point cloud);
3. Generate the initial point cloud;
4. Generate 2D Voronoi control points by point type, line type, and surface type features, these control points are randomly generated by random number n control;
5. Generate the control Voronoi polygons and extract the polygons representing point type, line type, and surface type respectively;
6. the three corresponding polygons are divided, rounded, offset, and other operations;
7. Merge into the final set of closed curves;
8. Calculate whether the point cloud and the curve set are contained or not, and remove the points contained by the curve set;

9. Loop x times to get the points kept in each layer, these points form the final point set. In the calculation, it is found that the more the number of layers, the more laminar the generated form is. In order to eliminate the laminarization, a formula is experimentally derived that, let when the number of layers is x , for a random number n , every $(x - 7)/7$ cycles, $n = n + 1$.

$$n = n + \left\lceil \frac{x - 7}{7} \right\rceil \quad (8)$$

10. Using Isosurface to convert the points to mesh, the effective range of iso is calculated by comparing and setting the number of layers to x as follows.

$$\text{effective range} = \frac{3000}{x - 53} \quad (9)$$

As can see in Fig. 7, When the value of n is larger, which has larger density ρ of points in the volume, the more detailed carvings the generated shape has. The smaller the point density is, the rougher the generated shape is. Also, with different seed, multiple different simulated rock shape can also be generated from the same initial volume.



Fig. 7. Different input of n , seed and the generated results

4.1.1 Computational Time Complexity

Next, the computational time complexity is estimated for the described 3D algorithm as well as for the optimization algorithm of the 2D stack. For the same input mesh, whose volume is V , set the point cloud density to ρ , the number of points is calculated by multiplying the volume by the density as N .

For the algorithm that directly simulates the weathering process, each point needs to be calculated with N points, a total of N points is calculated. It takes N^2 steps to calculate through all points, and N steps to assign the value. The time complexity can be estimated as N^3 , ignoring constant V , the time complexity O_1 is as follows.

$$O_1(\rho) = \rho^3 \quad (10)$$

For the 2D stacked layer algorithm, the number of points per layer is $\sqrt[3]{N^2}$, and the loop operation is $\sqrt[3]{N}$ steps from the bottom loop to the end of the topmost layer. The time complexity can be estimated as N , ignoring constant V , the time complexity O_2 is as follows.

$$O_2(\rho) = \rho \quad (11)$$

Comparing time complexity O_1 and O_2 , the 2D stacked layer algorithm can greatly reduce the time complexity of the algorithm since $\rho > 1$.

4.1.2 Practical Application Value

This optimization further clarifies the design logic and improves the practical design application value of the generated forms. Since there are different spatial attributes and spatial characteristics required for specific functions in architectural design, the layer-by-layer calculation and then superposition calculation method can make the computer-generated morphology more consistent with the design language, which can better serve the architectural design and actual construction, and then form a space truly used for human living, dwelling and sharing, and the human feeling in the space is more comfortable.

4.2 Algorithm Design Applications

Apply the 2D Stacked Layer Algorithm in to architecture design. First generate pore spaces in a rock, then the pore space is further designed as an office building. The input mesh, generated result, the architecture elevation, the indoor and outdoor renderings are shown in Fig. 8.

5 Prospects

The algorithm-controlled morphological simulation will allow the otherwise uncontrollable natural forms to grow as the designer or the people want, and also facilitate the storage of information needed for spatial orientation. The rich organic pore form of tafoni, the multi-directional penetration of horizontal and vertical space, the flowing non-linear curved form, the reasonable force structure, and consumable rate all reflect the application value and potential of this form, which will bring infinite possibilities for future urban planning and architectural creation.

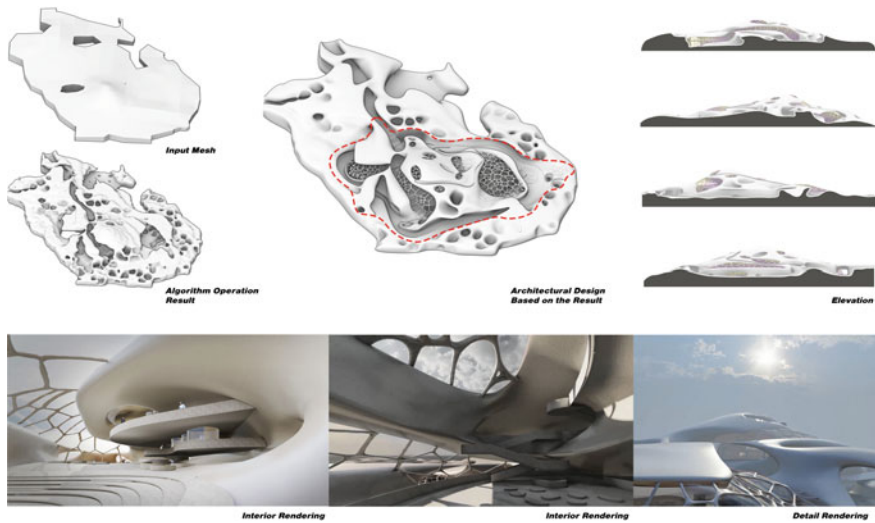


Fig. 8. The input mesh, generated result, the architecture elevation and renderings

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