Building a three dimensional sealed geological model to use in numerical stress analysis software: A case study for a dam site

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**Abstract**

The dam area of the SUOXI hydropower project shows high terrain undulation and complex geological conditions, containing 6 faults and 7 weak inter-beds. A geometric model developed to represent the geology and engineering structures should incorporate the geological realities and should allow suitable mesh generation to perform numerical stress analysis. This is an important precondition to perform rock mass stability analysis of a dam foundation based on a numerical stress analysis software such as FLAC3D. Using the modeling tools available in FLAC3D, it is difficult to construct a complex geological model even after performing a large amount of plotting and data analyses. The 3-D geological modeling technique suggested in this paper, named as Sealed Geological Modeling (SGM), is a powerful tool for constructing complex geological models for rock engineering projects that require numerical stress analysis. Applying this technique, first, the geological interfaces are constructed for the dam area of SUOXI hydropower project using various interpolation procedures including geostatistical techniques. Then a unitary wire frame mesh is constructed and the interfaces are connected seamlessly. As the next step, a block tracing technique is used to build a geological model that consists of 130 seamlessly connected blocks. Finally, based on the Advancing Front Technique (AFT), each block is discretized into tetrahedrons and a mesh is generated including 57,661 nodes and 215,471 tetrahedrons which is suitable to perform numerical stress analysis using FLAC3D.

**Keywords:** 3-D geological modeling, Sealed model, Numerical stress analysis, Wire frame, Block tracing, Tetrahedral mesh generation

**1. Introduction**

With the development of computational techniques, numerical stress analysis has become an indispensable tool for solving geotechnical problems. To help in developing designs and executing construction for hydropower, dam, foundation, tunnel and mine projects researchers often utilize numerical stress analysis methods, such as the Finite Element, Finite Difference and Discrete Element methods to investigate stability and deformation of rock masses associated with complex geological conditions. However, for rock engineering problems associated with complicated geology, it will be a challenging problem to obtain results close to the reality through such numerical modeling. One of the main reasons for this is the significant difference that exists between the geological model created by using the software package and the real geological system that exists in situ. Most of the numerical stress analysis software packages, such as FLAC3D [1,2], provide tools for users to build geological models. However, due to lack of effective tools for simulating complex geological and engineering objects, users have to make simplifications in building geological models. Therefore, the reliability of computational results decreases with increasing complexity of the geological system.

The technique suggested in this paper for 3-D geological modeling is a convincing tool for simulating complex geological objects. After several decades' of research, a great progress has been made in the relative fields of foundational theories [3,4], spatial data models and their topological representation [4–6], simulation methods of complex geological interfaces and features [4,7–14], integration and refinement methods of multi-source data [15–17], and the development of modeling systems. Using this technique, researchers can simulate complex regional geological structures [18] and build integrative models with geological and engineering objects [3,14,19,20]. To improve the computational reliability and the modeling efficiency, a few researchers have made some initial efforts to provide computational models for numerical simulation incorporating the geological modeling technique [21–25]. However, the conventional techniques of 3-D geological modeling cannot be used directly as a geometrical modeling tool for...
numerical simulation, because great differences, such as modeling purpose and method, and data formats, exist among them. The primary purposes of 3-D geological modeling are to digitize and visualize geological information, and to store and manage the data. The geometrical modeling for numerical stress analysis requires that a geometrical model not only be accordant with the geological and engineering objects but also be discretized into meshes with comparatively high quality. Therefore, we propose a 3-D geological modeling method, named as Sealed Geological Modeling (SGM). It is a tool not only for simulating geological and engineering objects but also for building geometrical models for numerical stress analysis. SGM is one important function of ROCKMODEL, which is a program package developed by the authors of this paper.

As a case study, SGM is used to build a geometrical model for the dam site area of SUOXI hydropower engineering in Hunan province, China to use with FLAC$^3$D to analyze the stability of the dam and bedrock. This model can seamlessly simulate the complicated geological and engineering objects in the dam area, and be directly discretized into tetrahedrons to use with FLAC$^3$D.

2. Methodology

2.1. Concepts

2.1.1. Sealed geological model built using SGM

A sealed geological model is a closed and finite size object consisting of many topologically and continuously connected blocks, and each block is an empty volume enclosed by some topologically connected surfaces which are comprised of many topologically connected triangles. In a sealed geological model, vertices, edges, surfaces and blocks are fundamental geometric components, and they must satisfy the following topological conditions:

- Any triangle is composed of three vertices and three orderly connected edges; each edge has a starting vertex and an ending vertex; any two edges must intersect on one vertex.
- Any two topologically connected triangles can only intersect on one vertex or two vertices (an edge); their intersections must be one vertex or an edge of any of the two triangles.
- Any surface is composed of many topologically connected triangles; any two topologically connected surfaces can only intersect on vertices and edges of the triangles.
- Any block is enclosed by many topologically connected surfaces; the intersections of any two topologically connected blocks must be vertices, edges and triangles of their boundary surfaces.

A geological model meeting the above topological conditions can be directly discretized into tetrahedrons to use with FLAC$^3$D.

2.1.2. Numerical model for FLAC$^3$D

Generally speaking, for FLAC$^3$D, a numerical model, also called as mesh for computation, is composed of topologically and continuously connected tetrahedrons or hexahedrons, named as elements. These elements are usually separated into several groups. Elements in one group are located in the same stratum, fault, or inter-bed, and share the same physical and mechanical parameters.

In this paper, when each block is discretized into topologically connected tetrahedrons by using AFT without any change on its boundary surfaces, a sealed geological model becomes a numerical model for FLAC$^3$D. Any triangle on the boundary surfaces of each block of a sealed geological model is a side face of one tetrahedron. Therefore, any two blocks touching each other can be connected topologically after being divided into tetrahedrons.

2.2. Method of building a numerical model

The modeling tool embedded in FLAC$^3$D is a Surface-based solid modeling approach. So users of FLAC$^3$D can connect points to create edges, extend edges to create faces, and sew faces to create a closed shell. The collection of edges forms a wire frame. Then with a mesh preprocessor, the solid model enclosed by a shell can be discretized into elements [1,2]. When using this tool, users have to draw a lot of points, edges and faces; therefore, the tool is not suitable for building a model with complex geological interfaces which may contain thousands and millions of irregular points.

To develop a suitable tool for building a numerical model with complex geological structure, we propose SGM and embed it in a software package. The main steps of SGM are as follows:

- construction of crude interfaces with interpolation methods based on sampling data;
- computation of the intersections of interfaces to form a unitary wire frame;
- modification and reconstruction of the interfaces while treating the wire frame as a fixed constraint; and
- tracing of blocks enclosed by the interfaces and separation of each block into topologically connected tetrahedrons (Fig. 1).

There are two main differences between the SGM and the geometrical modeling tool of FLAC$^3$D:

(1) In SGM, all interfaces are simulated by interpolation computations based on sampling data, and each one is composed of topologically connected triangles; therefore, SGM is suitable for simulating complex geological interfaces.
(2) When a model is built by SGM, its wire frame is constructed through intersection computations between any two interfaces, and all interfaces are sewn together seamlessly along the wire frame.

The procedures of SGM involve the following:

(1) Refining and standardization of the sampling data.

In this paper, sampling data are used to interpolate geological interfaces. They are a series of spatial points located on geological interfaces and extracted from geological maps, borehole logs and other resources. All sampling data must be expressed as 3-D digital coordinates and recorded in text format.

(2) Simulation of unedited geological and engineering interfaces.

Simulation of interfaces is the first step to build a sealed geological model. An interface simulated at this step is called as an unedited interface because it will be modified at a later stage. The unedited interfaces involve geological and engineering interfaces and boundary surfaces. A geological interface can be normally simulated by interpolation methods, because its shape is generally controlled by sampling data from boreholes and geological maps. While, engineering interfaces and boundary surfaces, which are designed according to human purposes, can often be represented by parametric surfaces, such as planes and quadric surfaces. In addition, all the interfaces are triangulated in this paper.

(3) Construction of a unitary wire frame.

On a sealed geological model, the wire frame is composed of borderlines, including the intersections and boundaries of all the interfaces, and used to connect interfaces seamlessly and topologically. The main procedures to construct a unitary frame are:
computing intersections of any two interfaces, computing intersection points of any two borderlines, modifying the borderlines and dividing them into simple arcs. A simple arc is an oriented curve, comprised of orderly connected segments. Among all the nodes of one simple arc, only the start and end nodes can be shared with other arcs.

(4) Modification and reconstruction of interfaces.

After the wire frame is generated, the borderlines of all the interfaces are divided into simple arc sets. The changed borderlines of each interface form a new outline. The old triangles on an unedited interface cannot match the new outline anymore. Therefore, the old triangles must be deleted and reconstruct the interface according to the sampling data and the outline.

(5) Tracing of blocks.

After modification and reconstruction, each interface of a model is divided into a set of simple surfaces that have been newly re-triangulated. A simple surface is a continuous surface comprised of connected triangles. These simple surfaces are connected by simple arcs to ensure sealed connection among all interfaces of a model, and divide the model into a set of closed blocks. Using the block tracing algorithm, a series of blocks surrounded by corresponding simple surfaces can be obtained, and finally a sealed model can be created. These blocks are then connected by simple surfaces seamlessly.

(6) Generation of tetrahedral mesh in every block.

Each block is enclosed by several seamlessly connected simple surfaces, and each simple surface is composed of topologically connected triangles. Therefore, the boundary of a block is a closed triangulated surface. A tetrahedral mesh in each block can be generated using the Advancing Front Technique (AFT) [26] while treating the triangles on the block’s boundary as fixed constraints.

(7) Refining and optimization of tetrahedral mesh.

Refining and optimization of tetrahedral mesh of each block can improve the mesh quality. The Laplacian method [27] is used to optimize the mesh. Specially, if, in a model, there are some merging of two layers and thin layers, such as faults and inter-beds, the quality of mesh will be reduced greatly. The methods to optimize the tetrahedrons in the pinch-outs and thin layers are proposed in this paper.

3. Geological setting and data preparation

3.1. Geological setting

The SUOXI hydropower engineering project, located on the upper reaches of the SUO River, is a medium-sized water conservancy project for multifunctional utilizations including electricity generation, flood prevention and water supply. The dam site lies in a stream valley with the shape “U”, whose two sides are sharp and approximately symmetrical. On the dam area, the elevation of the riverbed is about 348 m and the width of the valley bottom is 36.8 m in general. The barrage, with the maximum height 81 m and arc length 192 m, is a hyperbolic arch dam made of concrete.

The dam site is situated in the southwest turning point of SANGUANSI pitching syncline. The bedrock in the dam area is mainly composed of medium thickness bedded argillous quartzose sandstone on the middle Devonian YUNTAIGUAN Fm stratum. There are four controlling faults approximately parallel to the river – F1 and F2 on the right bank and F7 and F8 on the left bank [28]. Two faults F3 and F4, situated on the upstream and the downstream of the dam respectively, are approximately perpendicular to the river. The fault fracture zones, about 1–3 m wide, generally filled with uncremented fault clay and cracked rock masses, affect the stability of the dam to a great extent. There are seven weak siliceous shale inter-beds in the dam area, that is, B1, B3, B5 and B7 on the left bank, and B2, B4 and B6 on the right. The thickness of each inter-bed is about 1–3 m. All inter-beds are likely to become sliding faces because of low shear strength, and may result in failure of the dam. Therefore, the faults and inter-beds are the key geological objects that will be simulated. The geological map of
the dam area at the elevation of 380 m is shown in Fig. 2, and its
typical geological section (I–I on Fig. 2) is shown in Fig. 3.

3.2. Data preparation

In this paper, 14 geological interfaces, including the boundaries
of faults and inter-beds, the terrain surface, and dividing surfaces
between different rock masses, are simulated by interpolation
method. The sampling data, used to interpolate these geological
interfaces, are extracted from five horizontal geological sections,
like the section in Fig. 2, at the elevations from 250 m to 450 m.
There is an intersection between one interface and one section.
Some points, expressed with 3-D coordinates, on each intersection
are extracted and treated as sampling data. The sampling data of
each interface are recorded in a text-format file.

4. Building a sealed geological model of the dam site area

4.1. Simulation of unedited interfaces

4.1.1. Geological interfaces

On the dam site, the interfaces of faults, inter-beds, strata, and
the terrain surface are main geological interfaces, and each of them
will be simulated by an interpolated surface composed of connected
triangles.

Simulation of interfaces of F1–F8 and B1–B7. After analyzing
the sampling data from the horizontal geological maps, it was
found that the feature of each of the interfaces of F1–F8 and B1–
B7 approximates to a plane. The following method, named as the
direct interpolation with dispersed data, can be used to simulate
these interfaces:

Step 1: Projecting the boundary of an interface on a given plane
to form a region enclosed by the projection of the boundary
(Fig. 4a).
Step 2: Triangulating the region to create a planar triangular
mesh, which is composed of topologically connected triangles
(Fig. 4b).
Step 3: Performing Kriging interpolation [29] based on the sam-
pling data to calculate the spatial coordinates of the nodes on
the triangular mesh to create a geological interface (Fig. 4c).

Each fault or inter-bed is not a surface but a thin layer filled
with a weak rock-mass. Therefore, it will be simulated by two par-
allel interfaces. Based on the above method, all the interfaces of F1–
F8 and B1–B7 are constructed by interpolated surfaces (Fig. 8).
Simulation of the terrain surface. Since there are several vertical scarps on both sides of the river, the terrain surface is much more complex than the interfaces of the faults and inter-beds on the dam site. If the terrain surface is simulated by the above approach, the triangular mesh quality must be quite low. For this reason, a dynamic interpolation based on DSI [4] and a mesh refinement method [30] are chosen here to produce this kind of interface. This method is introduced along with the construction of the terrain surface as follows:

Step 1: Construction of a crude terrain surface. Using the direct interpolation method mentioned above, first, the projection area of the terrain surface is triangulated; then spatial interpolation is applied to construct the crude interface $S$ (Fig. 5). Obviously, the triangles on the vertical scarps on both sides of the river are stretched and sharp-angled with low quality.

Step 2: Refining of triangles on the crude surface. Triangles in the areas with larger gradient on $S$ are elongated because of interpolation. In this paper, the recursive bisectional mesh refinement method [30] is adopted to adjust the triangles with low quality. First, for any triangle $T_i$ on $S$, if the length of any segment of $T_i$ is larger than a controlling value, which is determined by mesh densities, the midpoint of the segment is treated as a new node. Secondly, if new nodes are added to the segments of $T_i$, $T_i$ will be subdivided into 2, 3 or 4 new triangles according to the approach shown in Fig. 6. Then $T_i$ is deleted and the new triangles are added to the set of triangles. The above procedures are repeated until the length of any segment is shorter than the corresponding controlling value. Then a new interface $S'$ is created (Fig. 7a).

Step 3: Re-interpolation with the discrete smooth interpolation (DSI) method. After mesh refinement, the stretched triangles have been subdivided into several ones, so the quality of mesh has been improved. But mesh refinement cannot change the interface shape. An interface with closer to real shape can be obtained by redoing the DSI interpolation computation on the nodes of mesh. Normally, the sampling data are converted into constraints, named as Control-point Constraints, and added to the DSI equation. These constraints can be dynamically updated at each step of the iterative process. In this paper, the DSI equation is a quadratic function taking the spatial coordinates of all the mesh nodes as independent variables, including two parts: the global roughness and the degree of violation of linear constraints functions. The global roughness function is the sum of the local roughness functions defined at each mesh node. The local roughness function of any node $a$ is directly proportioned to the square of the difference between the estimated value of the spatial coordinate of $a$ and the average of the spatial coordinates of the nodes in the neighborhood of $a$. The smaller the global roughness function, the smoother the surface is. In DSI, each sampling data is expressed as a linear constraint. The

![Fig. 4. Procedures for simulating a geological interface with interpolation: (a) creating a projection plane of the interface; (b) generating triangular mesh on the projection plane; (c) performing interpolation computation to create an interpolated geological interface.](image1)

![Fig. 5. Crude terrain surface with stretched and sharp-angled triangles.](image2)

![Fig. 6. Means of adding midpoints on segments and subdivision of triangles.](image3)
degree of violation function of linear constraints reflects the consistency between interpolation results and sampling data, where the smaller the former, the more consistent the latter are. When the values of the DSI equation reach minimum, the spatial coordinates of mesh nodes are the interpolation results. More detailed information about DSI can be found in Mallet's paper [4].

Generally, the second and third steps must be executed circularly for several times until the terrain surface is closer to the real shape and has a higher quality mesh (Fig. 7b).

Additionally, the dividing surfaces between different rock-masses are also complex and can be simulated by the above method.

4.1.2. Interfaces of engineering structures and excavation

The shape and size of interfaces of engineering structures and excavations are designed by engineers. Therefore, this kind of interfaces can be simulated with parametric surfaces. The technique of simulating a parametric surface has already come to maturity, so it will not be introduced any more here. In order to connect engineering structures, excavation surfaces and geological objects seamlessly, all engineering objects are required to satisfy the following conditions: (a) each engineering object must have one closed outer boundary and zero or several inner boundaries satisfying the conditions of continuity and topological consistency; (b) interfaces of any other objects cannot be included in the interior of an engineering object; and (c) all engineering interfaces must be triangulated. Any engineering object, satisfying the above conditions, can be added to the model directly just as the geological objects.

All the unedited interfaces on the dam site are shown on Fig. 8a.

4.2. Construction of wire frame of geological model

The interfaces of the geological model must be seamlessly connected. Construction of a unitary wire frame is the key to build a sealed geological model. It includes two main procedures:

4.2.1. Computation of intersections of any two interfaces

From a mathematical perspective, it is easy to compute the intersection of any two triangulated surfaces. However, this often fails due to floating-point arithmetic. Intersections and boundaries are called as borderlines. The whole borderlines of a sealed model constitute a crude wire frame.

4.2.2. Modification of the borderlines and dividing them into simple arcs

For any two borderlines on the crude wire frame, there are three possible relationships: intersecting at some nodes, overlapping completely or partly, and un-attaching. The next step is to compute intersections of any two borderlines and divide them into simple arcs as follows: ① computing the intersection points of any two borderlines on the crude wire frame, and inserting them into the borderlines; ② merging nodes located on different borderlines, if they possess the same coordinates, and making sure every node is unique on the wire frame; and ③ dividing each borderline into orderly connected simple arcs, and making sure every simple arc is unique on the wire frame.

Using the above steps, a unitary wire frame was constructed as shown on Fig. 9a.
4.3. Modification and reconstruction of the unedited interfaces

The outline of every interface is one part of the wire frame of a model, and constructed while the wire frame is built. Every interface is divided into several parts by its outline (Fig. 9b). If some parts of one interface are redundant, we can select and delete them; then triangulate and interpolate the others to reconstruct a new interface. We introduced this method along with the construction of the interface of F4 as follows:

Step 1: Drawing the interface’s outline on a projection plane (Fig. 10a).
Step 2: Tracing closed loops based on the outline and dividing the interface into several parts (Fig. 10b).
Step 3: Deleting redundant parts of the interface based on the geological analysis to form a new outline (Fig. 10c).
Step 4: Re-triangulating the interface while treating the edited outline as a fixed constraint to form a new triangular mesh (Fig. 10d).
Step 5: Re-interpolating the new triangular mesh to form an edited interface.

By executing the above procedures on every interface of the model one by one, a new collection of edited interfaces was obtained (Fig. 8b).

4.4. Tracing of blocks

The next task is tracing of closed blocks surrounded by the edited interfaces. Actually, tracing a closed block is to search the triangles surrounding the block, because any edited interface is composed of triangles. In a sealed geological model, if a triangle is on the outer boundary of the model it will be shared by only one block; otherwise, it will be shared by two blocks. For convenience, in this paper, the positive and negative directions of a triangle are called as two half triangles. The minimum clockwise angle rule can be used for tracing blocks. This rule will be introduced here as shown in Fig. 11. Let e be a directed edge perpendicular to one plane $\Gamma$ at point $P$. $QP$ is the intersection between the current half-triangle and $\Gamma$. Except for the current half-triangle, e is shared by $n$ ones. $PL$, $PM$, ..., $PQ$ are the intersections between $\Gamma$ and these $n$ half-triangles. The clockwise angles between $QP$ and the intersection lines are $x_1$, $x_2$, ..., $x_n$, respectively. Of those, $x_1$ is the minimum, so the half-triangle on which $PL$ lies is the next half-triangle.

The block tracing algorithm is described briefly as follows:

1. Save all triangles in an array $T$ and create another empty array $B$ for storing blocks.
2. For each triangle on the outer boundary of a sealed model, set its properties $pUse = 0$ and $nUse = 1$. Set $pUse = 0$ and $nUse = 0$ for any other triangles. $pUse$ is a variable indicating...
if the positive side of one triangle has been selected as one boundary triangle of one block or not, while \( nUse \) indicates the negative side.

3) Select one triangle \( e \) from \( T \) and set one-half of \( e \) as the current base half-triangle; also set \( pUse = 1 \) or \( nUse = 1 \). Then, create a new block \( b \), save it in \( B \), and save one-half of \( e \) as a boundary triangle of \( b \) in the array \( t \), which is used to store all boundary triangles of \( b \). Remove \( e \) from \( T \) if its properties \( pUse \) and \( nUse \) are both equal to 1.

(4) Search the next half-triangle \( e' \) with the minimum clockwise angle rule, and add one-half of \( e' \) to the array \( t \) of block \( b \). Set its property \( pUse = 1 \) or \( nUse = 1 \).

(5) Delete the triangle with property \( pUse = 1 \) and \( nUse = 1 \) from \( T \).

(6) Repeat (4) until all the half-triangles adjacent to \( e \) have been found.

(7) Select another half-triangle from array \( t \), treat it as a new base half-triangle and execute (4)–(6) until block \( b \) has been closed.

(8) Delete all the half-triangles in \( t \).

(9) Repeat (3)–(8) until all the triangles in \( T \) are deleted.

Using the above algorithm, 130 blocks were found in the sealed model of the dam site. The sealed model is shown in Fig. 12a, and some separated blocks are shown in Fig. 12b.

5. Converting the geological model to tetrahedral mesh to use with FLAC3D

After tracing blocks, the model is divided into 130 closed and separated blocks. A tetrahedral mesh for the model was generated after dividing every block into topologically connected tetrahedrons by AFT while treating the boundary of the block as fixed

Fig. 11. The minimum clockwise angle between a triangle with others.

Fig. 12. (a) Sealed geological model of the dam site area; (b) separated blocks in the model.

Fig. 13. Tetrahedral mesh placed in FLAC3D.
constraints. The tetrahedral mesh is composed of 57,661 nodes and 215,471 tetrahedrons. These blocks are divided into six groups. The tetrahedrons in each group share the same physical and mechanical parameters, such as density, elastic modulus, and coherence. To improve the tetrahedral mesh quality, the Laplacian method is used to optimize the mesh. According to the data format of FLAC3D, the tetrahedral mesh is recorded in a text file and inserted into FLAC3D for computation (Fig. 13).

6. Conclusions

At present, almost all the numerical simulation software packages provide geometrical modeling tools. Most of them are rooted in the traditional CAD technique but not in the special geological modeling technique. Therefore, when modeling complex geological objects, users have to spend a great deal of time and do a lot of simplification frequently. The technique of 3-D geological modeling is a convincing and special tool for modeling complex geological realities, and already used to some extent for geological modeling and visualization in the fields of hydropower, mineral engineering, geophysics, geotechnics, etc. When this technique is used as the geometric modeling tool for numerical stress analysis software, the reliability of calculation results and the efficiency of modeling can be improved greatly.

The models for numerical stress analysis methods, such as the finite element and finite difference, must satisfy the conditions of geometrical continuity and topological consistency. This is the major difference between the models for finite elements/finite difference and those for discrete element. The numerical model built using this method for FLAC3D is geometrically continuous and all blocks and elements are topologically and continuously connected. In this paper, to model discontinuities, the fault is treated as a thin layer with thickness if the thickness of a fault is large; otherwise, the discontinuities can be simulated by the interface element in FLAC3D. However, the continuity between blocks is not required when building a model for 3DEC, which is a numerical stress analysis software package based on the discrete element method. To meet these requirements, a sealed geological modeling method is proposed in this paper for FLAC3D. The method includes five main procedures as follows: (1) simulation of unedited geological and engineering interfaces, (2) construction of the wire frame of the model, (3) modification and reconstruction of the interfaces, (4) tracing of blocks, and (5) generation of tetrahedral mesh.

As a case study, a sealed geological model is built to use in FLAC3D to investigate the stability of the dam and the bedrock of SUOXI hydropower engineering project in Hunan province, China. In the model, all complex geological objects, such as faults, interbeds, and the engineering objects are simulated and connected seamlessly.

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