



## ORIGINAL ARTICLE

# Simulation and Analysis of Fluid-Solid Coupling of Wave Impact Sandcastle Based on COMSOL

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**Abstract:** It is a complex problem to study the interaction between sand castle and flowing water, which needs to consider the complexity of seawater flow and the stress of sand castle structure. The authors use the fluid-solid coupling model to establish the connection between the fluid field and the structural mechanical field, and use the finite element analysis to complete the simulation modeling of the transient process of wave impact and sandcastle foundation deformation. This paper analyzes the stress and the first principal strain of the sand castle foundation in the direction of flow velocity when the sand castle foundation is hit by waves, as a method to judge the strength of the sand castle.

The best shape: the boundary value of sand castle collapse caused by strain have been determined, so as to obtain the maximum stress that a sand castle foundation can bear before collapse, which makes it possible to use the fatigue strength calculation theory of sand castle solid to carry out the quantitative calculation of sand castle durability. At the same time, the impact of waves is abstracted as wave motion equation. Finally, the finite element analysis technology is adopted to calculate the main strain of sandcastles of different shapes under the impact of the same wave, and through the comparison of the main strain, the authors get the sandcastle shape with the strongest anti-wave impact ability, which is the eccentric circular platform body.

Affected by rain: the authors considered the effect of rainwater infiltration on the sandcastle's stress, and simplified the process of rain as a continuous and uniform infiltration of rain into the sandcastle's surface. The rain changes the gravity of the sand on the castle's surface. Simulation analysis is adopted to calculate the surface stress of sand castle with different degree of water seepage and different geometry. By comparison, it has been found that the smooth cone is more able to withstand the infiltration of rain without collapse.

**Keywords:** Fluid-Solid Coupling; Finite Element Analysis; Variable-Stress Fatigue Strength Calculation; First Principal Strain

## 1. Introduction

### 1.1 Overview

Making sand castles is an important item of beach entertainment, anywhere in the world where there is a leisure beach, there seem to be children (and adults) building sandcastles on the coast. Sandcastles need to be cut and plastic based on a basic shape to produce beach masterpieces of different shapes. Because waves and rain water often rush up to damage the masterpiece, how can the sandcastle be more defensive?

This involves the modeling of the wave and sand pile model, the simulation of the erosion model and the feedback of the simulation results to the sand pile model for optimization. In the process of literature indexing, the authors found that few scholars studied this project in depth: although the treatment and flow of granular materials accounted for about 10% of the world's energy consumption, there are few quantitative studies on the mechanical properties of wet sand, only 2%<sup>[1]</sup>. The paper will introduce a series of general mathematical models that will model beach entertainment

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abstractly, and fill this theoretical gap through reliable physical principles and rigorous theoretical analysis.

## 1.2 Nomenclature

The list of terms used in this report is defined as follows.

Parameter	Meaning
u	The velocity at any point in the vertical section of the wave
h	The height of any point on the vertical section of the wave
w	Mass ratio of water to sand
$\sigma_i$	Stress on sand castle foundation
$N_i$	The maximum number of times a sandcastle foundation is subjected to stress
$n_i$	Sand castle foundation has been subjected to stress
E	Young's modulus
e	Void ratio

## 1.3 Simplifying assumptions

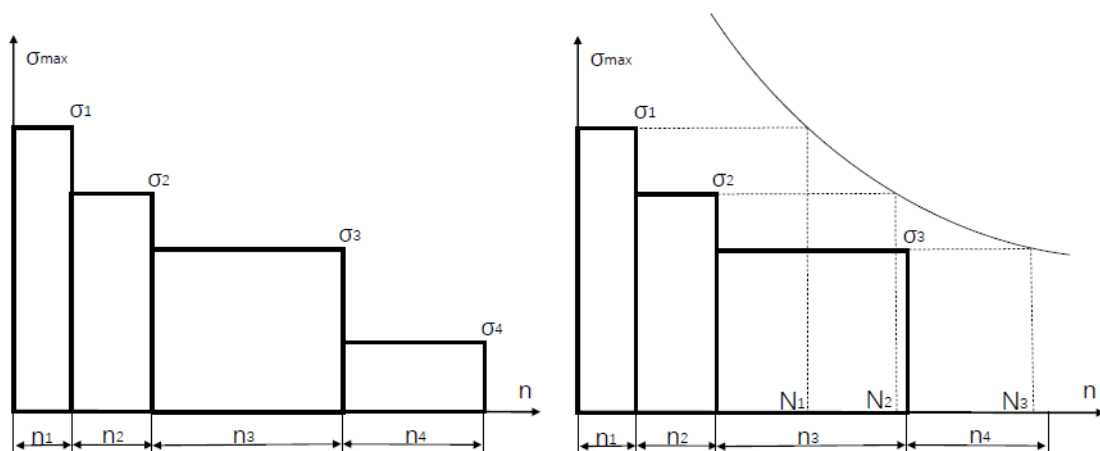
The accuracy of the model depends on some key simplified assumptions. These assumptions are as follows:

- (1) The near sea wave can be regarded as a stable laminar flow model.
- (2) When the waves hit the sand castle, they only hit the side of the sand castle, so the moisture on the surface of the sand castle can be ignored. When it rains, the water will seep into the sand castle, so it is necessary to consider the change in water content.
- (3) Under the action of gravity, sea water is considered to be an incompressible fluid.
- (4) In the process of rain, it is assumed that rain water falls on the surface of the sandcastle at a uniform speed.

## 2. Model theory

The wave impact can be regarded as the regular unstable variable stress, and the variation of the variable stress parameters has a simple rule. Miner's law, also known as fatigue damage accumulation hypothesis, was introduced to carry out mathematical modeling of the sand pile. The effect of the wave on the sand pile can be expressed by the stress of the wave on the sand pile. The diagram on the left of Figure 2 shows a regular unstable variable stress.

In the figure,  $\sigma_1, \sigma_2, \sigma_3, \dots$  is the stress of sand pile under the action of ocean waves.  $n_1, n_2, n_3, \dots$  is the number of times to bear the corresponding stress. In Figure 2, the curve at the top right of the right figure is the curve corresponding to the unstable variable stress and the maximum bearing times of the corresponding stress. When the wave applied stress is  $\sigma_1, \sigma_2, \sigma_3, \dots$ , the maximum number of sand pile bearing is  $N_1, N_2, N_3, \dots$ , then the damage of each impact to the sand pile is  $\frac{1}{N_1}$  false,  $\frac{1}{N_2}$  false,  $\frac{1}{N_3}$  ...



**Figure 2.** Schematic diagram of regularly unstable variable stress (left) and corresponding curve of maximum stress bearing times of unstable variable stress and corresponding stress (right).

When using sand  $\sigma_1$  the size of the stress waves strike  $n_1$  times, sand castle damage rate is:

$$\frac{1}{N_1} \times n_1 = \frac{n_1}{N_1}$$

Similarly, the sand pile is subjected to stress shock of  $\sigma_2, \sigma_3 \dots$  magnitude  $n_2, n_3 \dots$  times. The sum of these quantities is the total damage degree to the sand pile caused by waves. When the damage degree accumulates to 1, the sand pile will be damaged. This is Miner's law:

$$\sum_{i=1}^z \frac{n_i}{N_i} = 1 \quad (2-1)$$

In this formula,  $n_i$  is stress size for  $\sigma_i$  number of waves on the impact of sand. Choosing the actual data of the waves in a region, and after wave model transformation, the impact stress of sand castle model can be drawn at any time. The stress of sand size within a certain time  $\sigma_i$  and exert times  $n_i$  can be deduced. The wave statistics of every cycle time make it possible to achieve the real-time wave impact model sand. However, values of  $N_i$  vary along with different stress, with complex calculating process. Therefore,  $N_i$  is calculated by  $\sigma_i$  conversion based on material fatigue strength theory. According to the right curve in Figure 2 for the limited fatigue life stage  $\sigma$ - $N$  fatigue curve, and according to the linear fatigue curve formula:

$$\sigma^m \bullet N_i = C \quad (2-2)$$

Where  $C$  is a constant, and  $m$  is a material constant only related to the material properties. With the difference of the stress  $\sigma m$ , the exponential function curve uniquely corresponds to the allowable stress times  $N$ . Analogy to the sand pile model, each parameter is defined as the parameters of the sand pile model:  $\sigma m$  is the size of the sand pile under the impact stress of waves,  $N$  is the number of the sand pile under the corresponding stress condition, and  $m$  is related to the sand water content. Assume that when the stress is  $\sigma_0$ , the number of sand pile bearing impact is  $N_0$ . For different stresses  $\sigma_i$ , the maximum number of  $N_i$  that can bear this stress can be linked by formula 2-2:

$$N_0 \sigma_0^m = N_1 \sigma_1^m = N_2 \sigma_2^m = \dots = C \quad (2-3)$$

By combining equation 2-3 with equation 2-1 to eliminate  $N_1, N_2, N_3 \dots$ :

$$\frac{\sum_{i=1}^z n_i \sigma_i^m}{N_0 \sigma_0^m} = 1 \quad (2-4)$$

Where,  $m$  is a constant related to the water content of sand castle.  $\sigma_0$  is an arbitrary known wave stress, under which the maximum number of shocks the sand castle bears is  $N_0$ .  $n_i$  and  $\sigma_i$  are independent variables. As the simulation process goes on, the waves with the stress value of  $\sigma_i$  impact sand castle  $n_i$  times, and the sand castle fatigue degree is superimposed by the formula 2-4. As time accumulates, various simulated waves superposition the sand castle fatigue state to 1, the sand castle is destroyed.

## 2.1 Sandcastle foundation model

For the sand-pile model, the authors assume that the solid sandcastle foundation is linear elastic material, so the young's modulus of sandcastle foundation is the characteristic of its elastic deformation difficulty. The higher the young's modulus, the stronger the elastic deformation resistance of sand castle foundation. The following formula is used to calculate the young's modulus of sandcastle foundation for simulation.

$$G = \alpha \alpha \frac{1}{3} E \frac{2}{3} \gamma \frac{1}{3} \text{ false} \quad (2-5)$$

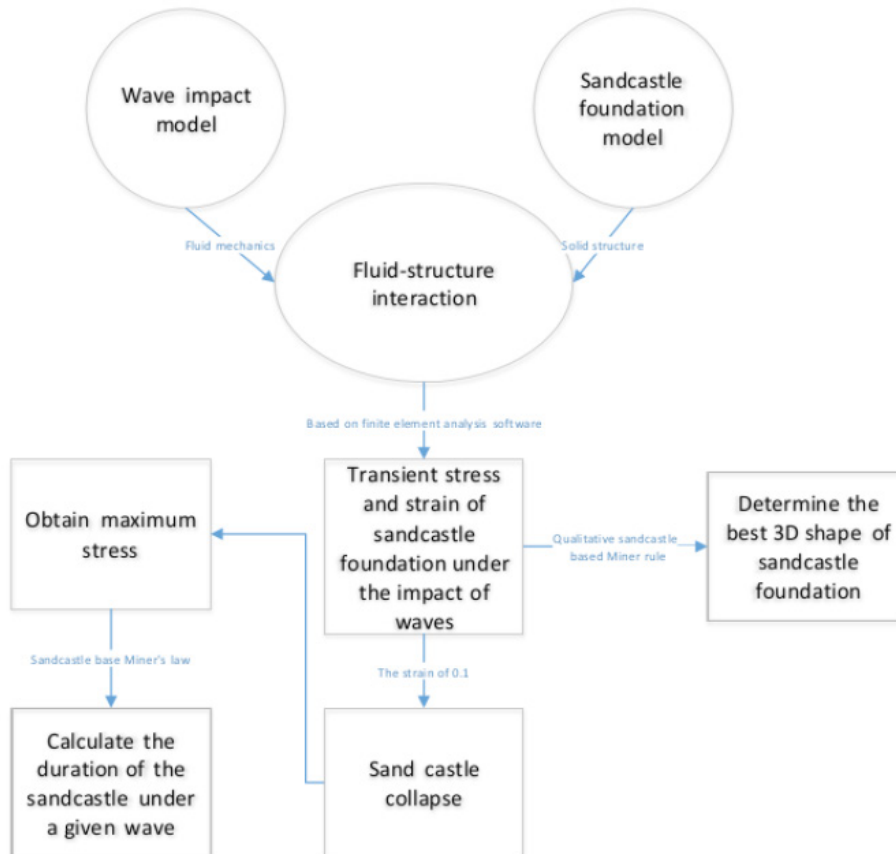
Where,  $a$  is the radius of the grain,  $E$  is the young's modulus of the grain material, and  $\gamma$  false is the surface tension of the liquid-gas interface,  $\alpha$  is the proportionality constant, which represents the amount of deformation of a single capillary sphere-ball bond relative to the strain applied to the whole<sup>[7]</sup>. In order to calculate the estimated value of  $\alpha$ , the authors take a simple cubic crystal with a frictionless ball and average it in different strain directions to obtain a value of  $\alpha$  ( $\alpha \approx 0.054$ ). The function  $f(Vf) \approx 1$  is used to determine the maximum strength;  $f(Vf)$  shows the dependence of the elastic modulus on the liquid volume fraction and is uniform for the optimal volume fraction.

The authors set a certain threshold for the first major strain of the sandcastle foundation. When the threshold is exceeded, it can be considered that the sandcastle collapses or its shape changes to no longer meet the requirements of maintaining its shape. Here, it is assumed that the gate value is 0.1, that is, the length of 100mm has been deformed by

10 mm in the direction of maximum stress.

## 2.2 Erosion simulation

In the fluid erosion simulation model, it is necessary to establish a relationship between the model of ocean wave and the model of sand pile through the knowledge of fluid dynamics. First, it needs to look at the interface of the model of ocean wave and the model of sand pile left to the model of erosion simulation.



**Figure 2.** Flow chart of wave impact simulation model.

Sand damage using Miner fatigue damage model transformation can be different in sizes. The same number of different stress is applied stress to establish a quantitative relationship of known size. Knowing the sand castle on the known size number under stress, a series of different stress to the size of the number can be obtained, so that sand model can be applied to complicated stress conditions according to environment.

Therefore, in the erosion simulation model, the wave velocity field should be converted into a force field; the sandpile model shows that it's only necessary to count the number of times it takes for a given magnitude of stress to destroy the sandcastle foundation.

Firstly, the conversion of wave velocity field to force field is realized. From the

hypothesis, seawater is an incompressible fluid under the action of gravity. A rectangular wave fluid boundary without slippage is assumed. The navier-stokes equation is adopted for momentum conservation and the continuity equation for mass conservation. To simulate the actual transient situation of the wave fluid hitting the coast:

$$\rho \frac{\partial \vec{u}_{fluid}}{\partial t} + \rho (\vec{u}_{fluid} \cdot \nabla) \vec{u}_{fluid} = \nabla \cdot [-\rho \vec{l} + \vec{K}] + \vec{F} \quad (2-6)$$

$$\rho \nabla (\vec{u}_{fluid}) = 0 \quad (2-7)$$

$$\vec{K} = \mu \left( \nabla \vec{u}_{fluid} + (\nabla \vec{u}_{fluid})^T \right) \quad (2-8)$$

Among them  $\mu$  is the dynamic viscosity of seawater, which describes the relationship between shear rate and shear stress in a fluid.  $\rho$  is the density of the sea; the physical interface defines the initial velocity field  $u$  and its components  $p$ ,

as well as the pressure; here the initial state is assumed to be 0.

The authors define the solid mechanical physical quantity of the 3D sandcastle foundation model, and calculate the transient unit displacement by using the stress and strain assumption of 3D linear elastic material, kinematic equation and structural model formula of solid material, and explore the stress and strain of sandcastle foundation under the influence of waves.

$$\rho \frac{\partial^2 \vec{u}_{fluid}}{\partial t^2} = \nabla \cdot \vec{S} + \vec{F}v \quad (2-9)$$

$$\vec{S} = \vec{S}_{ad} + \vec{C} : \varepsilon_{el}, \varepsilon_{el} = \varepsilon - \varepsilon_{inel} \quad (2-10)$$

$$\varepsilon_{inel} = \varepsilon_0 + \varepsilon_{ext} + \varepsilon_{th} + \varepsilon_{hs} + \varepsilon_{pl} + \varepsilon_{cr} + \varepsilon_{vp} \quad (2-11)$$

$$\vec{S}_{ad} = \vec{S}_0 + \vec{S}_{ext} + \vec{S}_q \quad (2-12)$$

$$\varepsilon = \frac{1}{2} \left[ (\nabla \vec{u}_{solid})^T + \nabla \vec{u}_{solid} \right] \quad (2-13)$$

$$\vec{C} = \vec{C}(E, \nu) \quad (2-14)$$

In order to describe the fluid flow and stress wave on the beach in the deformation process of the transient impact, the authors build castle facilities of fluid-solid coupling model of fluid dynamics and physical field coupling between solid laws of structural mechanics, by using the finite element method to simulate the fluid flow shock wave solid structure of sand castle foundation. Sand castle is on the basis of the stress and strain. This force can make sandcastles foundation structure deformation, which depends on the size of the fluid pressure, flow rate and the shape of the sand castle foundation, and the actual structure. An ocean wave is simulated with known parameters, continuously hitting the sandcastle foundation until the deformation of the sandcastle foundation reaches the threshold. At this point, it can be concluded that the sandcastle model is destroyed when the strain exceeds the threshold value. The amount of impact at this point was recorded, and the amount of  $N0\sigma m$  was calculated. It can also be figured out that how long the sandcastle base will last underwater.

Through type 2-4, according to the fatigue damage of sand castle, the size of the quantitative calculation of stress wave can be carried out. At the moment, any actual waves on the beach are included in the statistics of erosion model, to create the actual wave effect on the sand castle model, so that the problem of inconsistent between different sand waves and the best shape sandcastle can be solved. Because after the initialization of the erosion model, the most appropriate sandcastles basic shapes can be determined according to different wave on the beach. From the above model, it can be concluded qualitatively that under the impact of simulated waves with the same velocity, the greater the stress on the sandcastle foundation, the greater the impact fatigue strength on the sandcastle foundation of this shape. To quickly determine the best wave impact environment based on 3D shape of the sand castle, after simplifying the above model, the authors directly simulate the high speed strong shock waves. By making full use of the sand castle shape under the influence of the value of the first principal strain directly over the brake, and continuously adjusting based on the geometry of a sand castle, rules and optimal geometric shapes under stress condition can be obtained .

### 3. Model implementation and results

#### 3.1 Optimization of sandcastle foundation shape

In the shape optimization of sandcastle foundation, the simulated waves should be adopted to carry out impact simulation on sandcastle of different shapes. By comparing the bearing time of various sandcastle foundation shapes to the impact of simulated waves, a foundation shape with the highest strength is screened out.

As time changes, the waves from different angles, in different period, different initial height impact the sandpile. From Table 1, it can be seen that the temperature changes with the passage of time, and viscosity of NaCl in the sea changes with temperature and the waves. Taking the NaCl concentration of 2.8% of the water, the change value of the

Florida water viscosity can be obtained. In addition, the variation of seawater density with temperature is shown in Appendix B, and the density and viscosity of seawater are shown in Appendix A.

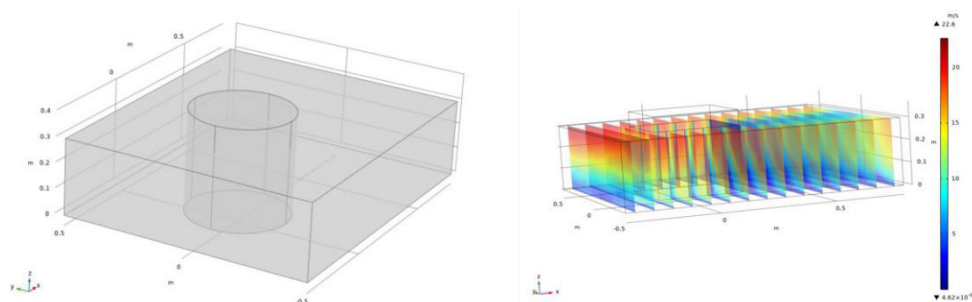
Density %	Temperature °C										
	-15	-10	-5	0	10	20	25	40	60	80	100
0.6	-	-	-	1.799	1.314	1.046	0.912	0.66	0.471	0.36	0.286
1.1	-	-	-	1.808	1.328	1.059	0.924	0.67	0.48	0.366	0.291
2.8	-	-	-	1.828	1.349	1.08	0.946	0.688	0.494	0.377	0.303
5.5	-	-	-	1.876	1.4	1.089	0.989	0.723	0.522	0.4	0.322
8.0	-	-	2.298	1.913	1.437	1.098	1.039	-	-	-	-
9.1	-	-	2.349	1.952	1.467	1.117	1.061	0.758	0.548	0.421	0.338
10.5	-	-	2.432	2.055	1.533	1.153	1.089	0.803	0.582	0.447	0.358
13.4	-	3.213	2.6	2.153	1.607	1.225	1.097	0.86	0.626	0.48	0.383
14.5	-	3.321	2.683	2.225	1.649	1.26	1.201	0.881	0.641	0.492	0.393
17.9	4.63	3.743	3.042	2.491	1.814	1.387	1.327	0.969	0.701	0.537	0.433
18.9	4.84	3.922	3.151	2.598	1.936	1.564	1.364	0.995	0.718	0.55	0.445
22.3	5.557	4.522	3.625	2.948	2.098	1.622	1.528	1.109	0.8	-	-
22.6	5.634	4.589	3.673	2.99	2.023	1.641	1.542	1.119	0.808	-	-
23.5	5.866	4.792	3.818	3.092	2.199	1.699	-	-	-	-	-
24.7	-	5.106	4.027	3.247	2.317	1.787	-	-	-	-	-
25.9	-	-	-	3.434	2.463	1.895	-	-	-	-	-
26.3	-	-	-	3.522	2.508	1.933	-	-	-	-	-

**Table 1.** The viscosity of NaCl solution, 10–3Pa.s

Similarly, the authors define a range of physical quantities for solids and assume that a solid sandcastle foundation with an optimal sand-water mixing ratio can be regarded as an isotropic linear elastic material. The density was  $2.6 \times 1000 \text{ kg/m}^3$ [1], the poisson's ratio was 0.3, and the young's modulus was  $5.9078 \times 106\text{pa}$ . In addition, it is assumed that the sandcastle foundation is only affected by its own gravity before being hit by waves, and there is no load, constraint or initial value. In order to study the stress change of sandcastle foundation under wave action, it is assumed that the bottom and foundation of sandcastle foundation are fixed constraints.

Assuming that solid sand castle foundation is linear elastic material, the young's modulus of sand castle foundation is the characteristic of its elastic deformation difficulty. The higher the young's modulus, the stronger the elastic deformation resistance of sandcastle foundation. The following formula is used to calculate the young's modulus of sandcastle foundation for simulation.

The authors built the sandcastle foundation with different 3D shapes. For the 3D shape of the non-rotating object, its direction is adjusted towards the waves. To simulate the same amount of sticky sand, the sand castle foundation has the same volume for all the shapes built. In order to simulate the equal distance between the sandcastle foundation and the coastline, the center of mass of all the sandcastle foundations built is equal to the fluid inlet. Obviously, since the sand castle has detailed sand sculptures, it will be damaged if it is hit from the sea. Therefore, the height of the sand castle foundation should be higher than that of the wave to reach the position. The simulation model is shown in Figure 3 (left), which is the sand castle foundation at the top of the fluid boundary.

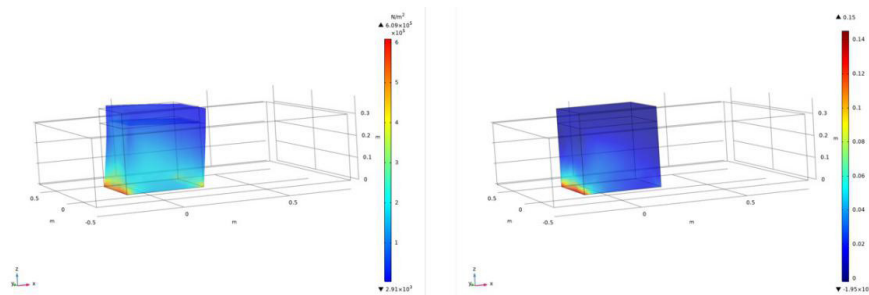


**Figure 3.** The finite element model configuration diagram and section velocity diagram of the wave impact simulation model at a certain time.

After the fluid-solid coupling simulation, the stress and strain of sand castle foundation in velocity direction are analyzed under the impact of strong wave. When the first principal strain reaches or exceeds 0.1, the collapse boundary caused by the sand castle strain is determined, so as to obtain the maximum stress that the sand castle foundation can bear before the collapse.

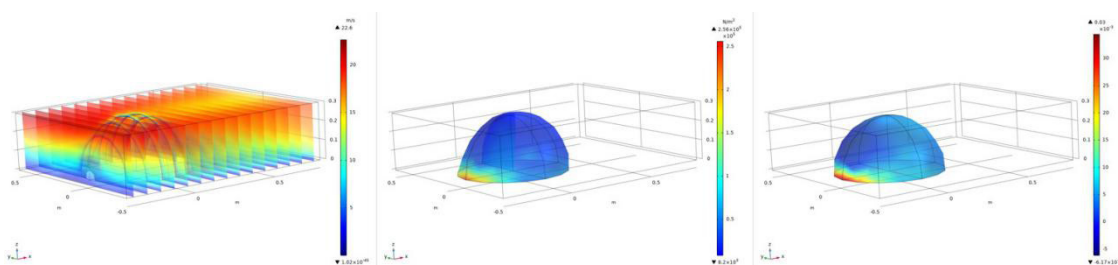


In order to quickly determine the 3D shape of sandcastle foundation to adapt to the impact environment of waves, the authors simplified the model on the basis of the above, and directly simulated the high-speed waves with strong impact force through the wave erosion simulation model. Under its impact, the first principal strain of most shabbits may directly exceed the gate value. According to the fatigue damage accumulation hypothesis model, under the impact of simulated waves with the same velocity, the smaller the stress on the sandcastle foundation, the stronger the impact fatigue resistance of the sandcastle foundation of this shape, and the stronger the durability under the impact of waves. The specific fitting results are shown in Figure 4 (right), which shows the simulation results of strong wave impacting sandcastle foundation. The figure shows the speed of each section at a given time.

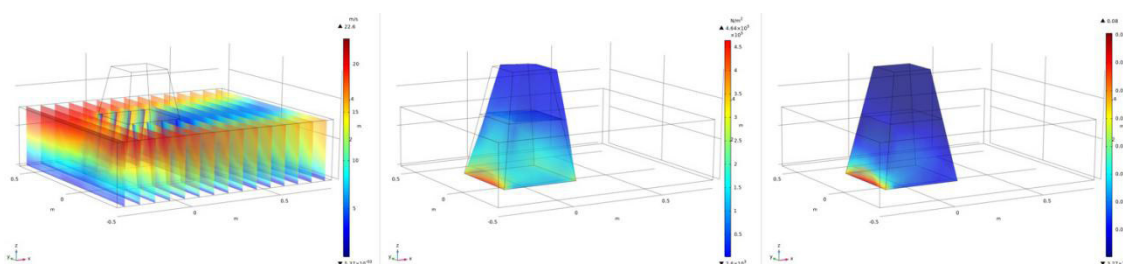


**Figure 4.** Stress maps (left) and strain maps (right) of the cubic wave impact simulation model.

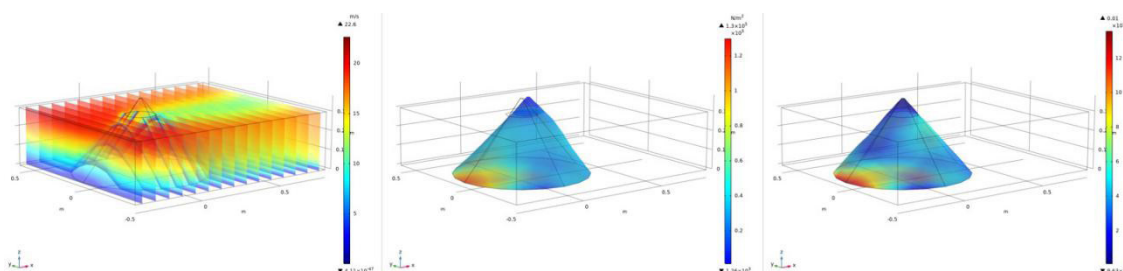
According to the analysis on Figure 4, the maximum stress of the cubic sand castle foundation under the impact condition is as high as 600 Kpa, while the stress of the sand castle foundation is mainly concentrated in the region of the fixed constraint end close to and facing the ground. The regional value of the first normal stress generated by the cubic sand castle is 0.14, which has exceeded the value of the collapse gate of the sand castle foundation. It is believed that sandcastles of this shape will be destroyed.



**Figure 5.** Wave impact velocity diagram (left), stress diagram (middle) and strain diagram of the semi-circular sandcastle foundation shape (right).

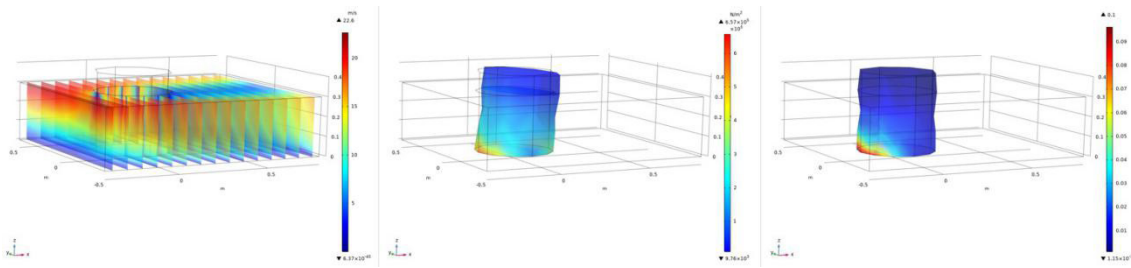


**Figure 6.** Wave impact velocity diagram (left), stress diagram (middle) and strain diagram (right) of the pyramid-shaped sand castle foundation shape.



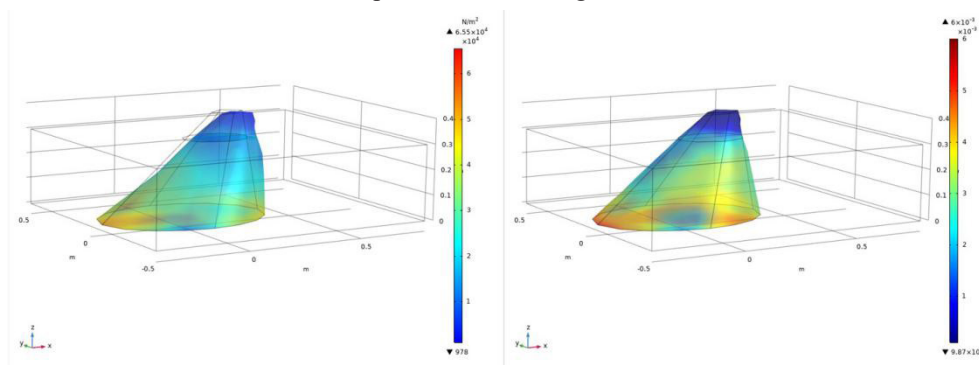
**Figure 7.** Wave impact velocity diagram (left), stress diagram (middle) and strain diagram (right) of the cylindrical sandcastle foundation shape.

sandcastle foundation shape.



**Figure 8.** Wave impact velocity diagram (left), stress diagram (middle) and strain diagram (right) of the conical sandcastle foundation shape.

As shown in Figure 5-8, to explore the more three-dimensional shape of the sand castle on the persistence of the cone frustum of a cone of fort foundation only 20 kpa, the maximum stress is 0.03; the first maximum principal strain is far less than the maximum stress and strain of the cube. Conical frustum body sandcastles can withstand bigger limit stress value, stronger than the durability of cubic sand castle foundation, with stronger wave impact resistance. According to shadow reverberation law, the authors carried out more simulation similar to the square wave impact under the same strong shock wave action. By comparing the stress and strain diagrams of various sand castle foundation shapes under the wave impact simulation, it has been found that the shape most suitable for sand castle foundation is the eccentric platform. Its stress and strain under the wave impact is shown in Figure 9.



**Figure 9.** Wave impact stress maps (left) and strain maps (right), most suitable foundation shapes for sandcastle (eccentric circles)

### 3.2 Shape optimization under rain conditions

Unlike the wave impact, the effect of rain on the sandcastle foundation is slow. In the wave impact model, ignoring the penetration of seawater on the sandcastle foundation, the long-term rain infiltration leads to the gradual infiltration of rainwater, changing the physical properties of the fort.

For the infiltration process of rainwater, since the rainwater will form a water film on the sandcastle foundation surface, the rainwater that can penetrate into the sandcastle is sufficient. The rainwater infiltration can be considered to be continuous and flow to the sand in the form of laminar into the fort foundation. Based on the premise of continuous infiltration and laminar flow infiltration, Darcy's law is introduced, which refers to the linear relationship between the water penetration rate in sand and the hydraulic gradient:

$$v = \frac{q}{A} = k\Delta h / L = ki \quad (3-1)$$

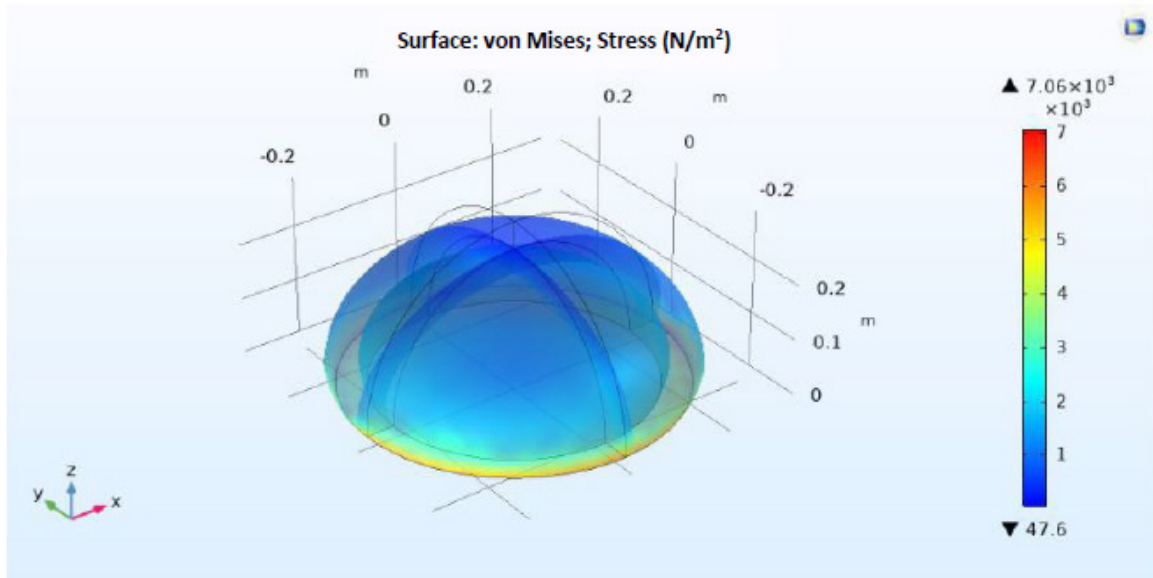
Among them, the ratio coefficient of k indicating soil permeability is called permeability coefficient, q is the permeation amount per unit time, v is the penetration rate, i is the hydraulic gradient. Darcy's law shows that under laminar flow conditions, the seepage velocity of water in soil is proportional to the hydraulic gradient and is related to the type of map.

In this model, the sandcastle foundation is divided into upper and lower parts. The upper part is the seepage part and the lower part is the non-seepage part. The boundary between the two parts moves uniformly downward according to Darcy's law. As the weight of the seepage part changes, and the rain gradually advances below the sandcastle foundation, the stress at the bottom of the sandcastle foundation gradually increases. The same materials can bear the



same stress, the stress conditions of the sand castle foundations can be judged which is of the same size and under the same size of rainwater after the same time.

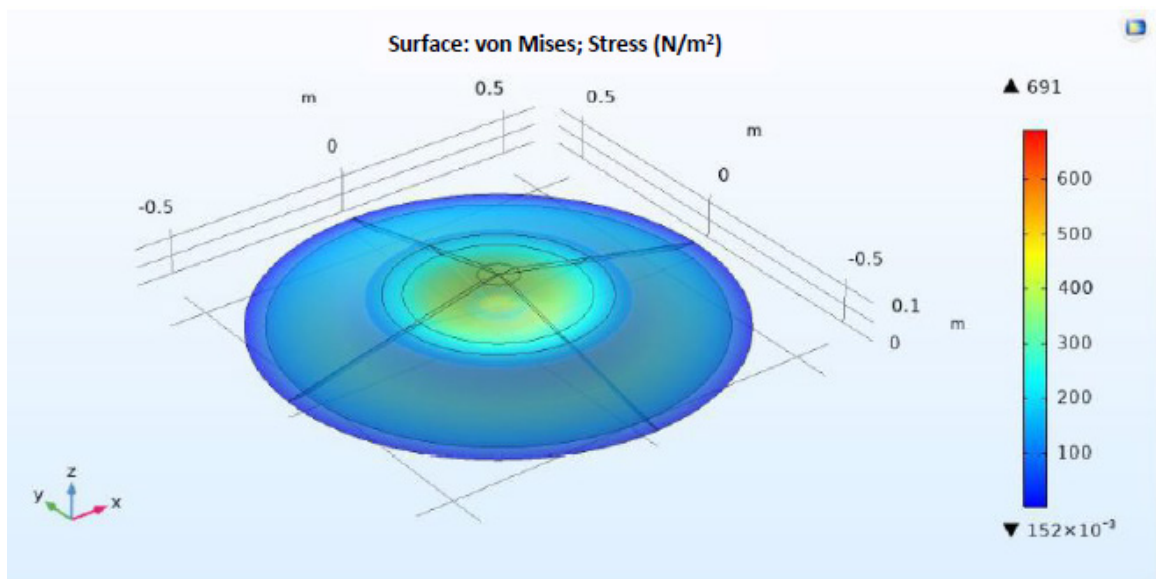
Equation 3-1 is introduced into the model established in Section 2.2. First, for the hemispheric sandcastle foundation, after 20 s of uniform rainfall simulation, the stress of the entire hemispheric sandcastle foundation is shown in Figure 10.



**Figure 10.** Surface stress diagram of hemispheric sandcastle foundation during 20 s of uniform rainfall simulation.

Figure 10 shows the surface stress field of the hemisphere after 20 s of rain penetration. The color indicates the magnitude of the stress intensity. It is obvious that the bottom stress of the courseware hemisphere sandcastle foundation has reached more than  $6 \times 10^3 \text{N/m}^2$  and there are serious stress concentration phenomenon.

Then the authors use the same volume of sand to build sandcastle foundations in different shapes, and also use 20 s uniform rainfall simulation to compare the surface stress of the entire sandcastle foundation. By repeatedly changing the three-dimensional shape of the sandcastle foundation model, a sandcastle foundation with a round table shape is established. After 20 s of uniform rainfall simulation, the surface stress of the sandcastle foundation with round table is shown in Figure 11.



**Figure 11.** Surface stress diagram of the round platform sandcastle foundation during 20 s simulation of uniform rainfall.

Observe the force applied on the surface in Figure 11. First, the stress distribution is uniform, and no stress concentration is formed at the edge or the middle. At the same time, the maximum stress does not exceed  $4 \times 10^3 \text{N/}$

m2. Based on the simulation of a large number of three-dimensional sandcastle foundation models, the authors finally concluded that the sandcastle foundation in the shape of a round platform is more conducive to carrying the additional stress load formed by the penetration of rainwater.

### 3.3 More strategies

#### 3.3.1 Shock weakening of near-shore waves based on seawater diversion

For weakening the impact of near-shore currents, a more direct method can be adopted except for the speed bump around the sandcastle foundation. Referring to the form of the moat, drainage links are added on the basis of the moat to achieve the effect of seawater diversion. Before the near-shore waves touch the sandcastle foundation, the sea water will fall into the moat in advance, so it will not impact the sandcastle foundation. When the seawater fades, the seawater in the moat will flow into the sea along the diversion channel, and the entire moat will be emptied, waiting for the next seawater impact.

Similarly, the foundation shape of the excavated moat is put into the wave simulation impact model. The simulation results are shown in Figure 13. The image on the left shows the surface stress of a sand pile foundation shape without a moat. It can be seen from the figure that the maximum stress is higher than  $1.6 \times 10^5 \text{N/m}^2$ . The picture on the right shows the surface stress on the shape of the sand pile foundation with moat. At this time, the maximum stress value is lower than  $1.15 \times 10^5 \text{N/m}^2$ . By comparing the maximum stress value, the moat has a good blocking effect on the waves.

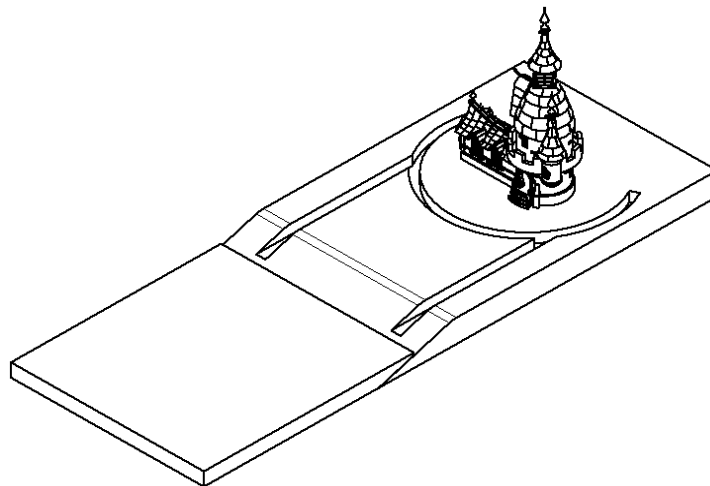


Figure 12. Weakening of near-shore wave impact based on seawater diversion.

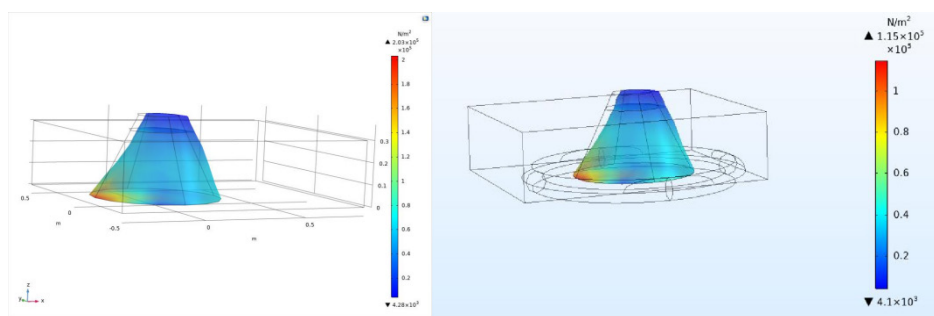


Figure 13. Offshore wave impact based on sea water flow is weakened.

#### 3.3.2 Weakening the speed of near-shore waves based on changing the roughness of the beach

After the near-shore wave surges onto the beach, under the gentle conditions of the beach, the flow of seawater is regarded as a laminar flow; in the new model, the beach around the sandcastle foundation can be dug into a shape similar to a speed bump. The flow is more likely to enter a turbulent state, with greater head loss to weaken the impact of the near-shore waves on the sandcastle foundation.

## 4. Final remarks

## 4.1 Conclusions

According to the authors' study, sandcastles are strongest at very low sand-water volume mixing scores of about 0.8%. In order to protect the sand castle, it is necessary to ensure that the sand castle foundation has a certain height to withstand the impact of waves. With the same amount of sand, the sand castle foundation with the circular body or eccentric circular head can usually withstand greater impact force and is more resistant to continuous impact. Making the slope of the eccentric platform facing the sea as smooth as possible (as shown in the figure) is the key to effectively resist the impact of waves. Rain will seep into the sand, making the sand on the upper surface of the fort heavier, which often causes the fort to collapse like a glacier. The best solution is to build the sandcastle into a flat cone. This will allow the sandcastle to better spread the weight of gravity to the ground as it becomes heavier under the influence of rain. More importantly, in order to prevent the sand castle from collapsing due to its weight, it is necessary to reduce the height of the sand castle foundation.



**Figure 14.** The shape model which is most suitable for sand castle foundation under the simulation results of nearshore wave erosion model.

Proper use of wire, stone, or other materials as support for sand castles can increase their strength. It is also a good idea to dig a canal in front of the castle.

## 4.2 Future model development

(1) In this paper, the wave velocity equation is used to model the impact of waves. However, air is also involved in the erosion of sandcastle by real waves. In the authors' model, the equation of air flow can be added to model the impact of waves in a more real way.

(2) In the model, the shape of sand castle is considered by enumerating the common geometric shapes. An optimization equation can be established for the shape of sand castle and nonlinear programming is adopted to obtain a theoretical optimal solution.

(3) More precise stress and strain solutions can be obtained by further refining the finite element mesh

(4) Considering that the sand castle foundation provides an effective space for the creation of sand sculptures, the best sand castle foundation shape is obtained by combining the creation space of waves, rain and sand sculptures.

(5) The sandcastle foundation Miner rule model can be further improved to calculate more accurate persistence time.

Appendix A: Sea breeze density and viscosity values at different temperatures

Celsius °C	D	ensity $\text{K g/m}^3$	Dynamic viscosity $10^{-5} \text{ P a} \cdot \text{s}$
-20		1.395	1.60788
-10		1.342	1.65988
0		1.293	1.711
10		1.247	1.76128
20		1.205	1.81074

30	1.165	1.85942
40	1.128	1.90735
50	1.093	1.95455
60	1.06	2.00105
70	1.029	2.04688
80	1	2.09205
90	0.972	2.13659

Appendix B: Density of seawater at different temperatures and concentrations

Density %	Temperature °C									
	0	10	20	25	30	40	50	60	80	100
1	1.00747	1.00707	1.00534	1.00409	1.00261	0.99908	0.99482	0.99	0.9785	0.9651
2	1.01509	1.01442	1.01246	1.01112	1.00957	1.00593	1.00161	0.9967	0.9852	0.9719
4	1.03038	1.0292	1.0268	1.0253	1.02361	1.01977	1.01531	1.0103	0.9988	0.9855
6	1.04575	1.04408	1.04127	1.03963	1.03781	1.03378	1.02919	1.0241	1.0125	0.9994
8	1.06121	1.05907	1.05589	1.05412	1.05219	1.04798	1.04326	1.0381	1.0264	1.0134
10	1.07677	1.07419	1.07068	1.06879	1.06676	1.06238	1.05753	1.0523	1.0406	1.0276
12	1.09244	1.08946	1.08566	1.08365	1.08153	1.07699	1.07202	1.0667	1.0549	1.042
14	1.10824	1.10491	1.10085	1.09872	1.09651	1.09182	1.08674	1.0813	1.0694	1.0565
16	1.12419	1.12056	1.11621	1.11401	1.11171	1.10688	1.1017	1.0962	1.0842	1.0713
18	1.14031	1.13643	1.1319	1.12954	1.12715	1.12218	1.11691	1.1113	1.0993	1.0864
20	1.15683	1.15254	1.14799	1.14533	1.14285	1.13774	1.13238	1.1268	1.1146	1.1017
22	1.17318	1.16891	1.16395	1.1614	1.15883	1.15358	1.14812	1.1425	1.1303	1.1172
24	1.18999	1.18557	1.1804	1.17776	1.17511	1.16971	1.16414	1.1584	1.1463	1.1331
26	1.20709	1.20254	1.19717	1.19443	1.1917	1.18614	1.18045	1.1747	1.1626	1.1492

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