ABSTRACT: During the exploration of hydrates or oil and gas exploitation through the hydrate layer, heat transfer causes hydrates to decompose. The gas and water generated by this decomposition increase the pressure of the gas in the decomposition zone, resulting in excessive pore pressure. The seepage of gas and water and the decomposition of hydrates lead to soil deformation, which may be caused by soil softening. This may lead to geological disasters, such as ocean landslides, seabed subsidence, and even gas explosions. The natural phenomena of soil eruption caused by hydrate decomposition currently include Siberian pits and Bermuda craters. From these two natural phenomena, climate change is considered to affect hydrate decomposition, causing ocean acidification and dissolved oxygen consumption, which may have more serious consequences than global warming alone. Therefore, it is extremely important to study how hydrate decomposition causes soil to erupt and release gas into the ocean and the atmosphere. This paper is primarily based on on-site data collected from the Siberian pit in the case of hydrate decomposition resulting in increased pore pressure, resulting in soil eruption. The relationship between the thickness of the upper cladding layer, the pressure causing the destruction of the upper cladding layer, and the destruction length of the upper cladding layer was obtained through numerical simulation.

1. INTRODUCTION
Energy, particularly oil and gas energy, is the material basis of human activities that powers the continuous progress of human society. As society develops and oil and gas energy consumption continues to increase, humans will face a serious shortage of oil and gas resources by the end of the 21st century. Natural gas hydrate (short for hydrate) is a natural gas energy carrier. It is widely distributed in the deep-water formation environment of the ocean and lakes and the high-latitude polar frozen soil environment. It exhibits good exploitation prospects and broad development scope.1–5 China is accelerating the exploration and exploitation of deep-sea oil and gas fields and has reported plans for the exploration and development of hydrates. Both the exploration and exploitation of deep-sea oil and gas fields or the development of hydrates will lead to decomposition in hydrate deposits.6 During the decomposition process, due to the low permeability of some deposits, the gas and water decomposed slowly migrate and flow, which will inevitably produce superstatic pore pressure, and the stress in the hydrate deposits will be redistributed, causing the skeleton to become deformed. When the stress reaches the destruction value of the sediment strength, the hydrate sediment layer will be destroyed.7–10 It may eventually evolve into seabed uplift, facilitate the rapid development of fissures in the sedimentary layer, or overburden, resulting in the overturning of the overlying layer of the hydrate sediment layer or large areas of gas protrusion. This can further lead to gas spurs. These processes will destroy deep-sea platforms, oil and gas pipelines, submarine cables, and other subsea engineering facilities as well as potentially cause huge ecological disasters, such as the destruction of marine ecological environments.11–15
In July 2014, a giant crater with a length of 80 m and bottomless depth was discovered on the Yamal Peninsula in Siberia, Russia. There are currently seven huge pits, plus dozens of smaller pillar pits, as shown in Figure 1. Scientists found that the edge of the pit was black, appearing as though it was caused by violent burning. It is now preliminarily determined that due to global warming, underground methane gas will decompose and accumulate to the point of explosion. In March 2016, a large number of submarine potholes were found in the Barents Sea in Northern Europe. The maximum diameter of the pothole is 800 m and the depth is 45 m, and it was formed after Norwegian methane gas accumulated and exploded (Figure 1). Nixon and Grozic conducted a theoretical analysis of this phenomenon.11 When hydrate decomposes...
under external environmental pressures, water and methane gas are released. When soil permeability around the hydrate deposit is low, excess water and gas will accumulate because there is no release path. Hydrate decomposition will also reduce the effective stress of the soil and its strength, increasing the probability of gas eruption.

Zhang et al. performed laboratory simulations on the spray pattern produced by hydrate decomposition. In the laboratory, the heating rod was placed in the center of the hydrate deposit. The hydrate gradually decomposed outward in a circular diffusion state, and the soil above the hydrate deposit exhibited low permeability and high intensity. When the decomposed gas accumulated to a certain degree, the pore pressure continued to increase, squeezing the upper soil layer and causing eruption failure. This analysis demonstrated that climate change will affect hydrate decomposition, causing ocean acidification and dissolved oxygen consumption, which may have more serious consequences than the effects of global warming alone.

Therefore, it is extremely important to study the problem of soil eruption and gas release into the ocean and the atmosphere following hydrate decomposition. The study of eruption caused by hydrate decomposition in the hydrate sediment layer is one of the most important issues in assessing and predicting the safe operation and effective development of hydrate energy in the deep sea.

In this study, a dimensional analysis of this phenomenon was first conducted to determine the control parameters that affect the deformation and destruction of formations caused by hydrate decomposition, establish a numerical model, and verify the model accuracy by conducting small-scale laboratory tests. Based on on-site geological data obtained from the giant pit in the Bermuda seabed, the relationship between the thickness of the overburden, the pressure causing the overburden damage, and the extent of the overburden damage was studied.

2. EXPERIMENTAL INVOLVEMENT

The experimental setup is shown in Figure 2.

The experimental device was a cylindrical iron drum with a diameter of 40 cm and a height of 30 cm. A sealed elastic gas container, pressure gauge, and photographing instrument were used to measure and photograph the entire destruction process of the upper cladding.

First, the samples were prepared. The gas-collecting container was arranged at the bottom of the cylinder, and the gas was filled with 0.1 MPa until the diameter of the container was 6 cm. The aeration was then stopped. The simulated hydrate decomposition diameter was 6 cm. The soil was composed of sand with a density of 1600 kg/m³, the moisture content was 6.8%, and the wet density of the soil was 1700 kg/m³. It is currently speculated that the giant crater in Bermuda is caused by gas eruption. The soil mechanical parameters were measured based on the field data of the Bermuda crater. The soil was placed into the cylinder as four layers: the first three layers were 5 cm thick, and the final layer was 2 cm thick. Each layer of soil was compacted upon filling.

The gas-collecting device was a sphere with good elasticity. First, the elastic sphere was placed on the bottom of the cylinder. The cylinder was filled with sand, and the sphere was filled with gas, maintaining a pressure of 0.1 MPa. Gas was released into the sphere until the overlying layer broke, after which inflation was terminated. The simulation indicated that after the hydrate decomposed, the surrounding soil has poor permeability, which causes the generated gas to continuously gather. When gas accumulates to a certain degree, the overlying layer undergoes eruptive destruction.

3. NUMERICAL SIMULATIONS

3.1. Laboratory Numerical Simulation. The model in Figure 3 was established based on laboratory experiments.

Because this study investigated the eruption of the soil following hydrate decomposition and the parameters are all isotropic parameters, a three-dimensional model was used. However, the findings reported by Zhang et al. indicate that the shape of the soil damage basically follows an axisymmetric model; thus, in order to simplify the calculation, the model was regarded as a plane model. The width was set to 1 cm.

According to the indoor experiment, a 1:1 model was established with a model length of 40 cm. An initial ground level was set. The boundary of the model was fixed at both ends, and lateral displacement was restricted. The bottom was fixed at normal, the upper surface was free, and a rectangle with a length of 6 cm and a height of 6 cm was established in the center of the model base to simulate the hydrate decomposition zone, as shown in Figure 4. Because the model was small, the calculation grid was densely divided. The grid
lengths of the hydrate decomposition zone and the undecomposed zone are 1 cm each, while the grid length of the overlying layer is 2 cm. There are 380 grids in total. The mechanical parameters of the soil are as follows: The overlying layer is 2 cm. There are 380 grids in total. The stress and strain descriptions mainly use Euler strain, and \( \sigma_{ij} \) is the stress per unit area defined in the current configuration.

The updated Lagrangian algorithm is mainly used in LS-DYNA. It uses the configuration when calculating all variables in the current configuration. In the formula, \( w_{\text{int}} \) is the internal energy per unit mass. Equation 5 can be derived as follows:

\[
\frac{D}{Dt} \int_V \left( \rho w_{\text{int}} + \frac{1}{2} \rho \dot{v} \dot{v} \right) dV = \int_V v \rho b_d dV + \int_A v t dA
\]

(5)

In the formula, \( w_{\text{int}} \) is the internal energy per unit mass.

Equation 5 can be derived as follows:

\[
\begin{align*}
\rho \frac{Dw_{\text{int}}}{Dt} &= \sigma_{ij} \dot{e}_{ij} \\
\rho_b \frac{Dw_{\text{int}}}{Dt} &= \Sigma \dot{e}_{ij} = \sum_{ij} \frac{d(\partial u_i/\partial X_j)}{dt} \\
\rho_b \frac{Dw_{\text{int}}}{Dt} &= S_{ij} \dot{e}_{ij}
\end{align*}
\]

(6)

where \( D_{ij} \) is the deformation rate, \( S_{ij} \) is Kirchhoff stress, \( E_{ij} \) is Green strain, and \( \sigma_{ij} \) is the stress per unit area defined in the current configuration.

3.2. Numerical Method. LS-DYNA uses the updated Lagrangian algorithm and the state equation to simulate the relationship between pressure and volume in the explosion process.

(1) Mass conservation equation:

The equation of conservation of mass per unit volume described by Lagrange is

\[
\rho(X, t)f(X, t) = \rho_0(X)
\]

(7)

where \( t \) is time and \( X \) is the particle vector diameter.

(2) Momentum conservation equation:

The momentum theorem states that the material derivative of the momentum of a body is equal to the sum of the external forces acting on the system, namely,

\[
\frac{D}{Dt} \int_V \rho \dot{v} dV = \int_V \rho \dot{b} dV + \int_A t dA
\]

(2)

where \( b \) is the force acting on the unit mass of the object, \( t \) is the surface force, and \( x \) is the position of the particle moving with time. From the above formula, the differential equation of motion of the object in the current configuration can be derived as

\[
\rho \frac{D\dot{v}}{Dt} - \rho \dot{b} = \frac{\partial \sigma_{ij}}{\partial x_j} = 0
\]

(3)

The differential equation of motion of the object in the initial configuration is

\[
\rho_0 \frac{\partial \dot{v}}{\partial t} = \rho_0 \dot{b} + \frac{\partial \Sigma_{ij}}{\partial X_j} = 0
\]

(4)

where \( x \) is the space coordinate, \( v \) is the instantaneous speed, and \( X_j \) is the component of the particle vector diameter \( X \) in the reference configuration, which can be called the material coordinate.

3 Energy conservation equation:

Regardless of the heat exchange and heat source, the rate of change of the total energy of the system is equal to the power of the external force, namely,

\[
\frac{D}{Dt} \int_V \left( \rho w_{\text{int}} + \frac{1}{2} \rho \dot{v} \dot{v} \right) dV = \int_V v \rho b_d dV + \int_A v t dA
\]

(5)

In the formula, \( w_{\text{int}} \) is the internal energy per unit mass. Equation 5 can be derived as follows:

\[
\begin{align*}
\rho \frac{Dw_{\text{int}}}{Dt} &= \sigma_{ij} \dot{e}_{ij} \\
\rho_b \frac{Dw_{\text{int}}}{Dt} &= \Sigma \dot{e}_{ij} = \sum_{ij} \frac{d(\partial u_i/\partial X_j)}{dt} \\
\rho_b \frac{Dw_{\text{int}}}{Dt} &= S_{ij} \dot{e}_{ij}
\end{align*}
\]

(6)

where \( D_{ij} \) is the deformation rate, \( S_{ij} \) is Kirchhoff stress, \( E_{ij} \) is Green strain, and \( \sigma_{ij} \) is the stress per unit area defined in the current configuration.

The updated Lagrangian algorithm is mainly used in LS-DYNA. It uses the configuration at time \( [t, t + \Delta t] \) as the reference configuration when calculating all variables in the interval \( t \). The stress and strain descriptions mainly use Euler stress \( \sigma_{ij} \) and the infinitely small strain \( e_{ij} \) on the current configuration.

The governing equations of the updated Lagrangian algorithm are as follows:

Conservation of mass:

\[
\rho(X, t)f(X, t) = \rho_0(X)
\]

Conservation of momentum:

\[
\frac{\partial \sigma_{ij}}{\partial x_j} + \rho \dot{b}_i = \rho \ddot{u}_i
\]

Conservation of energy:

\[
\rho w_{\text{int}} = D_{ij} \sigma_{ij}
\]

Deformation rate:

\[
D_{ij} = \frac{1}{2} \left( \frac{\partial \dot{v}_j}{\partial x_i} + \frac{\partial \dot{v}_i}{\partial x_j} \right)
\]

Constitutive relationship:

\[
\sigma = \sigma(D_{ij}, \sigma_{ij}, \ldots)
\]

Boundary conditions:

\[
\begin{align*}
(s_0 \sigma_{ij})|_{A_i} &= t_j \\
v_j|_{A_i} &= v_i
\end{align*}
\]

Initial conditions:

\[
\begin{align*}
\frac{\partial (s_0 \sigma_{ij})}{\partial t} &= \dot{u}_0(X) \sigma(X, 0) = \sigma_0(X) \\
or \\
\dot{s}_0(X, 0) &= s_0(X) u(X, 0) = u_0(X)
\end{align*}
\]

3.3. Geometrical Model. The main simulation was conducted for the Bermuda crater. According to the obtained on-site geological data, the thickness of the overlying layer is 46 m. According to the actual situation, the decomposition model was designed.
radius of the hydrate is set between 10 and 60 m. The influence of the thickness of the overlying layer and the decomposition range of hydrate on the surface destruction range of the overlying layer was studied.

A schematic diagram of the calculation model is shown in Figure 4.

Considering the boundary effect, the thickness of the overburden layer was 46 m, the thickness of the hydrate deposit layer was 10 m, and the soil thickness was 56 m in total. The length and width of the model were both set to 800 m to eliminate the influence of the boundary. The ground was initially level. The boundary of the model was fixed at both ends and limited lateral displacement, the bottom was fixed at normal, and the upper surface is a free surface. A hydrate decomposition zone was established at the center of the bottom of the model. The grid of the hydrate decomposition zone was finer, with a grid length and width of 1 m, while the grid of the hydrate undecomposed zone was larger, with a grid length and width of 5 and 2 m, respectively. The mechanical parameters of the soil are shown in Table 1. The eruption damage primarily occurred above the hydrate decomposition zone, spreading to both sides and forming a rounded platform (Figure 4). Among them, the displacement was the largest directly above the hydrate decomposition site.

### Table 1. The Mechanical Parameters of the Soil

| Parameter          | Value          |
|--------------------|----------------|
| overlying layer    |                |
| elastic modulus    | 70 MPa         |
| density            | 1700 kg/m³     |
| Poisson’s ratio     | 0.3            |
| friction angle     | 3°             |
| cohesion           | 35 kPa          |
| hydrate layer      |                |
| elastic modulus    | 260 MPa        |
| density            | 1800 kg/m³     |
| Poisson’s ratio     | 0.35            |
| cohesion           | 600 kPa         |

4. RESULTS AND DISCUSSION

#### 4.1. Verification of the Simulation

At the beginning of the experiment, the gas collection container was filled with gas at a constant pressure of 0.1 MPa; 5 s after opening the inflation valve, cracks appeared on the surface of the soil layer. The cracks gradually expanded, and the soil body was lifted. After 10 s, the soil layer is completely destroyed, the diameter of the crack range is approximately 30 cm, and the shape of the damage is a rounded mesa. The experimental images are shown in Figures 5 and 6.

**Figure 5.** Soil layer cracking at 5 s.

**Figure 6.** Total destruction of the soil layer at 10 s.

**Figures 7 and 8** show that the eruption damage of the overlying layer caused by hydrate decomposition mainly occurred above the hydrate decomposition area before spreading to each side and creating an upward rounded shape. The failure length of the overlying layer was approximately 26 cm, which is consistent with the failure length of 30 cm obtained experimentally.

The error between simulation and experimental data was mainly because the soil mechanical properties of the indoor experiment were not exactly same. Although the density and permeability of the soil in nature were consistent, the structure of the indoor filling and natural soil was still different. During the simulation process, when the overlying soil swells and cracks, the gas overflows, and the soil cracks stop. In the process of indoor experiments, a closed elastic gas collection container was used to simulate the process of gas accumulation, and the experimental results had errors.

The results indicate that the model established by numerical simulation can be used to simulate the overburden eruption caused by hydrate decomposition.

#### 4.2. Dimensional Analysis

In indoor experiments, tetrahydrofuran hydrate (THF) is often used as a good substitute for methane hydrate. Compared with methane hydrate deposits, a large amount of THF deposits can be synthesized more safely and economically because THF and water are completely miscible in any ratio, forming hydrates in the atmosphere and at normal temperatures. The operation is simple and nonhazardous. The density of THF hydrate is 0.97 g/cm³, which is close to the density of methane hydrate at 0.92 g/cm³.

From Zhang’s laboratory experiment, the physical process of gas eruption caused by hydrate decomposition can be described as follows: (1) Because of the heat source interference, once the phase equilibrium temperature is reached, the heat conduction causes the solid phase of the THF hydrate deposit to become water, liquid THF, and gas, forming hydrates in the atmosphere and at normal temperatures. The operation is simple and nonhazardous. (2) The released gas and water are confined in the decomposition zone, and a part of the gas and water in the upper part of the decomposition zone slowly penetrates the overlying sediment. Simultaneously, a superporous gas pressure is generated, which drives the eruption of the overlying layer. Due to excessive pore pressure and reduced cohesion in the soil, the effective stress of the soil in the decomposition zone is greatly reduced, even causing the liquefaction of the sediment. (3) As the overburden becomes thinner and softer, the shear strength of the overburden decreases, and the resistance of the soil decreases as the hydrate decomposes and expands. When both the decomposition zone in the hydrate deposit and the melting zone in the overlying layer expand to a critical level, the driving force...
becomes equal to or exceeds the resistance. (4) Because the energy of natural gas is large enough to maintain the continuous movement of gas and sediment, it causes gas eruption and plastic damage.

The physical mechanism is that heat transfer causes the expansion of the hydrate decomposition zone and the formation of super-pore pressure (driving force) and reduces the thickness of the overlying layer and the shear strength (resistance). According to the characteristic time, the sequence of heat transfer, and soil deformation, a decoupling analysis method was proposed. First, the analysis considers three phase transitions in the sediment, with the slowest being the controlled heat transfer process. Second, the empirical critical conditions for gas eruption are based on a simple mechanical equilibrium limit analysis. In general, once the driving force exceeds the resistance, the pressure and energy of the ultra-porous gas are greater than the resistance of the upper cladding layer, and the gas will erupt in the decomposition zone with the sediment. From the above experiments, we determined the control parameters that affect the deformation and destruction of the formation caused by hydrate decomposition. The calculation model is shown in Figure 9.

The following influencing factors were considered. Geometric parameters:
Thickness of the overlying layer \( h \).
Radius \( R \) of the hydrate decomposition zone.
Physical parameters:
Overlying layer: density \( \rho \), elastic modulus \( E \), Poisson’s ratio \( \gamma \), tensile strength \( \tau \), and shear strength \( S \).
Hydrate layer: elastic modulus \( E_1 \), Poisson’s ratio \( \gamma_1 \), and density \( \rho_1 \).
Other parameters: acceleration of gravity \( g \) and gas pressure of the hydrate decomposition zone \( P \).

Dependent variables: half of the diameter of the bulging range on the surface of the overlying layer (referred to as the radius of failure) \( R_f \).

The destruction radius \( R_f \) of the overlying layer can be expressed as a function of the above influencing factors.

\[
R_f = f(P, g; \rho, \gamma, \tau, S, E_i, \gamma_f, \rho_f; h, R) \tag{14}
\]

Taking the density of the overlying layer \( \rho \), the thickness of the overlying layer \( h \), and the acceleration of gravity \( g \) as the basic quantities, analyze the above parameters to obtain the dimensionless form.

\[
\frac{R_f}{h} = f \left( \frac{P}{\rho gh}, \frac{S}{\rho gh}, \frac{\tau}{\rho gh}, \frac{E_i}{\rho gh}, \frac{R}{h} \right) \tag{15}
\]

By simplified analysis of the above formula, under certain geological conditions, the mechanical parameters of the overburden and hydrate layer do not change. Therefore, this study only considers the influence of the gas pressure after the hydrate decomposition in the hydrate decomposition zone and the thickness variation of the overlying layer on the radius of destruction of the overlying layer.

The simplified formula is as follows:

\[
\int \left( \frac{P}{\rho gh} \frac{S}{\rho gh} \frac{R_f}{h} \frac{R}{h} \right) = 0 \tag{16}
\]

where \( R_f/h \) is the critical size ratio of the destruction of the overlying layer when the hydrate is decomposed, \( R/h \) is the ratio of the hydrate decomposition radius to the thickness of the overlying layer when the overlying layer fails, \( P/\rho gh \) is the excess pore pressure ratio, and \( S/\rho gh \) is the ratio of the shear strength of the overlying layer to gravity.

If the excess pore pressure ratio exceeds the ratio of the shear strength of the overlying layer to gravity (i.e., \( \frac{P}{\rho gh} > f \left( \frac{S}{\rho gh}, \frac{R_f}{h}, \frac{R}{h} \right) \)), the overlying layer will fail. The findings obtained by Zhang et al.\textsuperscript{17} demonstrate that when liquefied or gasified soil sediments are covered by poorly permeable soil, the cover layer can restrict the passage of pore water or gas. As the decomposition range gradually expands, the cover layer will be pushed away or even destroyed once the excess pore pressure ratio exceeds the ratio of the shear strength of the cover layer to the thickness of the cover layer. This causes the pore pressure at the interface between the saturated or vaporized sediment layer and the cover layer to suddenly unload. When the excess pore pressure is high, the overlying layer will be continuously broken and destroyed, which can cause an eruption.
4.3. Soil Failure of the Overlying Layer. 4.3.1. Constant h. When the thickness of the overlying layer is fixed, the different gas decomposition ranges of the hydrate lead to different gas contents of hydrate decomposition, which produces different pore pressure values. The results obtained in this study indicate that the critical failure pressure caused the eruption failure of the overlying layer in different decomposition ranges. When plastic failure occurs, 15% of the vertical strain is taken as its failure strength value. To conservatively estimate soil damage, it is assumed that the critical failure judgment condition for the overburden is that the maximum vertical settlement strain is 10% of the overburden thickness. Figure 10 shows that the eruption damage mainly occurs above the hydrate decomposition zone, spreading to both sides, forming a rounded platform. The displacement is largest directly above the hydrate decomposition site.

In Figure 11, the dark red part represents the area with the largest displacement. During the eruption, the soil above the hydrate decomposition zone was mostly displaced. The displacement of the soil above the undecomposed area of the hydrates is less than that in the middle position. As the hydrate decomposed and gas gathered, the vertical displacement at the center position rose linearly to the maximum position. When the displacement reached the maximum point, complete destruction of the soil was considered to occur, and the calculation was complete. Assuming that the pore pressure of the hydrate decomposition zone is a certain value at the beginning due to the decomposition of the hydrate, as the overlying layer arches upward, the volume of the hydrate decomposition zone gradually becomes larger. However, owing to the low tensile strength of the soil, cracks appeared on the surface of the overburden until the cracks penetrated the soil layer fully. After this point, the soil was sheared and destroyed, and the overburden was completely destroyed, causing the gas in the hydrate decomposition zone to overflow and the pressure to drop to the lowest value.

Considering that the thickness of the overlying layer was constant as the decomposition range changes, the change in the destruction range of the overlying layer is shown in Figure 12. Within a certain range, when the decomposition radius of the hydrate gradually becomes larger, the destruction length of the surface of the overlying layer gradually decreases, and the pressure required to cause the destruction also gradually decreases. When the decomposition radius is small, the damage shape of the overburden is inverted conical, and the soil body exhibits eruption damage. As the decomposition radius gradually increases, the destruction shape becomes trapezoidal before finally exhibiting a rectangular shape. The overburden soil is pushed upward by the gas in the hydrate decomposition zone. As can be seen from Figure 12, the larger the radius of the hydrate decomposition zone, the more likely the overlying layer is to break. This is because when the decomposition radius is small, the failure pressure that causes the upper cladding layer to break is higher, and the upper cladding layer mainly undergoes large-scale shear failure. The larger the angle of shear failure, the larger the radius of failure is. When the decomposition radius is large, the destruction of the overlying layer is mainly due to the gas pressure in the decomposition zone being stronger than the weight of the upper soil, pushing the soil body; thus, the destruction radius is small.

Figure 13 shows that the critical size ratio of the overburden failure when the hydrate decomposes increases continuously as the excess pore pressure ratio increases. However, when the ultra-pore pressure is relatively small (less than 1.0), the growth rate increases. When the ultra-pore pressure ratio is relatively large (greater than 1.0), the growth rate decreases. As the decomposition range gradually increases, the pore pressure required to fully destroy the overlying layer gradually becomes smaller, and the excess pore pressure ratio becomes smaller. When the decomposition range of the hydrate gradually decreases, the pore pressure required to cause damage to the overlying layer rapidly increases. This means that the smaller the decomposition range of the hydrate, the more difficult it is to damage the overlying layer.

4.3.2. Constant p. Assuming that the pore pressure in the hydrate decomposition zone is constant, as the decomposition range changes, the extent of the overlying layer failure also changes. Therefore, the following study is the relationship between the decomposition range of the hydrate and the thickness and damage range of the overlying layer when the critical pressure causing the eruption failure of the overlying layer is constant.

In Figures 14 and 15, the dark red part represents the area with the largest displacement. During eruption, the soil above the hydrate decomposition zone exhibited the largest displacement. The vertical displacement at other positions is smaller.
than that at the intermediate position. The figures illustrate that the vertical displacement area of the soil body is similar to a rounded platform. The soil that interacts with the soil in the middle position is deformed to a certain extent due to gas accumulation and will not greatly restrict the displacement of the middle soil. The soil at the side wall restricts the deformation of the soil due to the interaction with the surrounding soil.

Considering the condition of constant pore pressure in the hydrate decomposition zone with the change in the decomposition range and the thickness of the overlying layer, the change in the destruction length of the surface of the overlying layer is shown in Figure 16. In the hydrate decomposition zone, the pore pressure was constant, and the relationship between the hydrate decomposition radius and the destruction length of the overlying layer was evaluated. Through numerical simulation, a graph was drawn between the ratio $S_h$ of the hydrate decomposition radius to the thickness of the upper cladding and the ratio $S_{f_h}$ of the destruction length of the upper cladding to the thickness of the upper cladding. The pore pressure is constant, and the radius of the hydrate decomposition zone and the thickness of the overlying layer change within a certain range; the greater the ratio $S_h$, the higher the likelihood of damage is.

In the case of a certain pore pressure in the hydrate zone, as the thickness of the overlying layer increases, the excess pore pressure ratio also increases. Figure 17 shows that as the ratio of excess pore pressure gradually increases, the critical ratio of overburden failure also gradually increases. When the ultra-pore pressure ratio is less than 0.02, the rate of the failure critical ratio increases more rapidly. When it exceeds 0.02, the

Figure 14. Cloud map of the damage range.

Figure 15. Cloud map of displacement in the vertical direction.

Figure 16. Relation of the hydrate decomposition radius and failure radius.

Figure 17. Critical ratio of overburden failure with the excess pore pressure ratio.
increase rate slows down. Hence, when the pore pressure in the hydrate decomposition zone is constant, the smaller the excess pore pressure ratio is, and the more likely the overlying layer is to be damaged.

5. CONCLUSIONS

In this study, the hydrate deposits of the giant pits in the Bermuda seabed were evaluated as a prototype to determine the effects of hydrate decomposition. A numerical simulation calculation was conducted under simplified conditions to evaluate the phenomenon in which permeability of the overlying layer is low, gas decomposition is caused by hydrate decomposition, pore pressure increases, and eruption damages the overlying layer. The following conclusions were drawn.

When the thickness of the upper cladding layer is constant and the decomposition range of hydrate gradually increases within a certain range, the destruction length of the upper cladding layer gradually decreases, and the pressure required for the failure also gradually decreases. The destruction length of the overlying layer is nearly inversely proportional to the hydrate decomposition range. The critical size ratio of the destruction of the overlying layer in the case of hydrate decomposition continues to increase as the excess pore pressure ratio increases.

When the pore pressure in the hydrate decomposition zone is constant, the thickness of the overlying layer and the hydrate decomposition radius gradually change within a certain range. As the ratio R/h of the hydrate decomposition radius to the thickness of the upper cladding layer continues to increase, the ratio R/h of the destruction length of the upper cladding layer to the thickness of the upper cladding layer gradually decreases. With the gradual increase in the excess pore pressure ratio, the critical ratio of the burden failure also gradually increased. This result indicates that as the ratio R/h of the hydrate decomposition radius to the thickness of the overlying layer increases, the excess pore pressure ratio decreases; these conditions facilitate a higher likelihood of breakage.

These two conclusions can analyze the occurrence of seabed uplift, overburden overturning, or large-area gas eruptions in nature. When climate change causes hydrates to decompose, a large amount of gas accumulates, and the permeability of the overburden is low. Eventually, the overburden is erupted and destroyed. This work plays a key role in deep-sea safe operation and effective development of hydrate energy assessment and prediction.

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