

## Article

# Analysis of Factors Influencing the Stability of Submarine Hydrate-Bearing Slopes during Depressurization Production

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**Abstract:** Natural gas hydrate reservoirs, with shallow burial, poor cementation, and low strength, are prone to submarine landslides triggered by hydrate decomposition during extraction. Prior studies have inadequately considered factors such as the dynamic decomposition of hydrates during depressurization, and its impacts on the reservoir's geomechanical properties. In this paper, a coupled thermal–hydraulic–mechanical–chemical mathematical model of hydrate decomposition is proposed, and the dynamic geomechanical response and the effect of hydrate decomposition on seafloor settlement and slope destabilization during the process of depressurization mining are analyzed by combining the strength discount method with the example of a hydrate-bearing seafloor slope in the Shenhu area. Furthermore, the study employs an orthogonal experimental design along with range and variance analysis to gauge the impact of critical factors (degree of hydrate decomposition, seawater depth, hydrate reservoir burial depth, hydrate reservoir thickness, and slope angle) on slope stability. The findings suggest that hydrate decomposition is non-uniform and is influenced by stratigraphic temperature gradients and gravity. In the region where hydrate decomposition occurs, the decrease of pore pressure leads to the increase of effective stress. Additionally, the decomposition of hydrates decreases the shear modulus of sediments, leading to deformation and reduced permeability in the affected area. Over a three-year period of depressurization mining, the significantly reduced safety factor increases the risk of landslides. Various factors play a role in the control of submarine slope stability, with slope inclination being the primary factor, followed by the degree of hydrate decomposition, reservoir thickness, burial depth, and seawater depth. Among these factors, hydrate burial depth and seawater depth have a positive correlation with submarine slope stability, while increases in other factors generally decrease stability. These research findings have important implications for the safe exploitation of slopes that contain hydrates.

**Keywords:** natural gas hydrate; depressurization mining; coupled thermal–hydraulic–mechanical–chemical mathematical model; strength discount method; submarine slope stability; orthogonal experimental design



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## 1. Introduction

Natural gas hydrate is a form of ice-like crystalline compound with a cage structure and is formed by the interaction of small molecular-weight gases such as methane (CH<sub>4</sub>) and light hydrocarbons with water molecules in low-temperature and high-pressure conditions. Research suggests that over 90% of the total reserves of hydrates on the seabed are made up of methane hydrates [1,2], which are also called ‘combustible ice’ due to their flammability [3]. Research has confirmed that decomposing 1 m<sup>3</sup> of natural gas hydrate at standard atmospheric pressure yields 164 m<sup>3</sup> of methane and 0.8 m<sup>3</sup> of water [4]. Compared with the equivalent calorific value of coal, methane combustion per cubic meter of methane

can reduce methane emissions by 4.33 kg and will not produce dust, sulfide, or other hazards [5]. Because of its significant reserves, widespread distribution, low pollution, and high energy density, among other reasons, it is viewed as a promising potential replacement for conventional energy sources [6,7].

Currently, there are five primary approaches to hydrate exploitation: depressurization, thermal stimulation, chemical injection, carbon dioxide replacement, and solid-state fluidization [8–10]. The depressurization method has several benefits, such as low production cost, lack of continuous stimulation, easy operation, and improved gas production and production rate [11]. Depressurization, resembling conventional drilling and rapidly transmitting pore pressure, is deemed the most economical and straightforward hydrate extraction method [12]. Within natural gas hydrate reservoirs, hydrates are present in sediments and take various forms such as filling, cementation, support, and coverage [13–16]. This has a significant impact on the mechanical properties of the hydrate sediments. Depressurization mining alters sediment properties, impacting hydrate stability, releasing methane, weakening strength, and causing geological risks like subsidence and landslides [17–20]. Given complex geology, high testing costs, and risks of environmental disasters, scholars have generally employed numerical simulations when studying natural gas hydrate exploitation and its reservoir impacts. Zhao et al. [21] used TOUGH+HYDRATE to model the mechanical impact of hydrate extraction. Findings indicate that horizontal well extraction causes extensive seafloor subsidence, with the highest damage risk found to be above these wells due to substantial vertical displacement. Ye et al. [22] employed an OGS-based model to analyze sediment behavior during hydrate dissociation. Gravity effects expedite gas–liquid migration, soil deformation, and hydrate dissociation, with fluctuating gas and liquid saturations during mining. Zhang et al. [23] utilized CMG STARS to create a coupled model for hydrate extraction. Their findings reveal notable formation subsidence near production wells, with wellhead subsidence and gas output decreasing linearly as production pressure rises.

Seabed landslides, a major marine hazard, have been linked to hydrate decomposition. For ordinary slope stability problems, the limit equilibrium method and the numerical analysis method are widely used for analysis [24,25]. The limit equilibrium methods include Bishop's limit equilibrium, Janbu's approach, and plastic mechanics-based upper limit analysis [26–28]. Among numerical analysis methods, the strength discount method has been widely used [29,30]. Compared with land slopes, submarine slopes have a more complex geological environment, but they still have many commonalities and can be analyzed using similar research methods. Shi et al. [31] created 37 ABAQUS-based finite element models, employing the strength reduction method to evaluate stability in submarine hydrate-bearing slopes during pilot production, extracting safety factors, deformation, and displacement under varied operational stages. Tan et al. [32] assessed slope stability using the limit equilibrium method, considering evolving pore pressure and strength parameters during gas production. Their findings identified overpressure as the primary driver of slope instability. Kong et al. [33] analyzed gas hydrate-induced slope instability, highlighting hydrate dissociation's pivotal role in slope stability through a multifactor sensitivity study using the strength discount method. Currently, scholars primarily employ the strength reduction method to assess submarine slope stability affected by hydrate decomposition. However, studies often overlook the initial geostatic stress balance, impacting simulation accuracy. Achieving harmony between initial stress equilibrium, hydrate decomposition, and strength reduction is crucial. Moreover, as hydrate decomposition is dynamic, prior studies have often overlooked changes in reservoir mechanical properties during natural gas extraction, inadequately explaining its impact on slope instability. Comprehensive consideration of these factors is crucial when analyzing submarine hydrate slope stability.

In light of the understandings delineated above, a thermal–hydraulic–mechanical–chemical coupled mathematical model of hydrate decomposition process was established in this study, and the model was solved using COMSOL Multiphysics 6.1 software. Based on the actual seismic profiles in the Shenhu area of the South China Sea, a model of the

underwater hydrate-containing slope was constructed and balances the geostress of the model. The effects of hydrate decomposition on seafloor subsidence and slope instability were simulated. Using the orthogonal experimental method, five crucial factors, including the degree of hydrate decomposition, seawater depth, hydrate burial depth, thickness of the hydrate reservoir, and slope angle, were selected to construct 25 orthogonal experimental schemes. These schemes were then calculated using the finite element strength reduction method. Sensitivity analyses of the influencing factors were conducted using range analysis and variance analysis. The research results are of great significance for effectively predicting landslide instability disasters of a hydrate-bearing slope and ensuring the safe exploitation of natural gas hydrates.

## 2. Theoretical Model

In order to achieve a more accurate simulation of the hydrate decomposition process through the solution of the numerical model established in this paper, the following assumptions were made:

- (i) The natural gas hydrate is presumed to be a pure Type I gas hydrate, with the gas within the hydrate being exclusively composed of pure methane.
- (ii) The flow of both methane gas and liquid water in porous media follows Darcy's Law.
- (iii) The solid-phase hydrate entails the absence of relative motion between it and the sediment skeleton.
- (iv) The distribution of natural gas hydrates is uniform and isotropic within porous media.
- (v) The secondary production of natural gas hydrates in porous media is not taken into account.

### 2.1. Control Equations for the Coupled THMC Model

#### 2.1.1. Equation of Mass Conservation

The chemical equation for the reaction of gas hydrate during buck mining can be expressed as  $\text{CH}_4 \cdot \text{N}_h\text{H}_2\text{O} \rightarrow \text{CH}_{4(\text{gas})} + \text{N}_h\text{H}_2\text{O}_{(\text{liquid})}$ . Because the phase state of natural gas hydrate is mainly affected by temperature and pressure, the phase equilibrium equation can be expressed as [34]

$$P_{eq} = \exp\left(39.08 - \frac{8533}{T}\right) \quad (1)$$

where  $\text{N}_h$  is the hydrate coefficient and generally takes 6.  $P_{eq}$  is the hydrate phase equilibrium pressure, MPa;  $T$  is the temperature of natural gas hydrate reservoir porous media, K.

The natural gas hydrate decomposition process obeys the law of conservation of mass and its differential form can be expressed as [35]

$$\frac{\partial(\phi\rho_g S_g)}{\partial t} + \nabla \cdot (\rho_g \mathbf{q}_g) = \dot{m}_g \quad (2)$$

$$\frac{\partial(\phi\rho_w S_w)}{\partial t} + \nabla \cdot (\rho_w \mathbf{q}_w) = \dot{m}_w \quad (3)$$

$$\frac{\partial(\phi\rho_h S_h)}{\partial t} = -\dot{m}_h \quad (4)$$

where  $g$ ,  $w$ , and  $h$  represent methane, water and hydrate, respectively.  $\rho$  is the density of each phase,  $\text{kg}/\text{m}^3$ .  $\dot{m}$  is the mass change of each phase,  $\text{kg}/(\text{m}^3 \cdot \text{s})$ . The relationship between the quality of hydrate decomposition and the quality of natural gas and water production is  $\dot{m}_g + \dot{m}_w + \dot{m}_h = 0$ .  $\phi$  is the porosity, which is dimensionless; and  $S$  is the saturation, where the relationship between the saturation of each phase can be expressed as  $S_w + S_g + S_h = 1$ .  $\mathbf{q}_g$  and  $\mathbf{q}_w$  represent the Darcy velocities of methane gas and water, respectively, which can be expressed as [35]

$$\mathbf{q}_g = -\frac{kk_{rg}}{\mu_g}(\nabla P_g + \rho_g \mathbf{g}) \quad (5)$$

$$\mathbf{q}_w = -\frac{k k_{rw}}{\mu_w} (\nabla P_w + \rho_w \mathbf{g}) \quad (6)$$

where  $k_{rg}$  is the relative permeability of gas in the current reaction state and  $k_{rw}$  is the relative permeability of water in the current reaction state.  $k$  is the absolute permeability of the gas hydrate-bearing sediments, which can be described by the Masuda permeability decline model [36,37], expressed as  $k = k_0(1 - S_h)^\tau \exp[\gamma \times (\phi/\phi_0 - 1)]$ , where  $k_0$  is the initial absolute permeability of the sediment without gas hydrate,  $\text{m}^2$ ;  $\tau$  is Masuda's absolute permeability reduction factor, with a value ranging from 5 to 15;  $\phi_0$  is the initial porosity;  $\gamma$  is an empirical coefficient;  $P_g$  is the gas pressure in the current reaction state, MPa;  $P_w$  is the pressure of the water in the pore space, MPa;  $\mu_g$  and  $\mu_w$  are the dynamic viscosity of gas and water, respectively; and  $\mathbf{g}$  is the acceleration of gravity,  $\text{m/s}^2$ .

According to the VG model, the relative permeability of water  $k_{rw}$  and methane gas  $k_{rg}$  can respectively be expressed as [38]

$$k_{rw} = S_{we}^n \left(1 - \left(1 - S_{we}^{1/m}\right)^m\right)^2 \quad (7)$$

$$k_{rg} = (1 - S_{we})^n \left(1 - S_{we}^{1/m}\right)^{2m} \quad (8)$$

where  $m$  and  $n$  are VG model parameters;  $S_{we}$  is the effective saturation of water, which can be expressed as  $S_{we} = \frac{S_w}{S_w + S_g} - S_{wr}$ ; and  $S_{wr}$  and  $S_{gr}$  are the saturation of residual water and residual gas, respectively.

### 2.1.2. Equation of Hydrate Decomposition Kinetics

The decomposition rate of natural gas hydrate can be calculated by the Kim–Bishnoi kinetic equation [39]:

$$\dot{m}_h = -k_r M_h A_s (P_{eq} - P_g) \quad (9)$$

where  $k_r$  is the kinetic constant for hydrate dissociation in  $\text{mol}/(\text{m}^2 \cdot \text{Pa} \cdot \text{s})$ .  $A_s$  is the specific surface area of hydrates per unit volume participating in the reaction. According to the chemical equation for hydrate decomposition, the rate of methane and water generation can be expressed as  $\dot{m}_g = -\dot{m}_h \frac{M_g}{M_h}$ ,  $\dot{m}_w = -\dot{m}_h \frac{M_w}{M_h}$ , where  $M_g$ ,  $M_w$  and  $M_h$  represent the molar masses of methane gas, water and hydrate, respectively.

The capillary pressure is computed by  $P_c = P_g - P_w$ ,  $P_c$  and can also be represented by the VG model as [38]

$$P_c = P_0 \left(S_{we}^{-1/a} - 1\right)^{1-a} \quad (10)$$

where  $P_0$  is the reference pressure for the intake value in MPa and  $a$  is the soil–water characteristic curve parameter of the sedimentary layer.

### 2.1.3. Equation of Energy Conservation

Hydrate dissociation is an endothermic process. The decrease of temperature will limit hydrate dissociation and may also change the properties of fluids in pores, such as viscosity. Therefore, it is necessary to consider the influence of the temperature field in the multi-physics coupling numerical simulation of hydrate depressurization decomposition. In the process of hydrate dissociation, the temperature field follows the law of energy conservation. Under the condition that one considers factors such as heat conduction, heat convection and external environment heat supply and ignores the influence of kinetic energy and thermal radiation, the energy conservation equation in the process of hydrate decomposition can be written as follows:

$$\begin{aligned} & [(1 - \phi)\rho_s C_s + \phi\rho_h C_h S_h + \phi\rho_g C_g S_g + \phi\rho_w C_w S_w] \frac{\partial T}{\partial t} = \nabla \cdot k_t \nabla T \\ & - \nabla \cdot (\rho_g \mathbf{q}_g C_g T + \rho_w \mathbf{q}_w C_w T) - \dot{m}_h \Delta H_D + q \end{aligned} \quad (11)$$

where  $C_s$ ,  $C_g$ ,  $C_w$  and  $C_h$  are the specific heat capacities of the sediment skeleton, methane gas, water and hydrate, respectively.  $k_t$  denotes the thermal conductivity of hydrate reservoirs;  $\Delta H_D = c_1 + c_2 T$  is the latent heat of decomposition of the hydrate, where  $c_1$  and  $c_2$  are the regression coefficients of the Kamath regression equation [40]; and  $q$  is the heat recharge from the external environment to the hydrate-bearing sediments.

#### 2.1.4. Equation of Equilibrium of Forces

During the decomposition process of hydrates, the pore pressure of the hydrate-containing sedimentary layer will change, causing changes in effective stress that lead to deformation or even destruction of the sedimentary layer. The governing equation of the mechanical deformation field in hydrate decomposition is essentially the constitutive equation of the hydrate-containing sedimentary layer. This paper uses an ideal elastic–plastic constitutive model to describe the constitutive relationship of hydrate-containing sediments. The relationship between stress increment and strain increment can be expressed as follows:

$$d\sigma'_{ij} = D^{ep} d\varepsilon_{ij} = \nabla(D^{ep} : L : u) \quad (12)$$

where  $\sigma'_{ij}$  is the effective stress of the sediment skeleton in MPa;  $\varepsilon_{ij}$  is the strain of the hydrate-containing sediment;  $u$  is the displacement of the sediment skeleton;  $L$  is the partial differential operator;  $D^{ep}$  is the elastic–plastic matrix coefficient tensor, which can be expressed by the elastic matrix  $D^e$  subtracted by the obtained plasticity matrix  $D^p$ , expressed as follows:

$$[D^{ep}] = [D^e] - [D^p] \quad (13)$$

According to the associated flow law, the plastic matrix  $D^p$  can be expressed as

$$[D^p] = \frac{[D^e] \left\{ \frac{\partial F}{\partial \sigma} \right\} \left\{ \frac{\partial F}{\partial \sigma} \right\}^T [D^e]}{A + \left\{ \frac{\partial F}{\partial \sigma} \right\}^T [D^e] \left\{ \frac{\partial F}{\partial \sigma} \right\}} \quad (14)$$

where  $F$  is the yield function and  $A$  is the hardening function.

The yield function  $F$  adopts the Mohr–Coulomb criterion, and its mathematical expression is as follows:

$$F = \frac{1}{2}(\sigma_1 - \sigma_3) + \frac{1}{2}(\sigma_1 + \sigma_3) \sin \theta - c \cos \theta = 0 \quad (15)$$

where  $\sigma_1$  and  $\sigma_3$  are the maximum and minimum principal stresses, respectively, and  $c$  and  $\theta$  represent the cohesion and friction angle, respectively.

The elastic matrix  $D^e$  is related to the material parameters of hydrate-bearing sediments and can be expressed as

$$[D^e] = \frac{E}{(1+v)(1-2v)} \begin{bmatrix} (1-v) & v & v & 0 & 0 & 0 \\ v & (1-v) & v & 0 & 0 & 0 \\ v & v & (1-v) & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1-2v}{2} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1-2v}{2} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1-2v}{2} \end{bmatrix} \quad (16)$$

where  $E$  is the elastic modulus of hydrate-bearing sediments in Mpa and  $v$  is the Poisson ratio of hydrate-bearing sediments.

In summary, the governing equation of the mechanical deformation field of hydrate-bearing sediments, considering the change of fluid pore pressure, can be expressed as follows:

$$\nabla \cdot D^e (L : u - \varepsilon_p) - \beta \delta_{ij} \nabla \bar{P} + f_i = 0 \quad (17)$$

where  $L : u$  is the strain;  $\varepsilon_p$  is the plastic strain;  $\beta$  is the Biot consolidation coefficient;  $\delta_{ij}$  is the Kronecker function;  $f_i$  is the volume force component; and  $\bar{P}$  is the equivalent pore fluid pressure, which can be expressed as  $\bar{P} = S_w P_w + S_g P_g$ .

## 2.2. Submarine Slope Stability Model

In this paper, the finite element strength reduction method is employed for the stability analysis of hydrate slopes. This method involves systematically reducing the shear strength of the slope's soil mass until it reaches the point of failure. Subsequently, the program utilizes the results of elasticity calculations to determine the slip surface location and the corresponding slope's strength reduction coefficient  $FOS$ . This coefficient represents the safety factor for the slope in this context. The discounted shear strength parameter can be expressed as [41]

$$c' = c/FOS \quad (18)$$

$$\theta' = \arctan(\tan \theta / FOS) \quad (19)$$

## 3. Submarine Hydrate-Bearing Slope Model

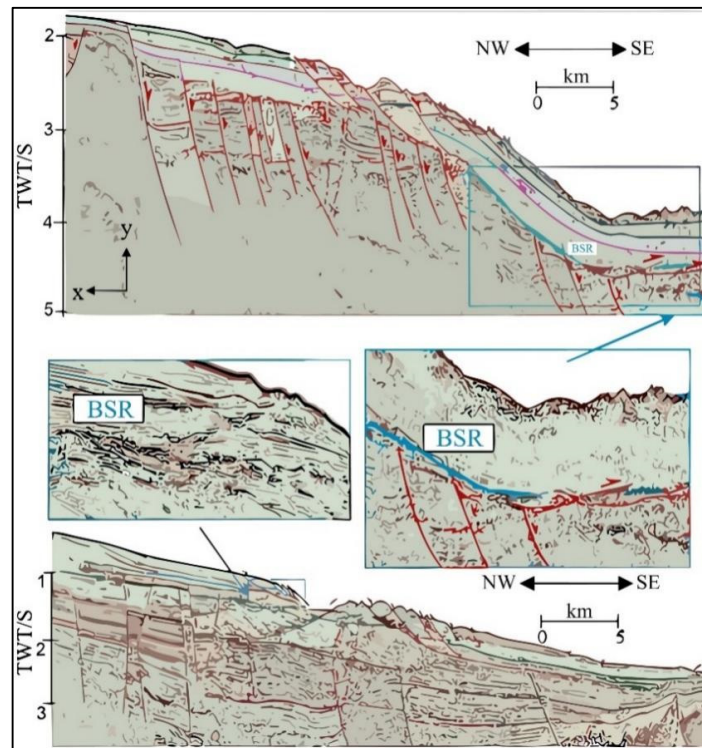
### 3.1. Geological Setting

The study area of this paper is the hydrate drilling area of the Shenhu Sea in the South China Sea, which is located in the middle part of the northern land slope of the South China Sea, tectonically belongs to the Baiyun Depression of the second depression of the Pearl River estuary basin, and is situated in the transition zone of the land slope from the shelf to the deep sea. The seabed topography in this area is complicated. Because of the long-term joint action of internal and external stresses, a complex and varied seabed geomorphological pattern has been formed. Due to tectonic effects, such as earthquakes and active faults, and erosive effects, such as gravity currents and bottom currents, disaster geological factors, such as submarine landslides and erosion gullies, have been widely developed (Wang Hongbin et al., 2003 [42]). In addition, the canyons and waterways are complex and have shaped the unique submarine topography of the Shenhu area. Since the Cenozoic era, the Shenhu Sea has experienced terrestrial, land-sea transitional, and marine sedimentation phases with a large sedimentation rate and a perfect fluid transportation system, both of which are geological conditions for the formation and storage of hydrates. The study area is the upper land slope of the northern land slope, the water depth is between 500 m and 2000 m, the slope range is mainly concentrated at  $4^\circ \sim 10^\circ$ , and the local area is greater than  $12^\circ$ . The seafloor temperature is  $3.3^\circ\text{C} \sim 3.7^\circ\text{C}$ , its heat flow value is higher, between  $28 \sim 62 \text{ W/m}^2$ , and the geothermal temperature gradient is  $4.5^\circ\text{C} \sim 6.7^\circ\text{C}/100 \text{ m}$  (Wu Nengyou et al., 2007 [43]; Zhang Wei et al., 2017 [44]). The higher heat flow and ground temperature gradient cause the distribution of hydrates to be limited to a certain extent and thickness, and the depth of burial is relatively shallow. The seismic reflection wave of the hydrate deposition layer has obvious bottom simulating reflector (BSR) characteristics, which represents the acoustic reflection interface between the deposits containing gas hydrate (gas hydrate is stable in the marine environment) and the underlying non-gas hydrate, and basically represents the bottom boundary of the stability zone of the hydrate. Figure 1 shows the seismic feedback data of a profile in the Shenhu area.

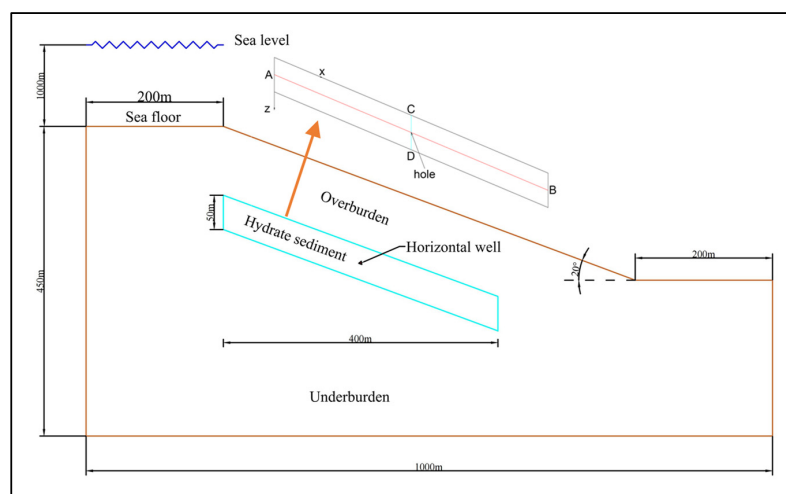
### 3.2. Numerical Modeling

In this study, a seafloor slope model has been developed using seismic feedback data from a profile in the Shenhu area. This model encompasses the hydrate reservoir and the surrounding soil layer. The slope of the model is considered an ideal three-dimensional homogeneous slope, which can be simplified to a two-dimensional planar model by means of elastoplastic theory. This study employs the horizontal well mining method for hydrate slope modeling. The geometric characteristics of the hydrate slope model, as illustrated in Figure 2, include a hydrate reservoir with a thickness of 50 m and a burial depth of 100 m. The horizontal extent of the hydrate reservoir is 400 m, and its distribution aligns with the

seafloor surface. To minimize the influence of ground stress and boundary constraints on the calculation results, the hydrate slope model extends 200 m on each side. Consequently, the total length of the hydrate slope model in this study is 1000 m, with the slope portion spanning 600 m and featuring a slope gradient of  $20^\circ$ . The extraction well for natural gas hydrates has a radius of 0.15 m. To facilitate subsequent analyses and discussions on the dynamics of hydrate dissociation and its impact on formation stability, two cross-sections were delineated within the hydrate reservoir model region: line AB, located centrally and parallel to the direction of the hydrate layer, and line CD, positioned centrally and parallel to the vertical direction.



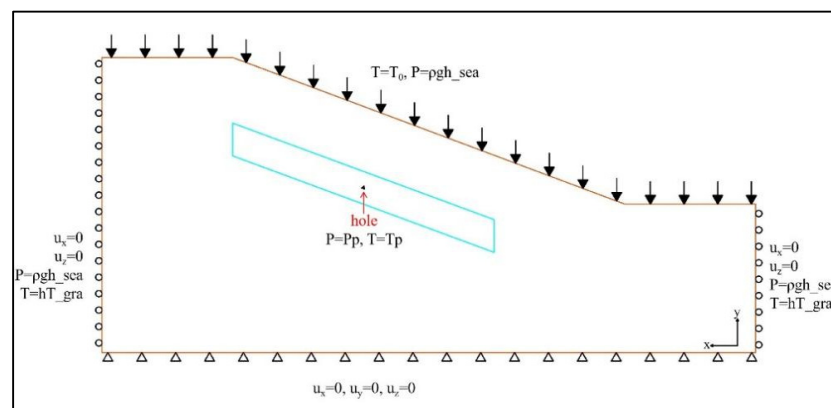
**Figure 1.** Seismic profile of hydrate stratigraphy in the Shenhu Sea, South China Sea. The red part shows extensional faults, while the purple, blue and green parts show stratigraphic boundaries. The square boxes are enlarged to show the stratigraphic foreproduct characteristics. BSR is the bottom simulation reflection.



**Figure 2.** Two-dimensional modelling of the hydrate-bearing slope.

### 3.3. Model Parameters and Initial Conditions

Combined with the analysis of typical slope instability and, at the same time, the actual situation of hydrate exploration in the Shenhu Sea area of the South China Sea, the upper seawater depth of the hydrate-containing slope model established in this paper is 1000 m (10 MPa), and the rest of the top boundary applies constant pressure according to the hydrostatic pressure distribution. The pore pressure distribution inside the slope is a hydrostatic pressure distribution. According to the temperature distribution range of the seafloor of the Shenhu Sea, the temperature on the surface of the hydrate-bearing slope model is set to 276.75 K, with a gradient of 0.0426 K/m. As shown in Figure 3, the mechanical boundary conditions used for the stability analysis of the slope are to limit the displacement in the horizontal direction of the two sides of the slope model (roll support in COMSOL) and to limit the displacement in all directions of the bottom boundary (fixed boundary conditions). The upper portion of the hydrate-bearing slope is a pressure boundary condition, which is sized to the magnitude of the hydrostatic pressure at that depth. Table 1 summarizes the numerical simulation parameters of the hydrate-bearing slope model developed in this paper. Considering the complexity of the actual division of the initial hydrate saturation region, this paper set the reservoir hydrate as the average value, and mainly studied the influence of the dynamic decomposition process of the hydrate on the slope stability during the mining process of the hydrate bearing slope.

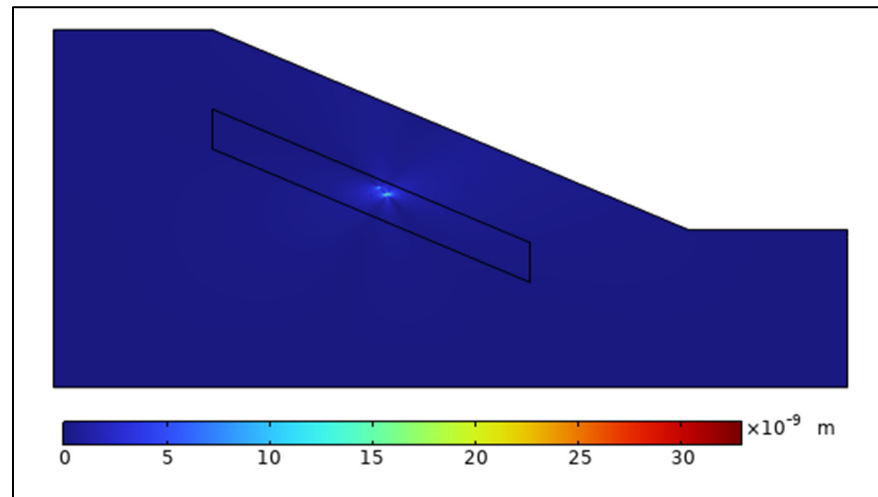


**Figure 3.** Numerical modeling boundary conditions.

**Table 1.** Numerical modeling of basic stratigraphic parameters.

| Parameters                                                                 | Values                 |
|----------------------------------------------------------------------------|------------------------|
| Initial hydrate saturation                                                 | 0.4                    |
| Initial water saturation                                                   | 0.6                    |
| Initial intrinsic permeability                                             | 200 mD                 |
| Density of hydrate-bearing reservoirs                                      | 1800 kg/m <sup>3</sup> |
| Porosity of hydrate-bearing reservoirs                                     | 0.35                   |
| Initial cohesion of hydrate-bearing reservoirs                             | 0.005 MPa              |
| Internal friction angle of hydrate-bearing reservoir                       | 28°                    |
| Initial modulus of elasticity of hydrate-bearing reservoirs                | 25 MPa                 |
| Poisson's ratio for hydrate-bearing reservoirs                             | 0.35                   |
| Initial intrinsic permeability of soils around hydrate-bearing reservoirs  | 0.5 mD                 |
| Density of soil layers around hydrate-bearing reservoirs                   | 2200 kg/m <sup>3</sup> |
| Porosity of soil layers surrounding hydrate-bearing reservoirs             | 0.35                   |
| Cohesion of soil layers around hydrate-bearing reservoirs                  | 0.05 MPa               |
| Friction angle of the soil layer surrounding the hydrate-bearing reservoir | 28°                    |
| Modulus of elasticity of soil layers around hydrate-bearing reservoirs     | 55 MPa                 |
| Poisson's ratio of soil layers around hydrate-bearing reservoirs           | 0.35                   |
| Dry thermal conductivity                                                   | 1 W/m/K                |
| Wet thermal conductivity                                                   | 3.1 W/m/K              |
| Specific heat of water                                                     | 4200 J/kg/K            |
| Specific heat of gases                                                     | 2180 J/kg/K            |
| Specific heat of hydrate                                                   | 2220 J/kg/K            |
| Specific heat of sediments                                                 | 750 J/kg/K             |

As shown in Figure 4, the displacement distribution cloud map of the hydrate-bearing slope model established in this article after geostress balance calculation shows that the displacement of the hydrate-bearing slope after geostress balance is between  $10^{-8}$  and  $10^{-9}$  m. For geotechnical engineering, the displacement after the geostress balance can reach  $10^{-4}$  m to meet the subsequent calculation requirements. Therefore, the initial geostress balance results of this model meet the needs of subsequent calculations.

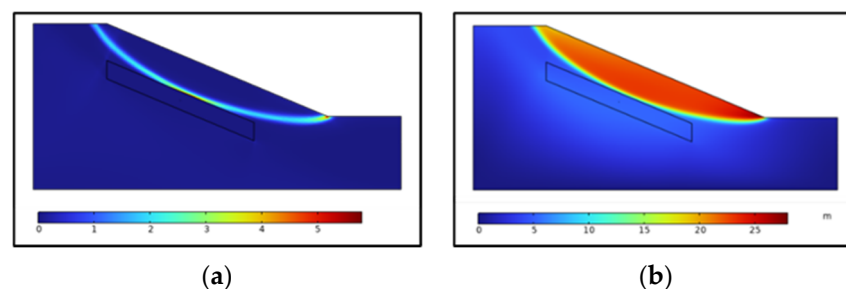


**Figure 4.** Hydrate-bearing slope modeling ground geostress balance result.

#### 4. Results and Discussion

##### 4.1. Analysis of Submarine Stability before Depressurization Mining

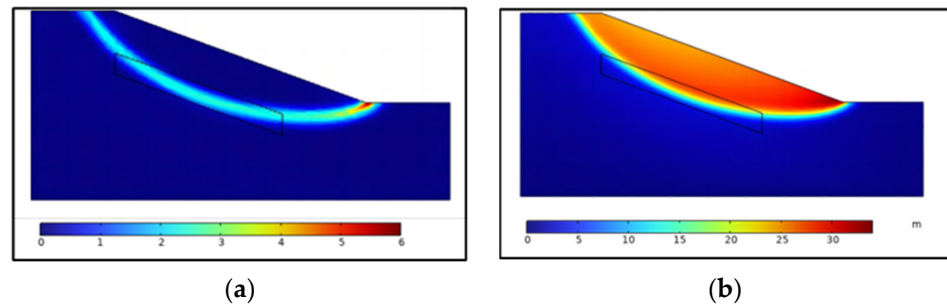
Figure 5a shows the situation of reduced slope strength and the distribution of plastic hinge zones at the end of the hydrate content analysis before subsidence. The presence of plastic hinge zones within the slope indicates that this geological layer has entered the plastic yielding stage, undergoing significant deformation under external forces. Figure 5b depicts the displacement distribution under the same analysis conditions. Comparing Figure 5a,b, it is evident that, in the case of slope instability, sliding primarily occurs along the interface between the gas hydrate reservoir and the surrounding soil, especially at the foot of the slope, where the displacement is greatest and reaches 27 m, thus far exceeding the displacement in other areas of the slope.



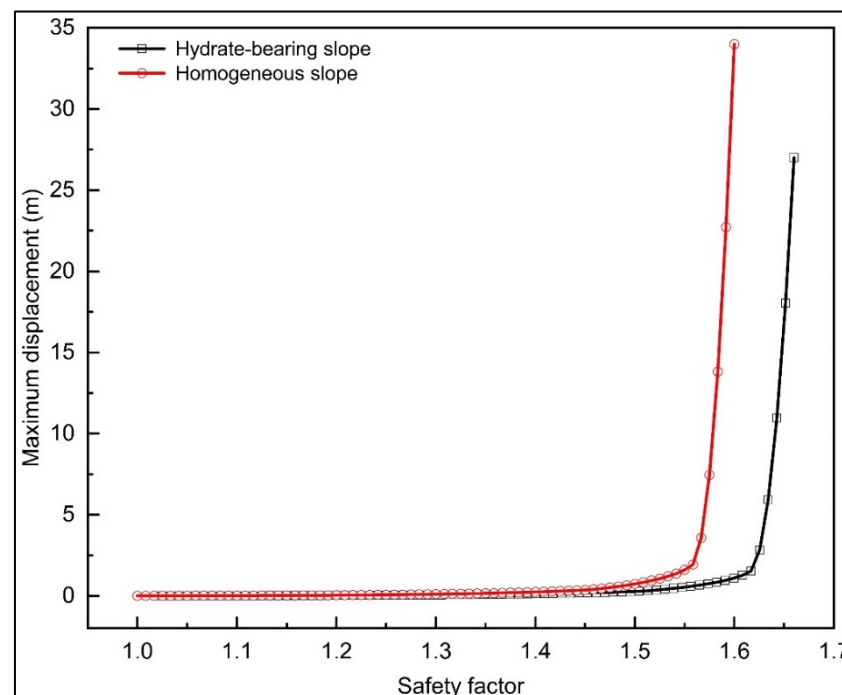
**Figure 5.** (a) Plastic zone contour at the end of the calculation of gas hydrate-bearing slope strength reduction (FOS = 1.66). (b) Displacement contour at the end of the calculation of gas hydrate-bearing slope strength reduction (FOS = 1.66).

To more clearly elucidate the impact of hydrate-bearing reservoirs on slope stability, the model established in this study substitutes the physical properties of the hydrate reservoir with those of the surrounding soil layers, transforming the model into a homogeneous slope without a hydrate reservoir. Figure 6a,b depict the displacement and plastic strain of the homogeneous slope at the end of the strength reduction analysis, respectively. Compared with the simulated results of hydrate-bearing slope, the maximum displacement at the base

of the slope increased by 34 m, and the range of the landslide (from the plastic connection zone to the slope surface) is broader when the slope is unstable. Figure 7 illustrates the relationship between the maximum displacement and the safety factor. As the safety factor decreases, the plastic deformation of the slope surface gradually increases, eventually leading to the termination of calculations due to non-convergence. At this point, the reduction factor reflects the slope's safety factor and can be used to assess its stability. The image indicates that the safety factor of the hydrate-bearing slope before depressurization mining was 1.66 and the safety factor of the homogeneous slope is 1.60, which is lower than that of the slope containing the hydrate reservoir. This suggests that the presence of a hydrate reservoir, when unexploited, contributes to the stability of the slope.



**Figure 6.** (a) Plastic zone contour at the end of the calculation of slope strength reduction without gas hydrates (FOS = 1.60). (b) Displacement contour at the end of the calculation of slope strength reduction without gas hydrates (FOS = 1.60).



**Figure 7.** Maximum displacement versus factor of safety (FOS).

#### 4.2. Analysis of Geological Formation Responses to Hydrate Decomposition during Depressurization Mining

##### 4.2.1. Parameter Distribution Characteristics during Depressurization Mining

Figure 8a shows the distribution of formation pore pressures over three years of simulated decompression mining. At the beginning of mining, the pore pressure in the near-well zone decreases significantly, while the pressure in the distal zone and the original formation remains almost unaffected. As mining proceeds, the affected area expands and

the pore pressures in the distal part of the reservoir and the inner part of the formation decrease, but the pore pressures propagate unevenly. This uneven propagation can be attributed to the decomposition of hydrates, increasing the reservoir permeability and the uneven seepage of gases and liquids in the reservoir under gravity. Figure 8b shows the variations in reservoir temperature throughout the production cycle. The temperature and pore pressure exhibit similar evolution trends. Initially, a noticeable temperature drop near the wellhead is observed due to heat absorption during hydrate decomposition. The changes in temperature and pressure gradually propagate from the wellbore to both sides during the depressurization mining process, with more pronounced changes in the lower right corner than in the upper left corner. In the complete hydrate decomposition zone, the temperature and pressure stabilize. With the decrease of hydrate reservoir temperature, the reservoir pressure difference decreases. This results in a decrease in the rate of gas hydrate decomposition, indicating the effective range of depressurized production in a single well. Therefore, in order to obtain higher gas recovery in actual production one might consider increasing the number of production wells.

Figure 8c shows the distribution of hydrate saturation during three years of depressurized production. Initially, the saturation around the horizontal wells gradually decreases and then eventually expands outward in a trapezoid shape. This is because the existence of a geothermal gradient makes the temperature at the bottom of the reservoir higher, which is more conducive to the decomposition of natural gas hydrate. Therefore, in actual production, if it is not possible to locate the perforation section of the entire hydrate reservoir, it is better to locate the perforation section at the bottom of the reservoir, as this can promote the faster decomposition of natural gas hydrate and thereby increase natural gas production. Figure 8d illustrates the distribution of effective stress in the formation over the three-year hydrate mining process. Throughout this process, the concentration of effective stress is primarily near the wellbore. This phenomenon occurs as a result of the depressurization mining process, where water and gas within the hydrate dissociation zone flow out due to the production pressure difference. Consequently, this leads to a reduction in pore pressure within the dissociation zone, thereby increasing the effective stress. The uneven distribution of effective stress around the wellbore is attributed to the reservoir's heterogeneity in hydrate decomposition, resulting in an uneven distribution of reservoir strength.

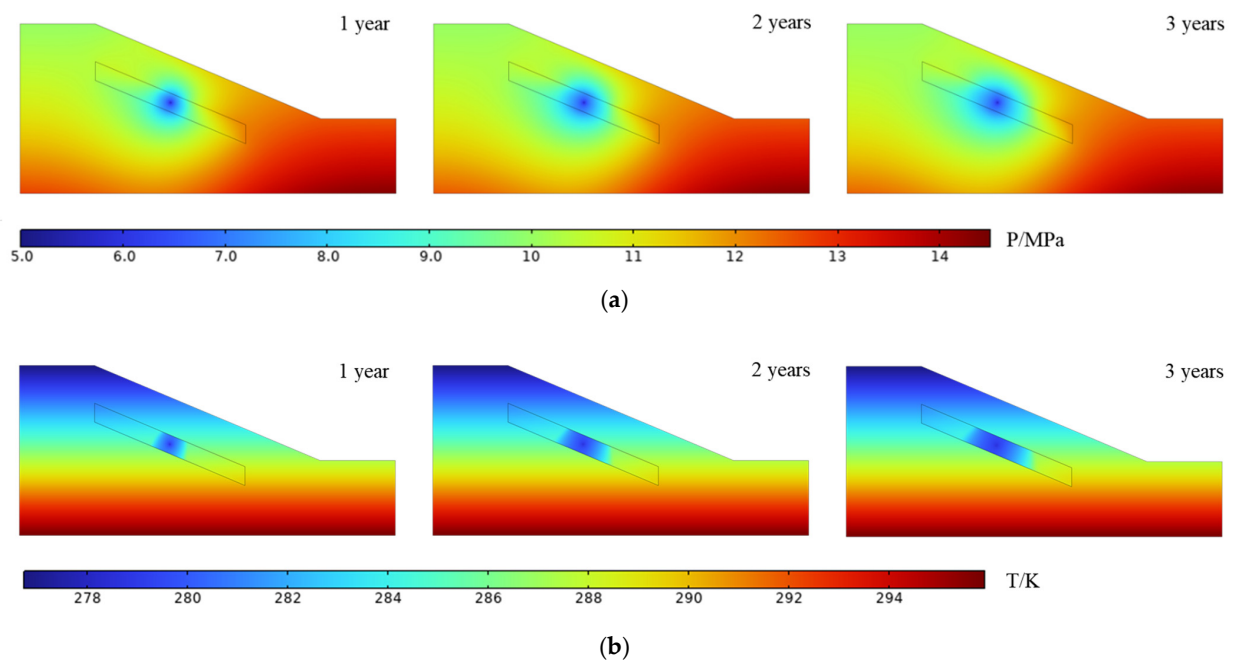
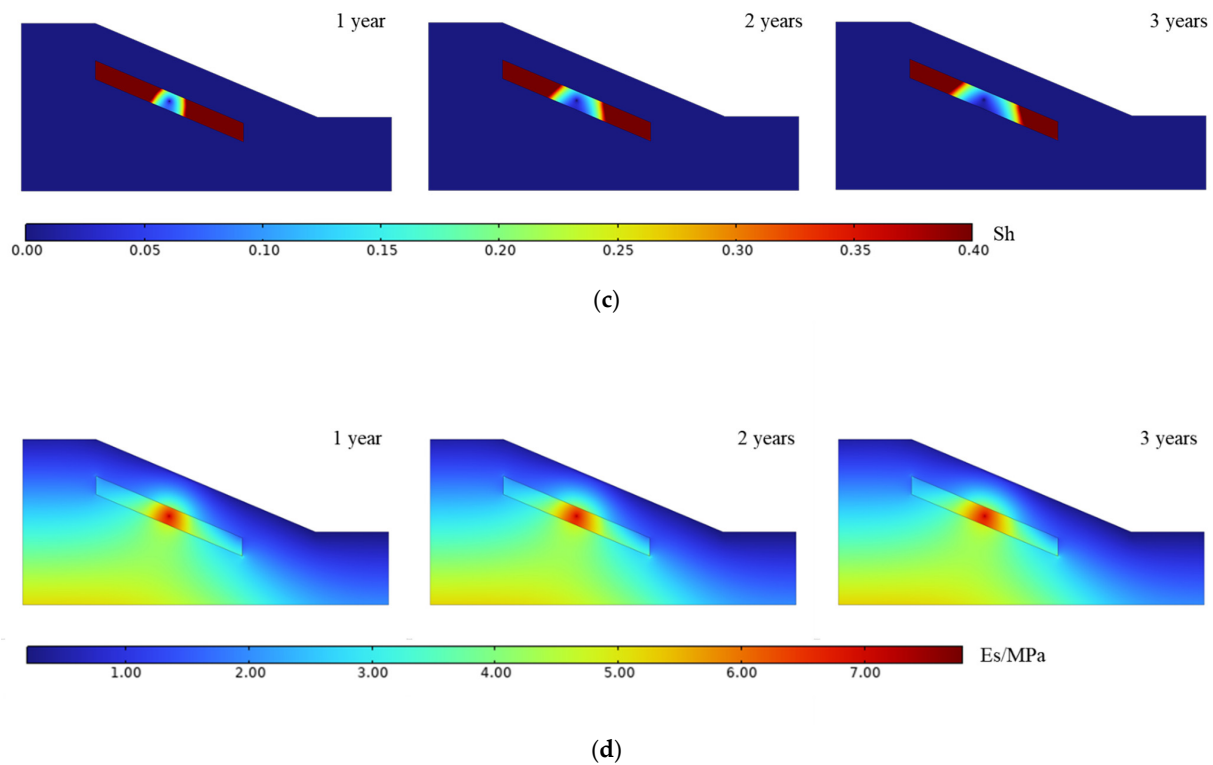
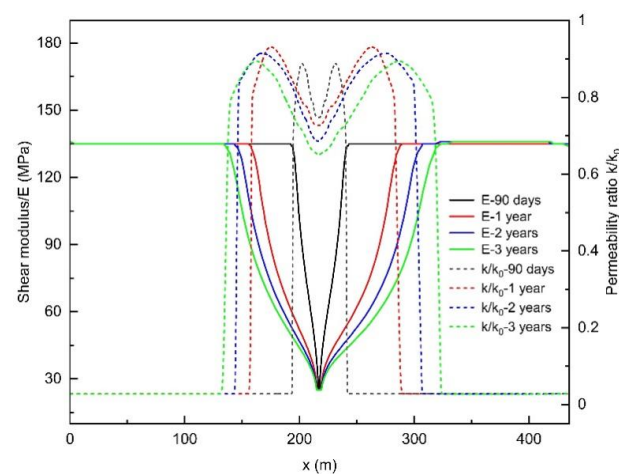


Figure 8. Cont.



**Figure 8.** The distribution of parameters during the mining process. (a) Pore pressure, (b) temperature, (c) natural gas hydrate saturation, and (d) effective stress.

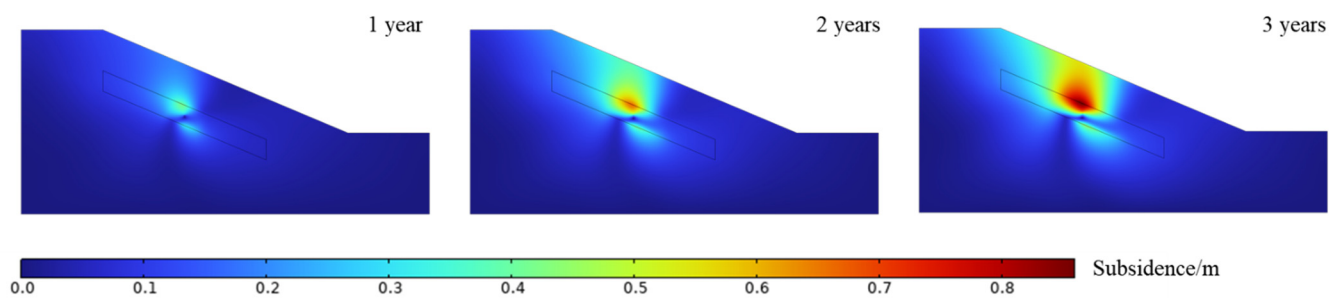
Figure 9 demonstrates the significant impact of hydrate decomposition on the shear modulus within the decomposition zone. This decrease in shear modulus as decomposition progresses ultimately weakens the load-bearing capacity of the zone, making it more susceptible to deformation and causing reservoir subsidence, increasing the likelihood of submarine landslides. Deformation in the decomposition region leads to a decrease in porosity and thus a decrease in permeability. In the undecomposed region of the reservoir, the presence of solid hydrate in the sediment pores obstructs the fluid flow and reduces the permeability ratio. In light of these findings, the implementation of appropriate well protection measures during mining is critical to prevent the risk of wellbore failure.



**Figure 9.** Shear modulus and permeability ratio distribution and evolution pattern curves along the AB cross-section.

#### 4.2.2. Characteristics of Strata Subsidence Response

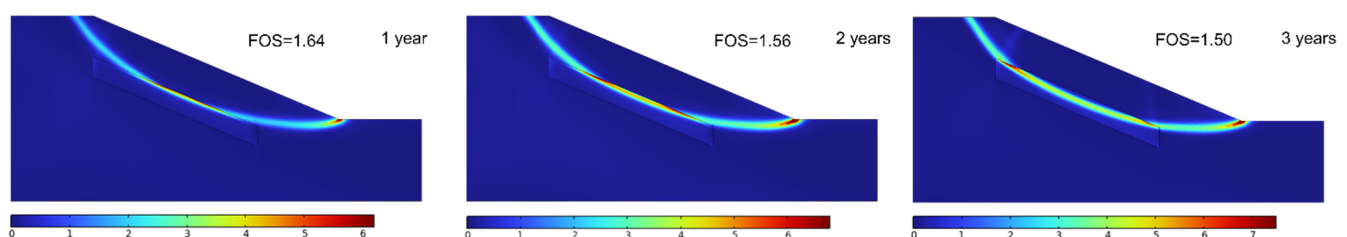
Figure 10 illustrates the evolution of strata subsidence over a three-year mining period. As mining progresses, the amount of strata subsidence significantly increases. The subsidence areas are mainly concentrated above the hydrate reservoirs and adjacent wellbores. This is due to the decrease in pore pressure in the hydrate decomposition zone, weakening of cementation strength, and deformation under the vertical pressure of overlying strata, leading to subsidence. Continuous depressurization mining results in a gradual increase in strata subsidence; during the early stages of hydrate mining, the subsidence rate of seabed strata is relatively fast. With time, the rate of subsidence slows down. Considering the rapid subsidence rate during the initial depressurization phase, measures should be taken to prevent excessive relative displacement between production wells and strata, in order to avoid damage to the wellbore.



**Figure 10.** The evolution of reservoir subsidence during the mining process.

#### 4.2.3. Characteristics of Slope Sliding Response

Figure 11 shows a cloud diagram of the plastic zone contour at the termination of the strength reduction method calculation, during a three-year depressurization extraction process of a hydrate-bearing slope. This visual image clearly reveals the progressive migration of potential sliding towards the deep layers of hydrate reservoirs, and also reveals that the maximum equivalent plastic strain caused by the decomposition of methane hydrates leading to reservoir sliding mainly occurs in the hydrate decomposition zone and at the foot of the slope. During the three-year depressurization mining period, the slope safety factor significantly decreased, reflecting a negative correlation between hydrate decomposition and slope stability. The decrease in stability is mainly due to the decrease in formation cohesion and strength after the decomposition of hydrates, which affects the overall stability of the slope.



**Figure 11.** Plastic zone contour at the end of the calculation of gas hydrate-bearing slope strength reduction during hydrate extraction.

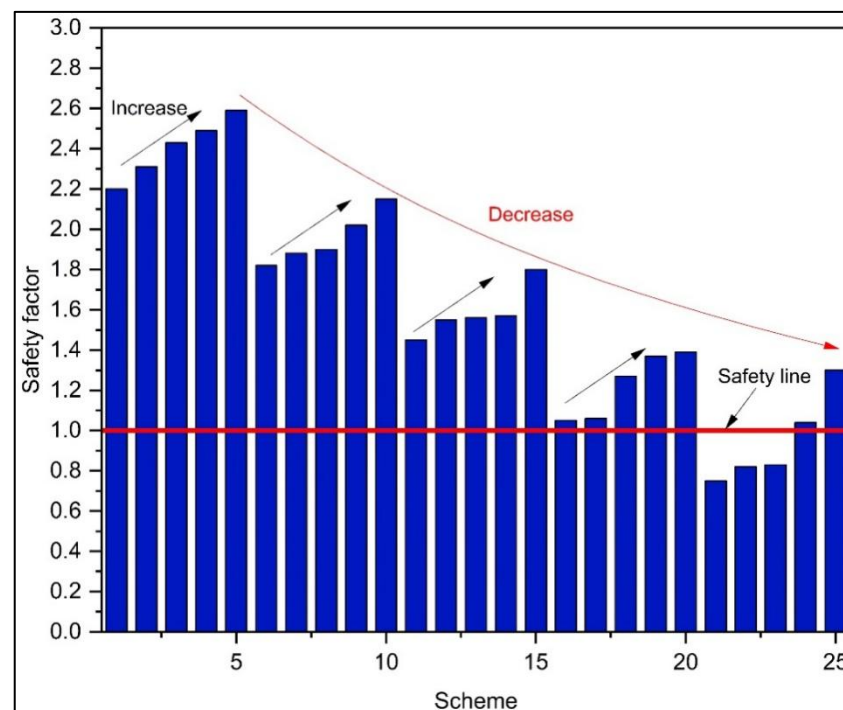
#### 4.3. Sensitivity Analysis of Factors Influencing Seabed Slope Stability

This study employed SPSS Statistics 26 software to design an orthogonal simulation experiment scheme, incorporating five factors (slope angle, seawater depth, degree of hydrate decomposition, hydrate reservoir thickness, and hydrate burial depth) across five levels. This scheme aimed to investigate how these factors affect the stability of submarine slopes. The specific experimental scheme is detailed in Table 2. According to the 25 groups of schemes shown in the table, simulation calculation was carried out through COMSOL

Multiphysics, and the safety factor of each group was obtained. The safety coefficients for various computational schemes are presented in Figure 12.

**Table 2.** Orthogonal experimental design.

| Scheme | Slope Angel/° | Seawater Depth/m | Hydrate Burial Depth/m | Hydrate Reservoir Thickness/m | Degree of Hydrate Dissociation/% |
|--------|---------------|------------------|------------------------|-------------------------------|----------------------------------|
| 1      | 15            | 800              | 50                     | 20                            | 0                                |
| 2      | 15            | 1000             | 250                    | 50                            | 75                               |
| 3      | 15            | 1200             | 200                    | 30                            | 25                               |
| 4      | 15            | 1400             | 150                    | 60                            | 50                               |
| 5      | 15            | 1600             | 100                    | 40                            | 100                              |
| 6      | 18            | 800              | 200                    | 50                            | 50                               |
| 7      | 18            | 1000             | 150                    | 30                            | 0                                |
| 8      | 18            | 1200             | 100                    | 60                            | 75                               |
| 9      | 18            | 1400             | 50                     | 40                            | 25                               |
| 10     | 18            | 1600             | 250                    | 20                            | 100                              |
| 11     | 20            | 800              | 100                    | 30                            | 100                              |
| 12     | 20            | 1000             | 50                     | 60                            | 50                               |
| 13     | 20            | 1200             | 250                    | 40                            | 0                                |
| 14     | 20            | 1400             | 200                    | 20                            | 75                               |
| 15     | 20            | 1600             | 150                    | 50                            | 25                               |
| 16     | 22            | 800              | 250                    | 60                            | 25                               |
| 17     | 22            | 1000             | 200                    | 40                            | 100                              |
| 18     | 22            | 1200             | 150                    | 20                            | 50                               |
| 19     | 22            | 1400             | 100                    | 50                            | 0                                |
| 20     | 22            | 1600             | 50                     | 30                            | 75                               |
| 21     | 25            | 800              | 150                    | 40                            | 75                               |
| 22     | 25            | 1000             | 100                    | 20                            | 25                               |
| 23     | 25            | 1200             | 50                     | 50                            | 100                              |
| 24     | 25            | 1400             | 250                    | 30                            | 50                               |
| 25     | 25            | 1600             | 200                    | 60                            | 0                                |



**Figure 12.** Safety factors for different schemes.

Through range analysis, the influence and relative importance of different factors on the experimental results were determined. The range analysis results for each factor level are listed in Table 3, in which  $K_{ij}$  represents the different levels of each factor, arranged in ascending order,  $\bar{K}_{ij}$  represents the marginal mean values of the safety factor under different

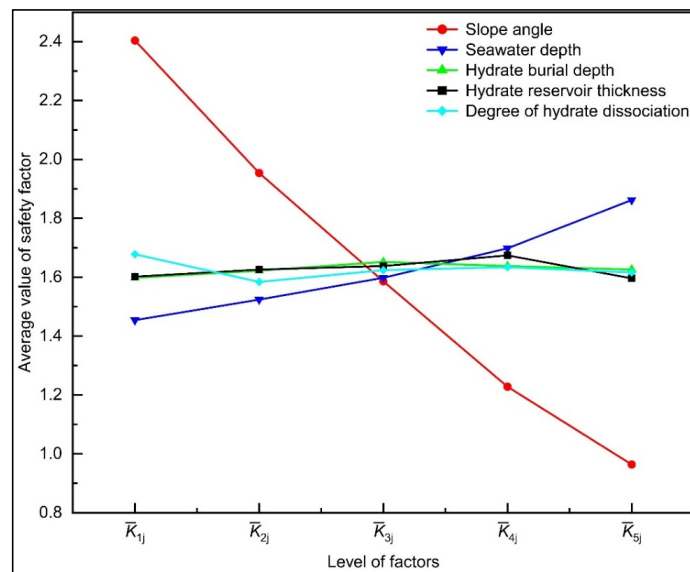
factor levels, and  $R_j$  denotes the range value. As indicated by the analysis in Figure 13, the strength of the factors affecting the experimental results is in the following order: slope angle > seawater depth > degree of decomposition > hydrate reservoir thickness > hydrate burial depth. As depicted in Figure 10, there is a notable trend in the variation of the safety factor, indicating a negative correlation with the slope angle and a positive correlation with seawater depth. This trend can be attributed to the nature of submarine sedimentary layers, generally characterized as weakly consolidated strata. With an increase in slope angle, the frictional resistance of particles along the slope surface diminishes, while the gravitational component acting along the slope surface escalates, consequently elevating the risk of landslides and lowering the safety factor. The increase in seawater depth enhances the overlying hydrostatic pressure. Because the undrained shear strength is positively correlated with this hydrostatic pressure, the soil's resistance to shear failure is strengthened, thereby increasing the safety factor. However, the relationship between safety factors and several parameters—namely, the degree of hydrate decomposition, the thickness of the hydrate reservoir and the burial depth of the hydrate—does not exhibit a monotonic relationship. This anomaly can be attributed to the significant influence of certain individual factors. Table 4 presents the results of a variance analysis for five influential factors. Given that the significance level of the slope angle and seawater depth is  $p < 0.05$ , it is evident that the slope angle and seawater depth significantly affects the safety factor of submarine slopes. Given that the impact of hydrate decomposition degree on the slope safety factor, exhibiting a negative correlation, has been previously discussed, it is imperative in subsequent analyses to isolate the effects of reservoir burial depth and hydrate reservoir thickness on the slope safety factor from the confounding influence of the slope angle and seawater depth. This approach ensures a more accurate understanding and clear delineation of the individual impacts of these factors, independent of the slope angle's interference, thereby providing a more robust analysis of the factors influencing submarine slope stability.

**Table 3.** Results of range analysis of five kinds of influential factors.

| Statistic      | Slope Angel | Seawater Depth | Hydrate Burial Depth | Hydrate Reservoir Thickness | Degree of Hydrate Dissociation |
|----------------|-------------|----------------|----------------------|-----------------------------|--------------------------------|
| $K_{1j}$       | 12.02       | 7.27           | 7.99                 | 8.01                        | 8.39                           |
| $K_{2j}$       | 9.77        | 7.62           | 8.11                 | 8.13                        | 7.92                           |
| $K_{3j}$       | 7.93        | 7.99           | 8.26                 | 8.19                        | 8.12                           |
| $K_{4j}$       | 6.14        | 8.49           | 8.19                 | 8.37                        | 8.17                           |
| $K_{5j}$       | 4.82        | 9.31           | 8.13                 | 7.98                        | 8.08                           |
| $\bar{K}_{1j}$ | 2.404       | 1.454          | 1.598                | 1.602                       | 1.678                          |
| $\bar{K}_{2j}$ | 1.954       | 1.524          | 1.622                | 1.626                       | 1.584                          |
| $\bar{K}_{3j}$ | 1.586       | 1.598          | 1.652                | 1.638                       | 1.624                          |
| $\bar{K}_{4j}$ | 1.228       | 1.698          | 1.638                | 1.674                       | 1.634                          |
| $\bar{K}_{5j}$ | 0.964       | 1.862          | 1.626                | 1.596                       | 1.616                          |
| $R_j$          | 1.44        | 0.408          | 0.054                | 0.078                       | 0.094                          |

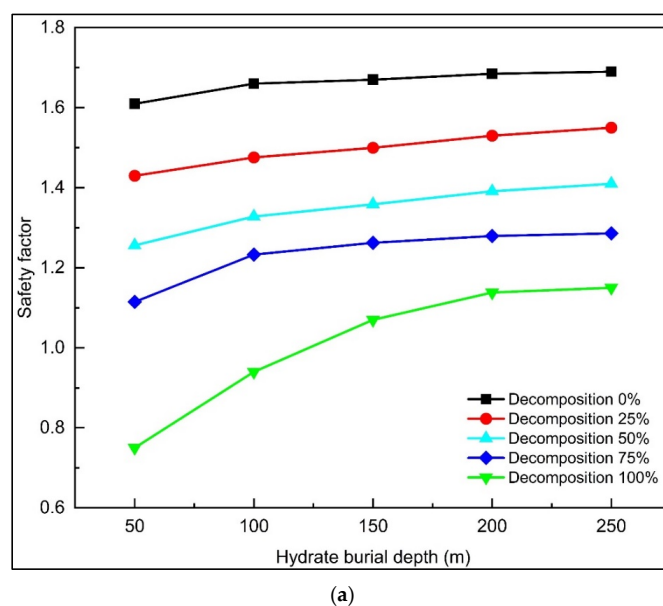
**Table 4.** Results of variance analysis of five kinds of influential factors.

| Factor                         | Deviation Square Sum | Degree of Freedom | Mean Square | F       | $p$    |
|--------------------------------|----------------------|-------------------|-------------|---------|--------|
| Slope angle                    | 6.556                | 4                 | 1.639       | 211.054 | 0.0005 |
| Seawater depth                 | 0.518                | 4                 | 0.129       | 16.675  | 0.009  |
| Hydrate burial depth           | 0.009                | 4                 | 0.002       | 0.285   | 0.874  |
| Hydrate reservoir thickness    | 0.008                | 4                 | 0.002       | 0.246   | 0.898  |
| Degree of hydrate dissociation | 0.033                | 4                 | 0.008       | 1.070   | 0.475  |
| Residual                       | 0.031                | 4                 | 0.008       |         |        |

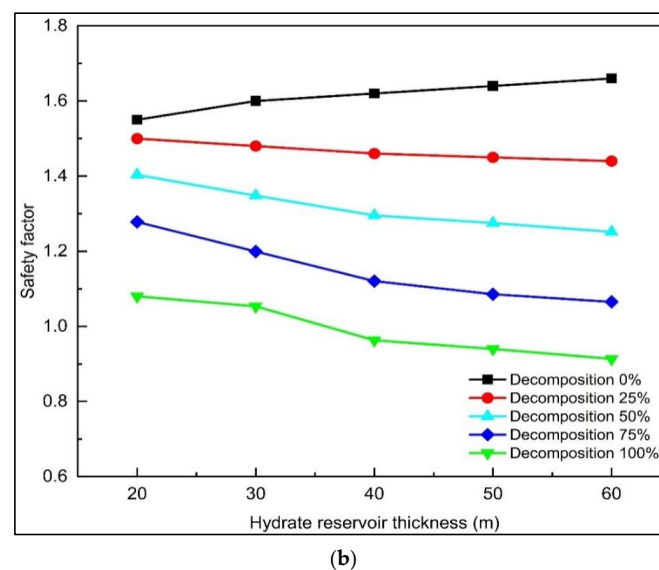


**Figure 13.** Variation pattern of safety factors at different factor levels.

In Figure 14, after controlling for variations in slope angle, set at 20 degrees, and water depth, maintained at 1000 m, the trends in the safety factor are analyzed in relation to variations in the hydrate layer's burial depth and thickness. As depicted in Figure 14a, for hydrate-bearing slopes without hydrate dissociation, the range of variation in the stability safety factor is relatively narrow. Conversely, post-dissociation of the hydrate reservoir, a predominantly positive correlation is observed between the slope stability factor and the hydrate layer's burial depth. This phenomenon can be attributed to the significant reduction in cohesion following hydrate dissociation, with the plastic failure zone extending through the hydrate layer. Greater burial depths of the hydrate layer result in thicker soil masses involved in sliding, thereby increasing resistance. Consequently, the slope stability safety factor for completely dissociated hydrate layers increases with greater burial depths, though the rate of increase diminishes over time, suggesting the existence of a critical depth beyond which further increases in burial depth have negligible impact on the safety factor.



**Figure 14.** Cont.



**Figure 14.** Different influences on slope stability. (a) Seawater depth and (b) hydrate reservoir thickness.

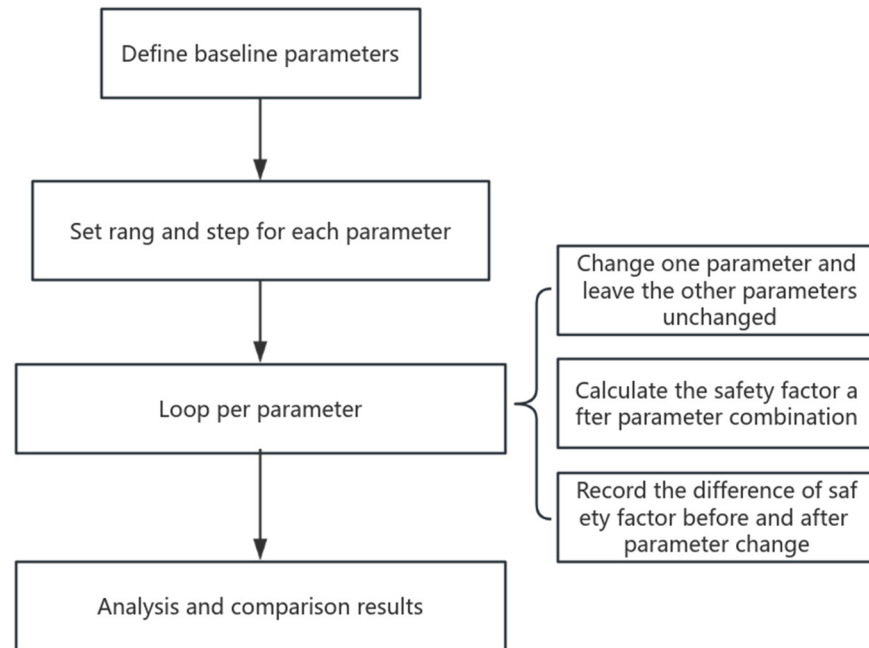
According to Figure 14b, the relationship between the safety factor and the thickness of the hydrate layer varies depending on the degree of hydrate dissociation. A positive correlation is observed when hydrates are intact, reflecting the higher mechanical properties (mechanical parameters) of the hydrate layer compared with surrounding rock layers, thus reinforcing the submarine slope. However, upon dissociation, the mechanical properties of the hydrate layer become inferior to those of the surrounding strata, reducing the slope strength. Consequently, it is observed that the safety factor increases with the thickness of the hydrate reservoir prior to hydrate dissociation. However, following varying degrees of dissociation, the safety factor diminishes as the thickness of the reservoir increases.

#### 4.4. Supplementary Statement

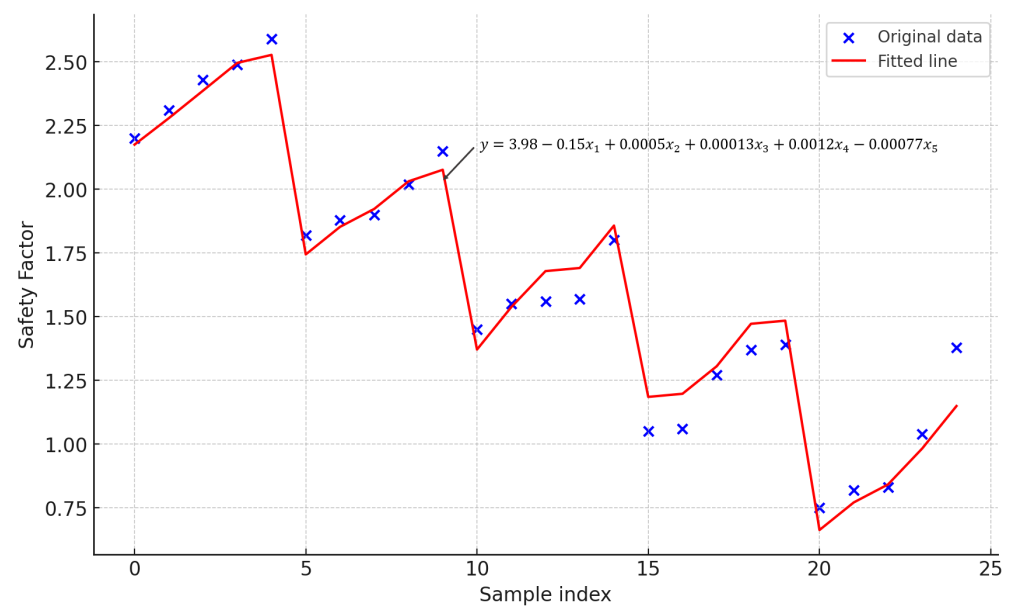
Through the study of the stability of the submarine slope in the process of hydrate decomposition, it can be analyzed that, in the process of depressurization mining of an ideal homogeneous layer, the decomposition of hydrate will weaken the mechanical properties of the reservoir, leading to the settlement of the slope surface and an increase in the risk of submarine landslide. However, due to the complex geological conditions of submarine slopes in general, the submarine slope modeling should be further improved and analyzed in order to reflect the influence of hydrate decomposition on slope stability under actual conditions. Consideration was given to inputting complete seismic data into the model to simulate the real process of hydrate extraction on submarine slopes. However, due to the limited seismic resolution, the geological model of underground development can be updated by using borehole data in a Bayesian framework for uncertainty quantification [45,46].

Through orthogonal variance analysis and orthogonal range analysis of the factors affecting the stability of the submarine slope, the main controlling factors affecting the stability of the submarine slope and the degree of each factor are obtained. However, due to the limited input range of selected factors, the conclusions obtained lack generality. Therefore, the one-at-a-time (OAT) sensitivity analysis method was selected for comparative verification. The principle diagram of the OAT sensitivity analysis method is shown in Figure 15. The sensitivity analysis equation required by the OAT sensitivity analysis method was obtained through linear regression analysis of the data in Table 2, as shown in Figure 16. In the figure,  $x_1$ ,  $x_2$ ,  $x_3$ ,  $x_4$  and  $x_5$  respectively represent slope angle, seawater depth, burial depth of the hydrate layer, thickness of the hydrate layer and degree of hydrate decomposition. The influence of each factor on the safety factor is obtained through repeated calculation, as shown in Figure 17. The impact on slope stability is in the following order: slope angle > seawater depth > thickness of the hydrate layer > degree

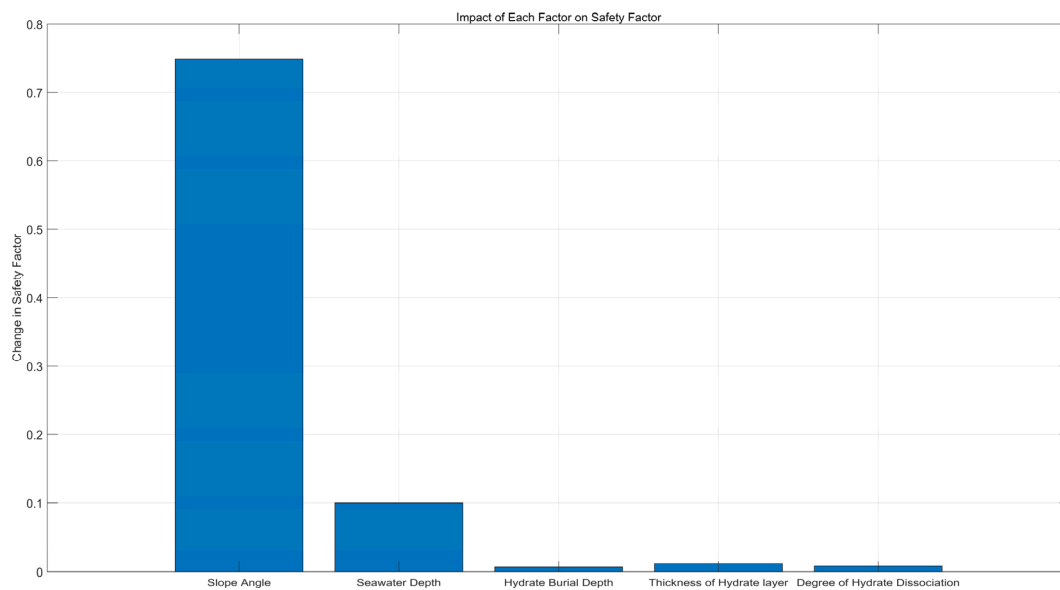
of hydrate decomposition > burial depth of the hydrate layer. Through comparison of sensitivity analysis results, it is found that the orthogonal ANOVA method is different from the OAT method, mainly in terms of the hydrate-related factors. Although the OAT sensitivity analysis method is simple, it does not fully explore the input space because it does not consider the simultaneous change of input variables [47]. There is also no way to detect whether there is an interaction between input variables. Therefore, the effect of hydrate decomposition degree, hydrate burial depth and hydrate layer thickness on the safety factor cannot be reflected correctly. More sensitivity analysis methods, such as Morris sensitivity analysis, will be adopted in subsequent studies to discuss and study.



**Figure 15.** Principle of the one-at-a-time (OAT) sensitivity analysis method.



**Figure 16.** The sensitivity equation related to the safety factor is obtained by multivariate linear fitting.



**Figure 17.** The influence degree of each factor on the safety factor.

## 5. Conclusions

In this paper, a thermal–hydraulic–mechanical–chemical coupled model for hydrate production is established using COMSOL Multiphysics. Based on the slope characteristics of the submarine hydrate reservoir in the Shenhu area of the South China Sea, the study employs numerical simulation methods to explore changes in the mechanical properties of the reservoir and the stability of the strata over a three-year period of depressurization mining. The influence and degree of various factors on the stability of the seabed slope were analyzed using SPSS software. The following conclusions were obtained:

1. Prior to the decompression exploitation of hydrates within the submarine slope, the presence of a hydrate reservoir in the seabed plays a reinforcing role, contributing positively to the stability of the submarine slope.
2. During depressurization extraction via horizontal wells, hydrate saturation and reservoir pore pressure around the wellbore show a gradual decrease. Influenced by gravity and geothermal gradients, an uneven distribution of hydrate saturation and pore pressure occurs within the reservoir. Near the lower boundary of the hydrate reservoir, the decomposition rate of the hydrates is faster, leading to a trapezoidal diffusion pattern of decomposition. As decomposition advances, the shear modulus in the decomposition zone decreases, lowering load-bearing capacity and causing deformation. This deformation leads to reservoir subsidence and increased landslide susceptibility. It also reduces porosity and, consequently, permeability.
3. Throughout the extraction process, hydrate dissociation leads to a reduction in the cohesion and cementation of the reservoir, resulting in sediment subsidence. The maximum subsidence is observed above the upper boundary of the hydrate layer near the horizontal wellbore.
4. Over the course of the three-year depressurization extraction, the slope stability safety factor decreased from 1.64 to 1.50. Although the safety factor remains above 1, indicating no immediate landslide risk, increasing degrees of hydrate decomposition can potentially escalate the instability risk of the slope.
5. Orthogonal design range analysis and variance analysis reveal that the impact on slope stability is in the following order: slope angle > seawater depth > degree of hydrate decomposition > burial depth of the hydrate layer > thickness of the hydrate layer. Among these, hydrate burial depth and seawater depth show a positive correlation with the slope safety factor, while slope angle, hydrate reservoir thickness and degree of hydrate decomposition have a negative correlation.

**Author Contributions:** Methodology, T.S. and J.Y.; Formal analysis, Z.H. and J.H.; Investigation, Z.W.; Writing—original draft, K.Y. All authors have read and agreed to the published version of the manuscript.

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