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Influence of Well Layout on Submarine Slope Stability during Natural Gas Hydrate Development

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Abstract: The exploitation of natural gas hydrates (NGHs) reduces the reservoir strength and increases the effective stress, which may trigger stratum settlement and submarine landslides. In particular, commercial-scale production requires the exploitation of NGHs through multiple wells at the same time, which increases the submarine landslide risk. Therefore, it is necessary to study the influences of well layouts on the stability of submarine slopes in the exploitation of NGHs. To this end, a thermo-fluid–solid multifield coupling model that considers the phase change of NGHs in the exploitation process was established. Considering the finite element strength reduction method, an evaluation model was built to analyze the slope stability in the multiwell exploitation of NGHs with the depressurization method. The results show that because NGH decomposition reduces the reservoir strength, the reservoir is compressed overall, and plastic yield zones first occur in the NGH decomposition zone and the slope toe. Finally, a coalesced plastic yield zone propagates throughout the slope. When exploiting NGHs, slope stability is enhanced with increasing well spacing in a multiwell pattern. The linear well layout along the slope dip direction is more conducive to maintaining slope stability than that perpendicular to the slope dip direction. The slope stability decreases with increasing well spacing density but increases with decreasing slope dip. The influence of well layout on submarine slope stability during natural gas hydrate development is studied, which provides a basis for well layouts during gas hydrate exploitation.



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Keywords: natural gas hydrate; multiwell production; slope stability; multifield coupling; finite element strength reduction method

1. Introduction

Natural gas hydrates (NGHs) have advantages including a wide distribution, abundant reserves, a high energy density, and low pollution and are therefore regarded as potential substitutes for traditional fossil energy [1]; thus, their large-scale exploitation is of important significance. However, methane emission to the atmosphere associated with the dissociation of natural gas hydrates may aggravate global warming [2]. NGH reservoirs are loosely consolidated and have low mechanical strength, while global warming has an adverse influence on the geomechanical stability of gas hydrate deposits in both marine and permafrost environments [3]. The exploitation of NGHs is likely to induce submarine landslides, which seriously threaten the exploitation safety of NGHs. Therefore, increasing attention has been given to the stability of submarine slopes.

The mechanisms underlying submarine landslides commonly include shear failure and soil liquefaction. The shear failure mechanism means that weak structural planes in slopes cause shear failure, which therefore induces landslides. According to the soil liquefaction mechanism, soil structures completely lose their strength and therefore are damaged when the pore pressure in the soil is equal to the overburden pressure. NGH decomposition may induce a high pore pressure in the seabed and accelerate shear failure

of weak structural planes and soil liquefaction of the seabed, thus triggering submarine landslides [4,5].

In previous research, Vanoudheusden et al. [6] studied different submarine landslides in the Costa area by analyzing geological technical data and found that NGH decomposition may induce large-scale submarine landslides. Paull et al. [7] investigated the Cape Fear landslide with a volume of 200 km³ and a sliding distance of 400 km at the South Carolina Continental Rise of the Atlantic Ocean, and their analysis revealed that NGH decomposition was one of the causes of the landslide. Lu et al. [8] established a submarine slope model containing hydrates and pointed out that hydrate decomposition affects the stability of a submarine slope, as well as analyzing the displacement at various locations of the slope during hydrate decomposition. Yang [9] analyzed the influences of hydrate decomposition on the mechanical parameters of rocks in submarine sedimentary formations and used the infinite slope equation to perform sensitivity analyses on the influencing factors of submarine landslides. Based on the theory of the upper bound of energy, An et al. [10] studied the influences of the burial depth of NGH layers and post-decomposition shear strength on the stability of a gentle submarine slope through limit analysis.

Different methods have been used to study slope stability during NGH exploitation. After building and analyzing a submarine slope model containing a hydrate layer, Song et al. [11–13] and Yan et al. [14] discussed the stability of the formation in the exploitation of hydrates and found that excessive production-induced pressure draw-downs, heat injection temperatures, and production scales caused an abrupt decrease in formation stability. Based on the limit equilibrium method, Lin et al. [15] investigated the influences of hydrate exploitation through depressurizing production via a single horizontal well and heat injection via double horizontal wells on the stability of submarine slopes. They also analyzed the slope stability after halting production under conditions of different well locations and production durations. Tang et al. [16] analyzed the influences of the amounts of decomposed hydrates before and during exploitation on slope stability by using the strength reduction method. Zhao et al. [17] analyzed slope stability by using the multistage reduction method based on strength reduction and proposed discontinuous pillar exploitation.

At present, the viewpoint that NGH decomposition in submarine slopes may reduce slope stability and even cause submarine landslides has been acknowledged by numerous scholars. However, previous research mainly focuses on submarine landslides induced by NGH decomposition under natural conditions while rarely investigating the influences of NGH exploitation on submarine stability. Moreover, existing research primarily studies NGH exploitation via a single well. To achieve the commercial-scale exploitation of NGH resources, it is necessary to arrange multiple wells in an NGH reservoir. Therefore, studying the stability of submarine slopes during the multiwell exploitation of NGHs can provide important theoretical support for the commercial-scale exploitation of NGHs.

A thermo-fluid–solid multifield coupling model that describes the exploitation of NGHs was established in this research. Combined with the finite element strength reduction method, an evaluation model for slope stability in the development process of NGHs was built to explore the influences of well layout on the stability of submarine slopes in the exploitation of NGHs.

2. Multifield Coupling Model for NGH Exploitation

2.1. Kinetic Equations of NGH Decomposition

Based on the NGH decomposition kinetics, the consumption rates of methane, water, and hydrates were studied [18]:

$$r_g = k^* M_g A_s (P - P_{eq}) \quad (1)$$

$$k^* = k_0^* \exp\left(-\frac{\Delta E_a}{RT}\right) \quad (2)$$

$$r^h = -r^g, r^w = nr^g \quad (3)$$

where r^g , k^* , and A_s represent the consumption rate of methane ($\text{mol} \cdot \text{L}^{-1} \cdot \text{s}^{-1}$), the kinetic constant for the generation or decomposition of hydrates, and the reaction surface area (m^2), respectively; P denotes the pressure at the local temperature (Pa); P_{eq} is the phase equilibrium pressure (Pa); k_0^* , E_a , and R refer to the intrinsic kinetic constants, activation energy ($\text{J} \cdot \text{mol}^{-1}$), and gas constant, which is $8.314 \text{ J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$; and r^h and r^w are the consumption rates of the hydrate and water, respectively ($\text{mol} \cdot \text{L}^{-1} \cdot \text{s}^{-1}$).

The decomposition rate of NGHs will be affected by the phase equilibrium pressure. Research reveals that the thermodynamic phase equilibrium of a hydrate system is affected by the presence of porous media [19] and there is an exponential relationship between the phase equilibrium pressure and phase equilibrium temperature of NGHs [20].

$$P_{\text{eq}} = \exp\left(e_1 - \frac{e_2}{T}\right) \quad (4)$$

where T represents the temperature of NGH reservoirs ($^{\circ}\text{C}$); and e_1 and e_2 are decomposition constants and are separately valued as 39 and 8533 when the temperature is above 0°C .

The model was established based on the kinetic equations for NGH decomposition and the phase equilibrium equation of NGHs, which enables dynamic changes in NGH saturation with pore pressure and the temperature of the strata.

2.2. Principle of Effective Stress

Changes in the effective stress may induce stratum deformation and variation in shear strength. The principle of effective stress was used in the model to describe the behaviors of the porous media, and the effective stress is:

$$\bar{\sigma}^* = (1 - n_t)\bar{\sigma} - n_t\bar{p}_t\mathbf{I} \quad (5)$$

where $\bar{\sigma}^*$, n_t , $\bar{\sigma}$, $\bar{p}_t$, and $\mathbf{I}$ denote the effective stress (Pa), the volume fraction of bound fluids in porous media (dimensionless), the effective stress of the skeleton, the average compressive stress of the bound fluids, and the internal force vector, respectively.

Based on the principle of virtual work, the discrete equilibrium equation of the reservoirs of porous media is obtained:

$$\int_V \sigma : \delta \varepsilon dV = \int_s t \cdot \delta v dV + \int_V f \cdot \delta v dV + \int_V (S_w + n_t)\rho_w g \cdot \delta dV \quad (6)$$

where $\delta \varepsilon$ and δv denote the virtual deformation rate ($\text{m} \cdot \text{s}^{-1}$) and the virtual velocity field ($\text{m} \cdot \text{s}^{-1}$), respectively, and t , f , S_w , ρ_w , and g represent the surface traction force per unit area ($\text{N} \cdot \text{m}^{-2}$), force vector (N), liquid saturation (%), liquid density ($\text{kg} \cdot \text{m}^{-3}$), and gravitational acceleration ($\text{m} \cdot \text{s}^{-2}$), respectively.

2.3. Conservation of Energy

Heat absorption due to the decomposition and heat exchange of fluids in the seepage process accompanies the production process of NGHs. Therefore, the influences of heat exchange need to be considered in the energy equations. Effective thermal conductivity highly depends upon the pore-scale habit of hydrates, and also includes the influence of many factors such as the change of the relevant effective stress [21]. In this study, based on the characteristics of the study area and previous studies [22], the selection equation is shown as Equations (7)–(9):

$$\frac{\partial}{\partial t}(C_t T) = \nabla \cdot (K_t \nabla T) + \nabla \cdot (\rho_g \vec{u}_g C_{pg} + \rho_w \vec{u}_w C_{w}) - r^h \Delta H_h + q_e \quad (7)$$

$$C_t = \varphi(\rho_w S_w C_w + \rho_g S_g C_g + \rho_h S_h C_h) + \rho_s C_s(1 - \varphi) \quad (8)$$

$$K_t = \varphi(S_w K_w + S_g K_g + S_h K_h) + K_s(1 - \varphi) \quad (9)$$

where C_t and K_t represent the comprehensive effective specific heat capacity ($\text{J}\cdot\text{kg}^{-1}\cdot^\circ\text{C}^{-1}$) and the comprehensive coefficient of thermal conductivity ($\text{W}\cdot\text{m}^{-1}\cdot^\circ\text{C}^{-1}$) of reservoirs; ρ_g , ρ_w , ρ_h , and ρ_s denote the densities of the gas, liquid, hydrate, and reservoir skeleton ($\text{kg}\cdot\text{m}^{-3}$); C_g , C_w , C_h , and C_s refer to the specific heat capacity of the gas, liquid, hydrate, and reservoir skeleton ($\text{J}\cdot\text{kg}^{-1}\cdot^\circ\text{C}^{-1}$); $\vec{u}_g$ and $\vec{u}_w$ are the seepage velocities of the gas and liquid ($\text{m}\cdot\text{d}^{-1}$), respectively; r^h , ΔH_h , and q_e represent the decomposition rate of the NGHs ($\text{mol}\cdot\text{L}^{-1}\cdot\text{s}^{-1}$), heat released by the NGH decomposition ($\text{J}\cdot\text{mol}^{-1}$), and heat transferred by the overlying and underlying strata (J); K_g , K_w , K_h , and K_s are coefficients of thermal conductivity of the gas, liquid, hydrate, and reservoir skeleton ($\text{W}\cdot\text{m}^{-1}\cdot^\circ\text{C}^{-1}$); S_g , S_w , and S_h denote the gas, liquid, and hydrate saturations (%), respectively; and ϕ is the porosity.

2.4. Conservation of Mass

In the production process of NGHs, NGHs are decomposed into natural gas and water. Therefore, the gas and liquid phases need to be added in the mass conservation equations, which are expressed as Equations (10)–(12) [22]:

The gas phase:

$$\frac{\partial}{\partial t}(\phi\rho_g S_g) = \nabla \cdot (\rho_g \vec{u}_g) + r^g + q_g \quad (10)$$

The liquid phase:

$$\frac{\partial}{\partial t}(\phi\rho_w S_w) = \nabla \cdot (\rho_w \vec{u}_w) + r^w + q_w \quad (11)$$

The hydrate phase:

$$-r^h = \frac{\partial}{\partial t}(\phi\rho_h S_h) \quad (12)$$

where ϕ is porosity; ρ_g , ρ_w , and ρ_h represent the gas, liquid, and hydrate densities ($\text{kg}\cdot\text{m}^{-3}$); S_g , S_w , and S_h denote the gas, liquid, and hydrate saturations (%), respectively; $\vec{u}_g$ and $\vec{u}_w$ are the gas and liquid seepage of ($\text{m}\cdot\text{d}^{-1}$), respectively; r^g , r^w , and r^h denote the decomposition rates of the gas, liquid, and hydrate, respectively; and q_g and q_w are the gas and liquid source/sink terms, respectively.

2.5. Physical Parameters of Reservoirs

NGHs occur in pores of strata in the form of solids that do not participate in fluid flow. Thus, the saturation of NGHs will markedly affect the practical permeability and effective porosity of strata. Based on previous studies [23], reservoir permeability has the following relationship with natural gas saturation:

$$k = k_0 \cdot (1 - S_h)^n \quad (13)$$

where k and k_0 are the permeability and initial permeability of the reservoir ($10^{-3}\mu\text{m}^2$); S_h denotes the hydrate saturation of the reservoir (%); and n represents the saturation exponent of the reservoir.

Porosity has the following relationship with natural gas saturation:

$$\phi_e = \phi_0 \times (1 - S_h) \quad (14)$$

where ϕ_e and ϕ_0 represent the effective and initial porosities, respectively.

The void ratio and permeability coefficient were adopted to describe the seepage property of materials in the model. The void ratio and porosity of a reservoir have the following relationship:

$$e = \frac{\phi}{1 - \phi} \quad (15)$$

where e and ϕ represent the void ratio and porosity of the reservoir, respectively.

The relationship between the permeability coefficient and the permeability of a reservoir is as follows:

$$K = \frac{\gamma k}{\mu} \quad (16)$$

where K and k refer to the permeability coefficient ($\text{m} \cdot \text{d}^{-1}$) and permeability ($10^{-3} \mu\text{m}^2$) of the reservoir, respectively; γ is the bulk weight of pore fluids ($\text{N} \cdot \text{m}^{-3}$); and μ is the dynamic viscosity of pore fluids ($\text{N} \cdot \text{s} \cdot \text{m}^{-2}$).

2.6. Mechanical Properties of NGH-Bearing Sediments

Taking the NGH reservoir in the northern South China Sea as the research object [24], mechanical tests were conducted on NGH-bearing sediments using a low-temperature triaxial apparatus for hydrates. The Mohr–Coulomb criterion was adopted to describe the plastic yield behavior of the NGH reservoir, and the deviatoric stress was determined from the effective confining pressure, internal friction angle, and cohesion [25]:

$$\sigma_1 - \sigma_3 = \frac{2 \sin \varphi(S_h)}{1 - \sin \varphi(S_h)} \times \sigma_3 + \frac{2 \cos \varphi(S_h)}{1 - \sin \varphi(S_h)} \times c(S_h) \quad (17)$$

According to the test results, the cohesion and internal friction angle of NGH-bearing sediments with different initial saturations were determined, resulting in the following relationship between the cohesion and saturation of NGH-bearing sediments [26]:

$$c = 0.35 + 1.5S_h \quad (18)$$

where c denotes the cohesion of NGH-bearing sediments (MPa) and S_h is the hydrate saturation.

2.7. Evaluation Criterion of Slope Stability

The strength reduction method was first proposed by Zienkiewicz et al. [27], and strength reduction is defined as the ratio of the maximum shear strength that can be provided by soil to the actual shear stress produced by external loads in the slope when the remaining external loads remain unchanged. The strength reduction method is characterized by the advantages of a clear physical meaning and simple calculation. Therefore, this method was used to analyze the stability of submarine slopes following the principle of calculating the shear strength of soil corresponding to different reduction factors through reduction. In the model computation process, the shear strength of the soil gradually decreases with an increasing reduction factor. If the strength of the slope's soil fails to bear the external loads, plastic yield zones form, and the soil fails.

When following the Mohr–Coulomb strength criterion, the shear strength parameter after reduction can be expressed as follows [28]:

$$\tau = \frac{c + \sigma \tan \varphi}{F_r} = \frac{c}{F_r} + \sigma \frac{\tan \varphi}{F_r} = c_m + \sigma \tan \varphi_m \quad (19)$$

$$c_m = c / F_r \quad (20)$$

$$\varphi_m = \arctan(\tan \varphi / F_r) \quad (21)$$

where τ is the shear strength of the soil (Pa); c and φ denote the cohesion (Pa) and internal friction angle ($^\circ$) that can be provided by the soil, respectively; σ denotes the normal stress on the shear plane of the soil (Pa); c_m and φ_m represent the actual cohesion (Pa) and actual internal friction angle ($^\circ$) of the soil, respectively; and F_r is the strength reduction factor. The strength reduction factor F_r at slope failure equals the safety factor F_s for slope stability. $F_s > 1$, $F_s = 1$, and $F_s < 1$ indicate that a slope is stable, metastable, and in the failure state, respectively.

3. Stability of Submarine Slopes during NGH Exploitation via Well Patterns

3.1. Establishment of the Numerical Model

3.1.1. Model Overview

Figure 1 shows a schematic diagram of the slope model. The total length of the submarine slope model is 2400 m, the height is 800 m, the width is 1200 m, and the upper water depth is 1100 m. The length and width of the NGH layer are 1200 m. The lengths of the upper and lower horizontal sections are the same, and the values are set according to the dip angle. The NGH layer is parallel to the slope surface. The rightmost side of the model is immediately below the slope crest, and the leftmost side is immediately below the slope toe. Section 1 is set along the slope dip direction, while Section 2 is perpendicular to the slope dip direction. Section 1 in Figure 2a is parallel to the XOZ plane and at the location of $Y = 600$ m, while Section 2 is at the location of $X = 600$ m, parallel to the YOZ plane. Wells are arranged along the sections of the NGH reservoir. The transverse distances of the NGH layer along the X and Y directions are both 1200 m. Wells are uniformly arranged along the sections of the NGH reservoir according to the set well spacing. Figure 2b shows the relative locations of wells when arranging a single well and multiple wells with well spacings of 400, 300, and 200 m in Sections 1 and 2, in which dotted lines indicate the locations of wells. X and Y indicate that wells are arranged parallel to the XOZ and YOZ planes, and the following numbers represent the number of wells, so that the design schemes are labeled X1, X2, X3, X5, Y1, Y2, Y3, and Y5. Considering the spatial symmetry of the model, test schemes X1 and Y1 are the same.

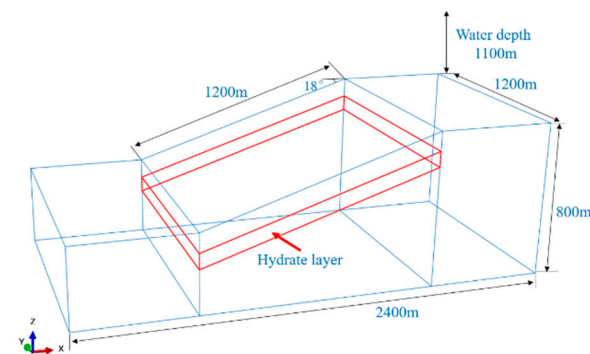


Figure 1. Schematic diagram of the submarine slope model.

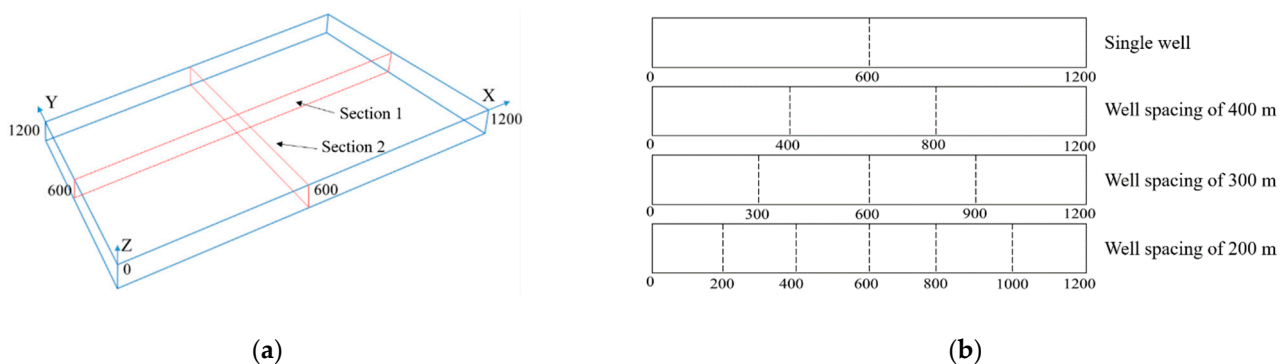


Figure 2. Schematic diagram of section and well placement. (a) Sections in the reservoir. (b) Locations of wells in the sections.

The finite element software was used to solve the model, and the solving flow chart was shown in Figure 3.

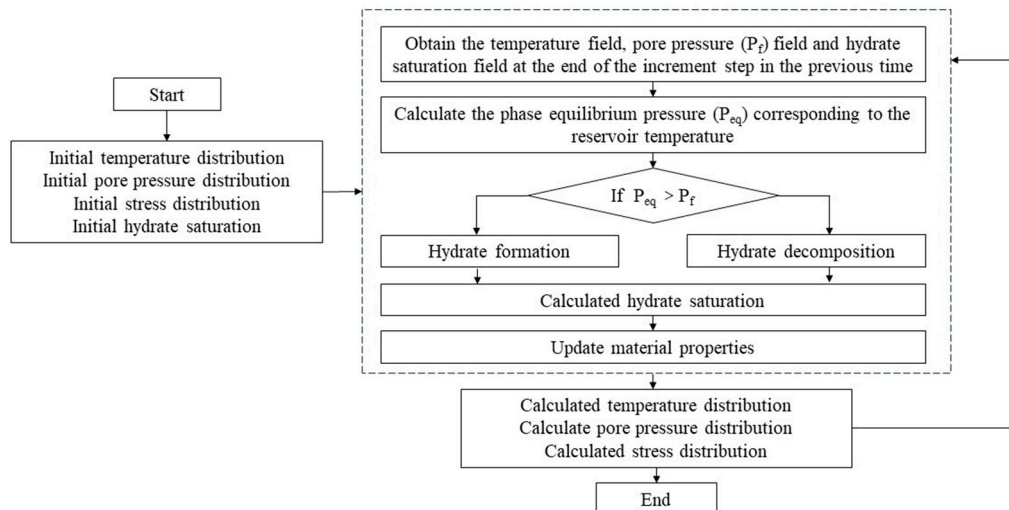


Figure 3. Solving flow chart of the submarine slope model.

3.1.2. Model Parameters

According to exploration data of the Shenhu area in the South China Sea [29], the slope dip in the research area is in the range of 0~20°. NGHs are distributed in sediments with seawater depths greater than 800 m and burial depths less than 400 m. The reservoir has low permeability and the NGHs have a variable distribution, meaning that the NGH saturation is 2~48%. Supposing that the seabed temperature of the model is fixed at 4 °C and does not change with the depth of the seawater, the geothermal gradient is 35 °C·km⁻¹ and the initial NGH saturation is 50%. The basic parameters of the model are shown in Table 1 [30,31].

Table 1. Basic parameters of the model.

Parameter	Value	Unit
Specific heat capacity of formation	1.0	kJ·kg ⁻¹ ·°C ⁻¹
Coefficient of thermal conductivity of formation	1.0	W·m ⁻¹ ·°C ⁻¹
Density of formation	2600	kg·m ⁻³
Intrinsic permeability	10	mD
Geothermal gradient	35	°C·km ⁻¹
Porosity	0.4	
Specific heat capacity of seawater	4.2	kJ·kg ⁻¹ ·°C ⁻¹
Coefficient of thermal conductivity of seawater	0.6	W·m ⁻¹ ·°C ⁻¹
Density of seawater	1040	kg·m ⁻³
Specific heat capacity of NGHs	2.1	kJ·kg ⁻¹ ·°C ⁻¹
Coefficient of thermal conductivity of NGHs	0.5	W·m ⁻¹ ·°C ⁻¹
NGH density	910	kg·m ⁻³

3.2. Production and Slope Failure Dynamics

The significant reduction in reservoir strength due to NGH decomposition is one of the causes of failure in NGH-bearing submarine slopes. NGH decomposition and the resulting dynamic response of formations are similar to slope failure. Therefore, the NGH decomposition dynamics must be studied, and the evolution of the physical parameters of the formations, deformation responses of the formations, and failure processes of the slope during NGH exploitation must be analyzed.

3.2.1. Production Dynamics

(1) NGH decomposition dynamics

When exploiting NGHs through depressurizing production, the pressure drop spreads from the production well, and NGHs begin to decompose when the pressure drop propa-

gates to the interior of the reservoir. The higher the formation temperature is, the lower the pressure drop needed for NGH decomposition. Therefore, the decomposition rate of NGHs in deep formations is obviously higher than that in shallow formations, and the NGH decomposition zone is spatially distributed in an irregular conical shape around the well.

Figure 4a shows contour maps of the NGH saturation along Section 1 in the slope after production using scheme X2 under 6 MPa for 720 d. In the exploitation process, the NGH decomposition front moves from the wellbore to the surrounding areas, and the NGH decomposition range induced by a single well is 150 m. There is a transition zone at the decomposition front of NGHs, where NGHs are not completely decomposed. Influenced by the propagation of the production pressure, the longer the distance from the wellbore is, the more difficult the NGH decomposition; therefore, NGH saturation increases away from the wellbore. Figure 4b illustrates contour maps of the NGH saturation along Section 1 in the slope after production using scheme X5 under 6 MPa for 720 d. Compared with Figure 4a, the NGHs surrounding each well are decomposed in the same manner when extracting NGHs using the same method, while the decomposition degree of the NGHs in the region between the wells rises as the well spacing is narrowed.

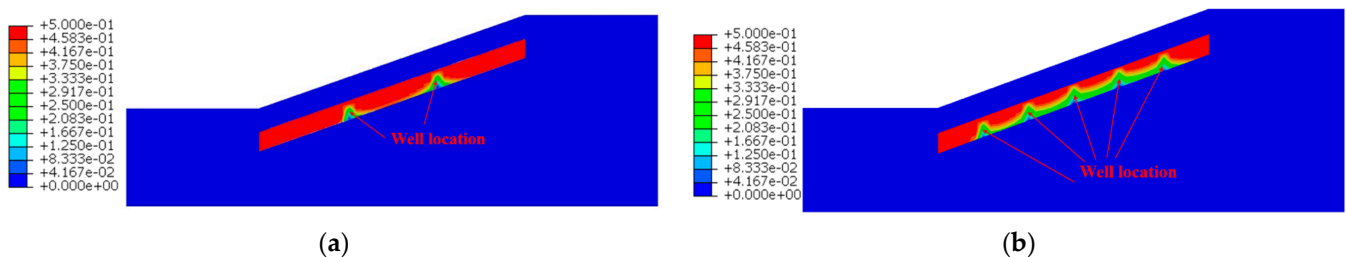


Figure 4. Hydrate saturation contour map along Section 1. (a) X2. (b) X5.

The exploitation duration of NGHs can be prolonged. When taking the maximum distance of the decomposition front of NGHs around a single well as the decomposition range of the NGHs, the changes in the decomposition range within 1500 d of NGH exploitation are attained, as displayed in Figure 5. The decomposition rate of NGHs increases at first and then decreases. In the initial period of exploitation, NGHs are slowly decomposed. This is because NGHs are present as solids in the pores of the reservoir, which reduces the initial permeability of the reservoir and results in a low effective void ratio so that the production pressure fails to rapidly propagate to the interior of the reservoir. As the NGHs are decomposed into fluids, the permeability and effective void ratio of the reservoir gradually increase, and the production pressure can effectively propagate to the deep part of the reservoir. As a result, the decomposition rate rises; as the decomposition range enlarges, the propagation distance of the pressure drop grows, and the pressure drop gradient at the decomposition front of NGHs drops, so the decomposition rate slows.

(2) Propagation dynamics of the pore pressure

Exploiting NGHs through depressurizing production promotes the redistribution of the pore pressure in the surrounding formations of wells by reducing the flowing bottomhole pressure of production wells. When the formation pore pressure is lower than the NGH phase equilibrium pressures, NGHs are decomposed. The propagation range of the formation pore pressure determines the decomposition range of NGHs.

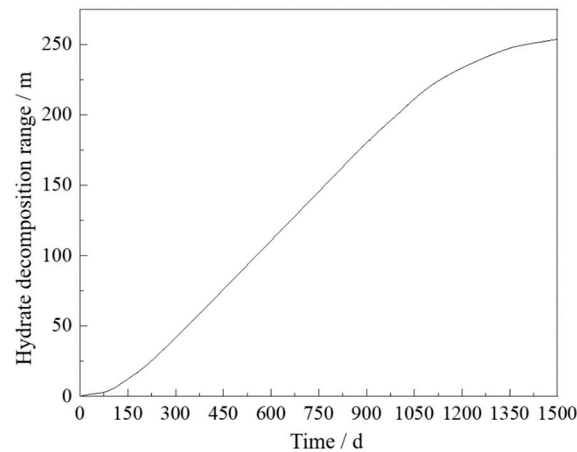


Figure 5. Hydrate decomposition rate.

Figure 6a displays contour maps of the pore pressure along Section 1 in the slope after production using scheme X2 under 6 MPa for 720 d. In the figure, the pressure drop spreads radially around the wellbore, thus forming a cylindrical high-pressure-drop region with the wellbore as the axis and a radius of 50 m. Because the effective porosity and permeability of the NGH reservoir increase significantly after NGH decomposition and production, the pore pressure propagates anisotropically in the slope, and the propagation velocity of the low pressure in the NGH reservoir is much faster than that in the overlying and underlying strata. Figure 6b shows contour maps of the pore pressure using scheme X5 under the same conditions, and its comparison with Figure 6a reveals that the pressure drop of each well propagates in the same manner, while the superimposed effect of the pressure drop is enhanced with the narrowing of the well spacing. Moreover, a comparison of the contour maps of the pore pressure and the NGH saturation also shows that the NGH decomposition zone is located within the high-pressure-drop range of the pore pressure and that the two have some correlations.

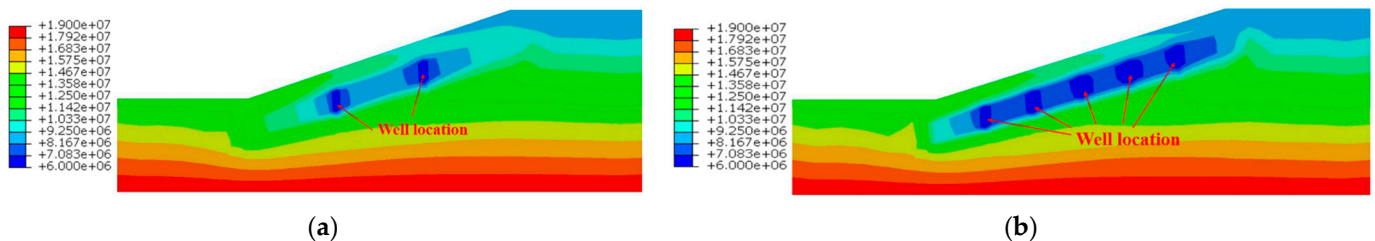


Figure 6. Pore pressure contour map along Section 1. (a) X2. (b) X5.

Monitoring points that are 50, 100, 150, and 200 m from the right wellbore (at $X = 800$ m) are set down the slope ($-X$ direction) and perpendicular to across the slope (Y direction). Figure 7 illustrates the change curves of the pore pressure at each monitoring point with time. Within the initial 200 d of depressurizing production of NGHs, the pore pressure in the surrounding formations of the well drops rapidly. As depressurizing production is prolonged, the decreasing trend of the pore pressure gradually tends to stabilize. Moreover, the magnitude of the pressure drop decreases with increasing distance to the wellbore. By comparing the pore pressures at monitoring points the same distance from the well but in different directions, the pore pressures in different directions are found to differ only slightly at distances of 50 and 100 m; the pore pressure in the X direction is lower than that in the Y direction when the distance is 200 m. This is because of the influences of the superimposed effect of the pressure drop caused by depressurizing production of the left well.

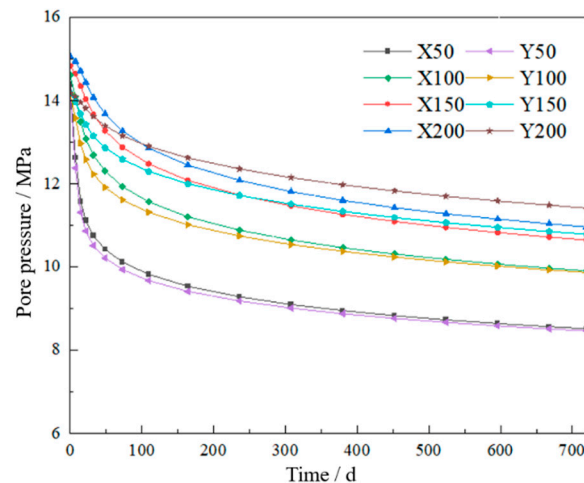


Figure 7. Variation curve of pore pressure at each monitoring point.

(3) Deformation responses of formations

Changes in the effective stress may cause deformation and variation in the shear strength of formations. Figure 8a,b illustrates the contour maps of the maximum principal stress and maximum principal strain along Section 1 in the slope after production following scheme X2 for 720 d. The region with strain in the formations is consistent with the NGH decomposition zone in Figure 4a.

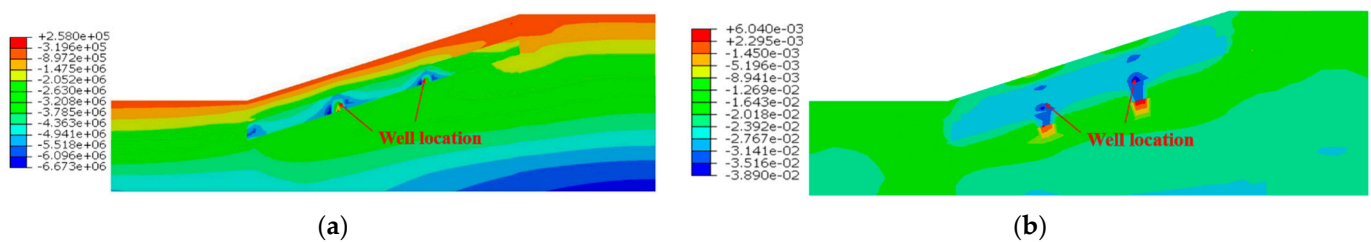


Figure 8. Maximum principal stress contour map and maximum principal strain contour map along Section 1. (a) Distribution of the maximum principal stress. (b) Distribution of the maximum principal strain.

When exploiting NGHs through depressurizing production, the pore pressure of the formations decreases, and the effective stress of the formations increases. However, the strength of the NGH reservoir declines with the decomposition of NGHs, and the effective stress that can be borne by the reservoir also decreases. The strength difference causes a local stress concentration at the decomposition front of the NGHs. Under this high effective stress, the NGH decomposition zone is squeezed and deformed, which triggers the settlement of overlying strata and even submarine landslides. As shown in Figure 8b, the underlying strata are lifted. This is because the NGH decomposition zone cannot compress the underlying strata; additionally, NGHs near the lower boundary of the reservoir are decomposed to a higher degree, and the reservoir strength is weakened more seriously.

The NGH decomposition zone is squeezed and deformed under the joint action of the high effective stress and the low reservoir strength, accompanied by corresponding changes in the porosity and permeability. Figure 9 shows contour maps of the formation porosity, which is correlated with the distribution of the maximum principal strain. The porosity decreases toward the NGH decomposition zone. The initial porosity of the formations is set to 0.4, while the minimum porosity drops to 0.3414 when production finishes, which is found in the complete decomposition zone of the NGHs.

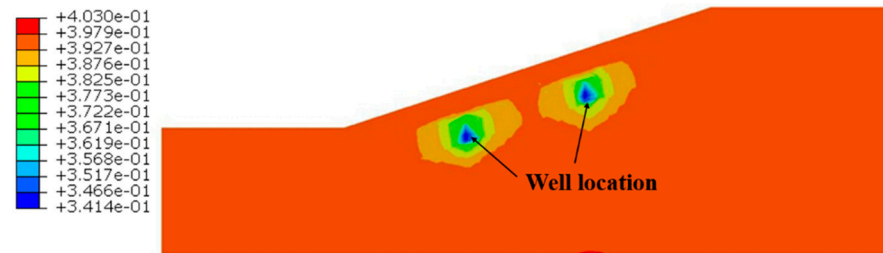


Figure 9. Porosity contour map along Section 1.

Contour maps of the vertical displacement along Section 1 of the slope at the end of production following scheme X2 are illustrated in Figure 10a. The strength of the NGH decomposition zone is lower than that of the overlying and underlying strata, which induces the settlement of the overlying strata and lifting of the underlying strata. Figure 10b shows contour maps of the total displacement vector along Section 1 of the slope when using scheme X2. The location of vector lines represents the location distribution of displacement in the slope, and the magnitude of displacement is indicated by the length and color of vector segments. Figure 10c,d displays the contour maps of the vertical displacement and total displacement vector under scheme X5. Compared with scheme X2, the decrease in the well spacing under scheme X5 results in enlargement of the region of the slope with formation deformation, which is more likely to induce submarine landslides.

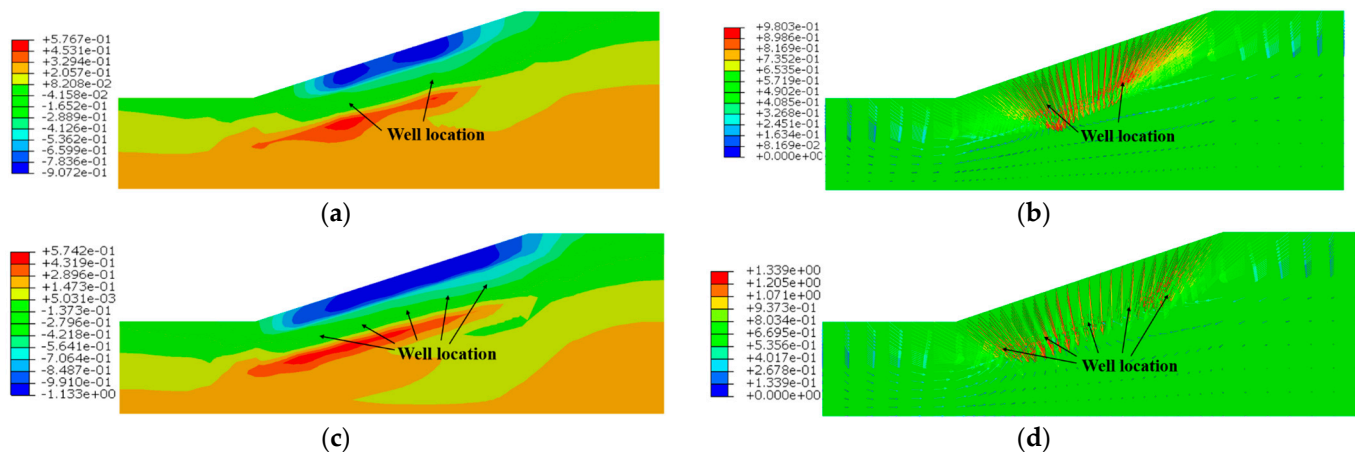


Figure 10. Vertical displacement contour maps and total displacement vector maps along Section 1. (a) Contour maps of the vertical displacement under scheme X2. (b) Vector maps of the total displacement under scheme X2. (c) Contour maps of the vertical displacement under scheme X5. (d) Vector maps of the total displacement under scheme X5.

Contour maps of the total displacement are shown in Figure 11. Because the strength of the NGH decomposition zone decreases, the NGH layer and the surrounding strata slide toward and therefore squeeze the NGH decomposition zone of NGHs, thus causing funnel-shaped deformation centered on the well in the formations. The formation deformation of the slope in the extraction process of NGHs is dominated by stratum settlement and induces the transverse slip of the surrounding strata.

Figure 12 illustrates the displacement curves of the submarine slope surface at different production times under scheme X2. Affected by the slope dip, the settlement curves of the seabed surface are not symmetric about the wells, and the settlement above the wells is largest. A comparison of the settlement curves at different times reveals that the settlement rate of the seabed is large in the initial production stage and that the maximum settlement reaches 0.504 m after production for 100 d. Later, the settlement rate of the seabed gradually decelerates, and the maximum settlement reaches 0.913 m after 720 d of production. Therefore, close attention needs to be paid to the monitoring of seabed

settlement in the initial production stage in practical engineering, and preventive measures should be taken.

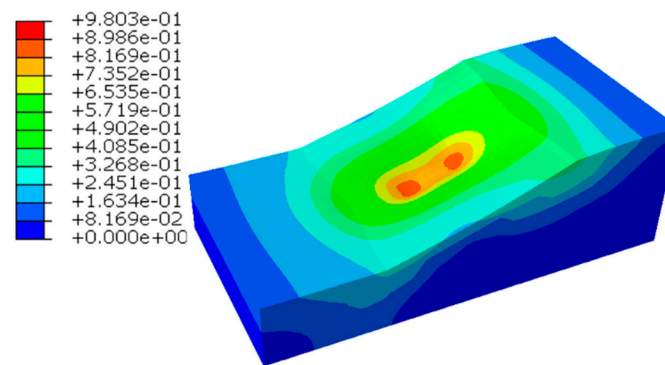


Figure 11. Contour map of the total displacement of the slope.

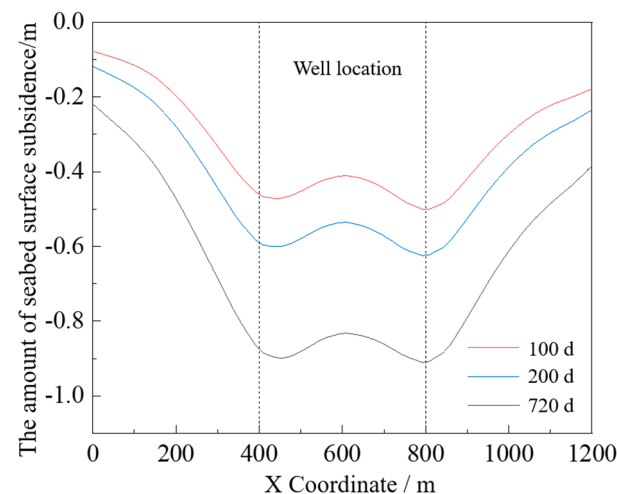


Figure 12. Seabed surface subsidence curves at different production times.

3.2.2. Failure Process of the Submarine Slope

During modeling, after the production of NGHs, the computational procedure enters the analysis step of strength reduction, and the reduction factor gradually increases. Through conversion, the obtained shear strength of the slope gradually reduces while the external load on the slope remains unchanged until the failure of the slope. In the reduction process, the stress in the formations is redistributed due to the changes in the shear strength of the reservoir. The strength reduction factor corresponding to the final failure of the slope is equal to the safety factor of the slope.

The appearance of plastic zones indicates that the pressure produced by loads on the slope exceeds the ultimate bearing capacity of the slope, local areas of the slope begin to yield in zones with unrecoverable deformation, and the slope begins to be damaged. When the plastic zones coalesce, the slope fails. Figure 13 illustrates the development process of plastic zones in Section 1 of the slope under scheme X2 corresponding to different reduction factors. With the increase in the reduction factor, the plastic zones first appear in the NGH decomposition zone, gradually developing to the slope toe to finally form a plastic yield zone. When the reduction factor is 0.6626, plastic zones appear in the NGH decomposition zone and the slope toe, and no obvious deformation is observed in the slope under these conditions. When the reduction factor is 1.2575, plastic zones in the NGH decomposition zone are connected to those in the slope toe. Under a reduction factor of 1.5281, a plastic yield zone is formed, and the strength reduction factor is equal to the safety factor of the slope. Because the NGH decomposition zone is small during double-well production,

the final yield zone does not pass through the NGH layer. Due to the large difference in the plasticity of the NGH reservoir and the yield zone, the red area in the yield zone represents the model error induced by boundary conditions when the reduction factor is 1.5281. This indicates that formation deformation during production under the double-well scheme X2 exerts a certain influence on wellhead stability but does not induce large-scale landslides. Figure 14 shows contour maps of the displacement vectors of the slope when the calculation ends. The maximum displacement is 98.6 m, and the slope mainly shows horizontal displacement in the X direction. In the Z direction, the left side of the slope is lifted while the right side slides downward.

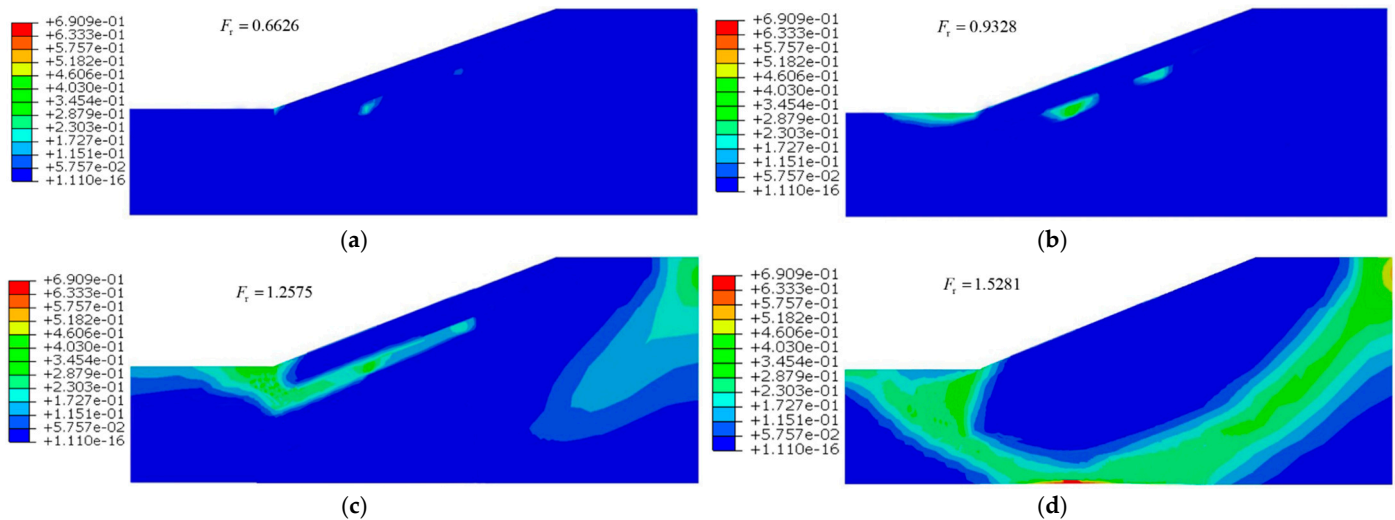


Figure 13. Plastic zone development process of X2. (a) Plastic zones when $F_r = 0.6626$. (b) Plastic zones when $F_r = 0.9328$. (c) Plastic zones when $F_r = 1.2575$. (d) Plastic zones when $F_r = 1.5281$.

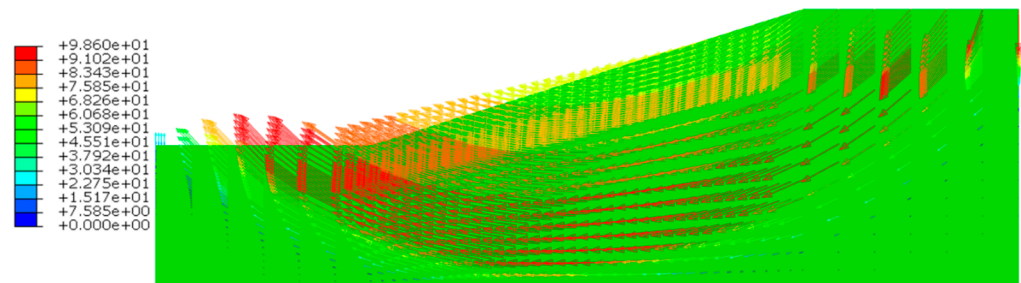


Figure 14. Slope displacement vector map along Section 1.

Figure 15 displays the development process of plastic zones in Section 1 of the slope under scheme X5 corresponding to different reduction factors. When the reduction factor is 0.963, plastic zones in the NGH decomposition zone are linked to those in the slope toe. The plastic yield zone is formed when the reduction factor is 1.170. Under these conditions, the strength reduction factor is equal to the safety factor of the slope. Compared with scheme X2, under scheme X5 with a narrower well spacing and more wells, the regions of connected plastic zones in the NGH decomposition zone and slope toe are larger, and coalesced plastic zones are more easily formed in the NGH layer. In addition, the safety factor of the slope decreases with the reduction in the well spacing.

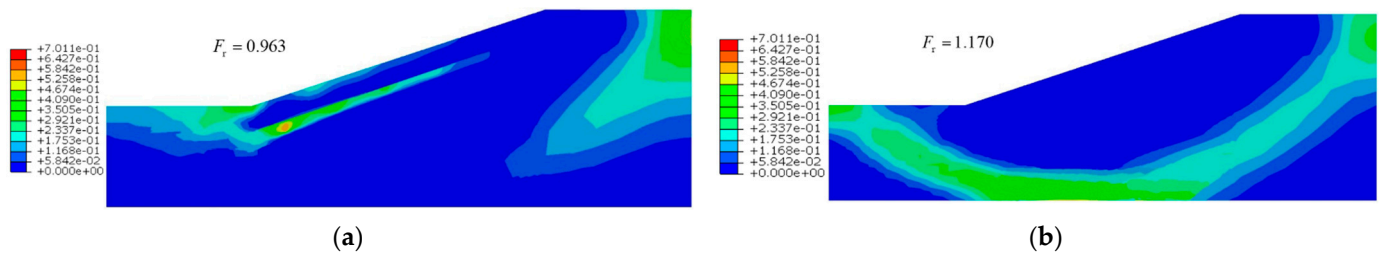


Figure 15. Plastic zone development process of X5. (a) Plastic zones when $F_r = 0.963$. (b) Plastic zones when $F_r = 1.170$.

3.3. Slope Stability during Exploitation through Well Patterns

3.3.1. Linear Well Layout along the Slope Dip Direction

Figure 16 displays saturation contour maps along Section 1 in the NGH reservoir after production for 720 d under schemes X1, X2, X3, and X5. The production law is similar under different schemes. When the wells are arranged with a spacing of 200 m, the decomposition degree at the lower boundary of the NGH reservoir in the region between wells increases under the superimposed effect of the pressure drop between wells.

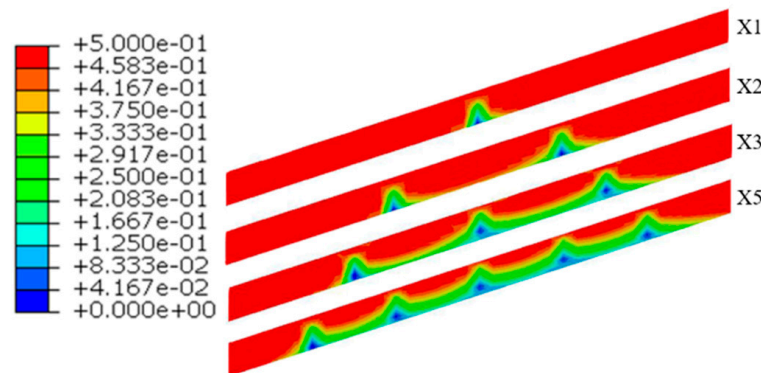


Figure 16. Saturation contour maps of the hydrate layer along Section 1.

Contour maps of the pore pressure after depressurizing production for 720 d under various schemes are displayed in Figure 17. The region 50 m around the wellbore is the high-pressure-drop region, which is small. A comparison of contour maps of pore pressures under different schemes shows that when exploiting NGHs via multiple wells, the superimposed effect of the pressure drop between wells gradually appears with the decrease in the well spacing. When the wells are arranged with a spacing of 200 m, obvious pressure drops are observed across the whole NGH reservoir, as displayed in Figure 17d.

Figure 18 illustrates the settlement curves of the seabed surface after production for 720 d under a production pressure of 6 MPa under various schemes. The schemes are listed in descending order as X5 (1.336 m), X3 (1.123 m), X2 (0.907 m), and X1 (0.735 m) according to the maximum seabed settlement, which indicates that the maximum settlement of the slope increases with the reduction in the well spacing. The settlement curves are not symmetric about the wells, while settlement above the well locations is larger than that at the well locations.

Figure 19 displays the safety factors of the slope when the production finishes under various schemes, which are ranked in descending order as X1 (1.602), X2 (1.528), X3 (1.402), and X5 (1.170). The safety factor decreases as the well spacing narrows. The safety factor under scheme X5 with a well spacing of 200 m is smaller than 1.2, which corresponds to a risk of failure in practical engineering. Therefore, the failure risk of slopes caused by an excessively small well spacing needs to be fully considered when arranging wells along the slope dip direction.

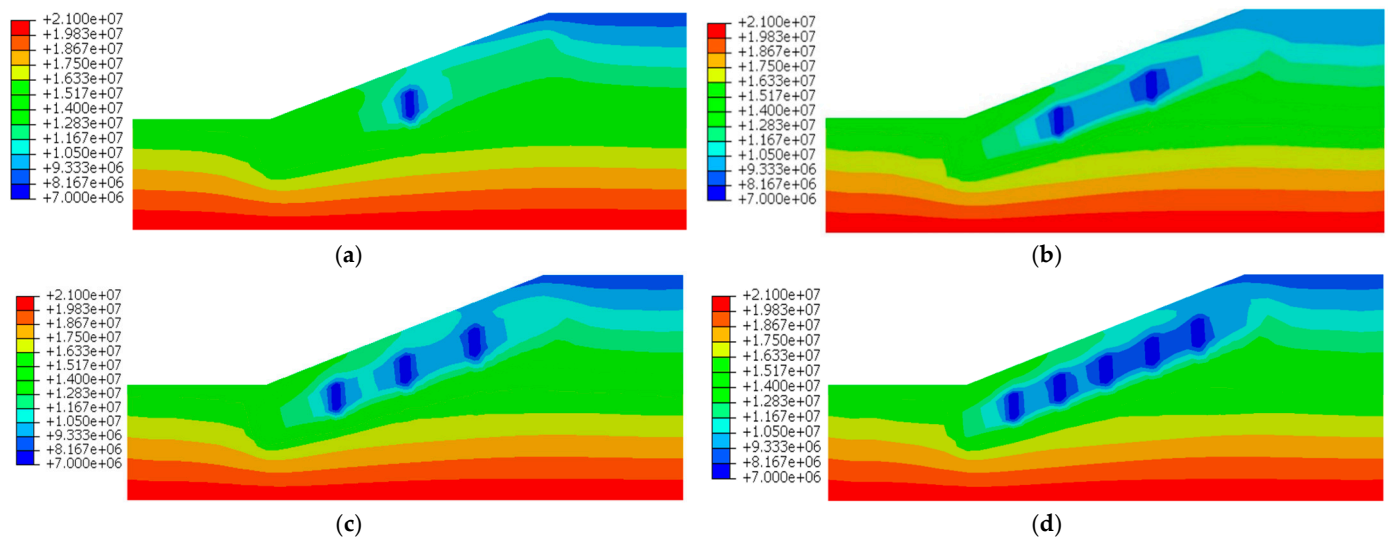


Figure 17. Pore pressure contour maps along Section 1. (a) X1. (b) X2. (c) X3. (d) X5.

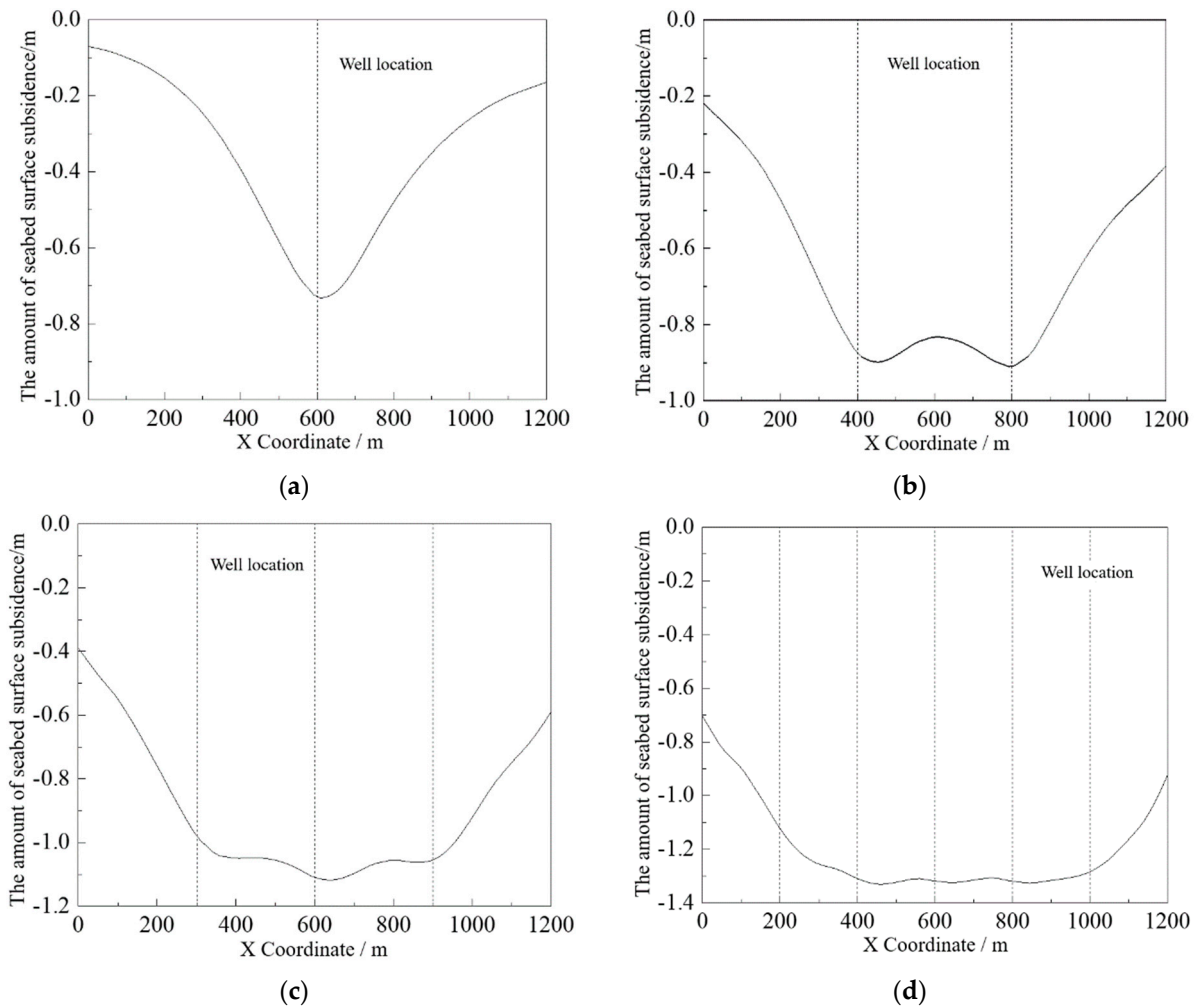


Figure 18. Seabed surface subsidence curves of each scheme. (a) X1. (b) X2. (c) X3. (d) X5.

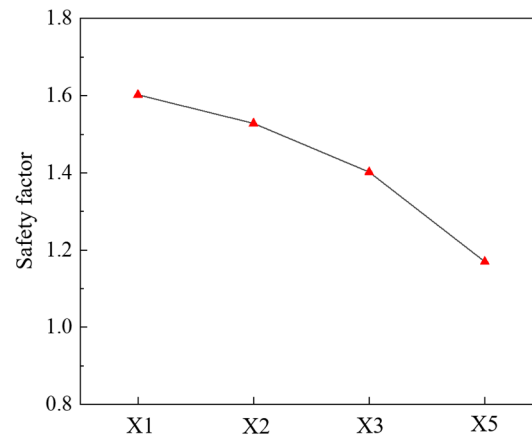


Figure 19. Safety factor of each scheme.

3.3.2. Linear Well Layout Perpendicular to the Slope Dip Direction

Figures 20 and 21 show contour maps of the pore pressure and saturation under schemes Y2, Y3, Y5, and Y1. Similar to the well layout along the slope dip direction, perpendicular to the slope dip direction, the production trends are also similar. With the reduction in the well spacing, the superimposed effect of the pressure drop in regions between wells is enhanced, and the lower boundary of the NGH reservoir in the region between wells begins to be decomposed under scheme Y5.

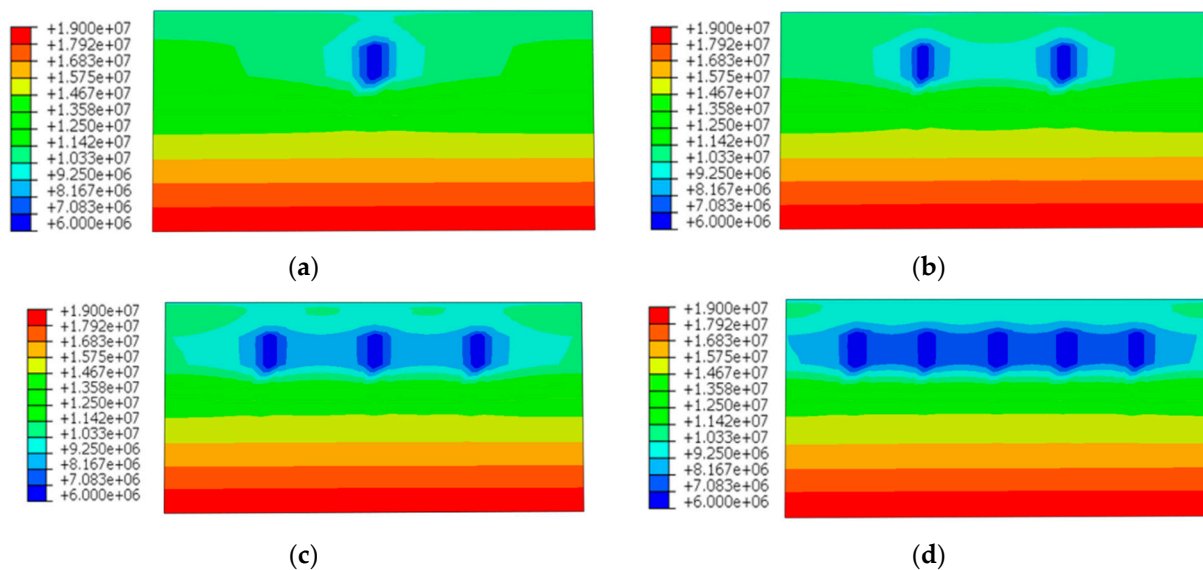


Figure 20. Pore pressure distribution along Section 2. (a) Y1. (b) Y2. (c) Y3. (d) Y5.

Figure 22 displays settlement curves of the seabed surface along Section 2 in the slope after production for 720 d under a production pressure of 6 MPa for various schemes. The schemes are ranked in descending order as Y5 (1.461 m), Y3 (1.199 m), Y2 (0.955 m), and Y1 (0.735 m) according to the maximum seabed settlement. As the well spacing decreases, the maximum settlement of the seabed surface enlarges, and the superimposed effect of settlement becomes remarkable. Because the schemes are not affected by the slope dip, settlement curves under various schemes are symmetrically distributed about the locations of the production wells in Section 2. The maximum settlement under Y1 is at the wellhead, while under Y2, it is in the region between the two wells. The settlement at the wellheads under Y3 and Y5 is slightly greater than in the regions between wells. This is, on the one hand, because of the accumulation effect due to the slipping of the soil on the two sides of a well toward the middle. On the other hand, this is because the superimposed effect

of the pressure drop is enhanced with the decrease in the well spacing so that the NGH decomposition degree is higher. In addition, the locations of the production wells show the highest decomposition degrees, where the underlying strata are uplifted due to the geostress, which influences the settlement at the locations of the production wells. Figure 23 illustrates contour maps of the vertical displacement along Section 2 in the slope, which shows that the overlying strata subside while the underlying strata are lifted.

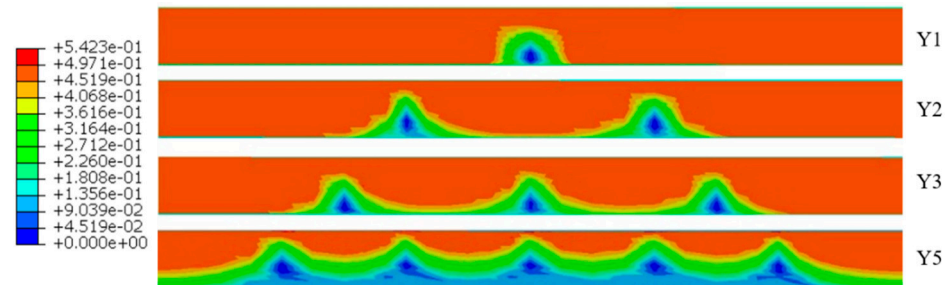


Figure 21. Hydrate saturation distribution along Section 2.

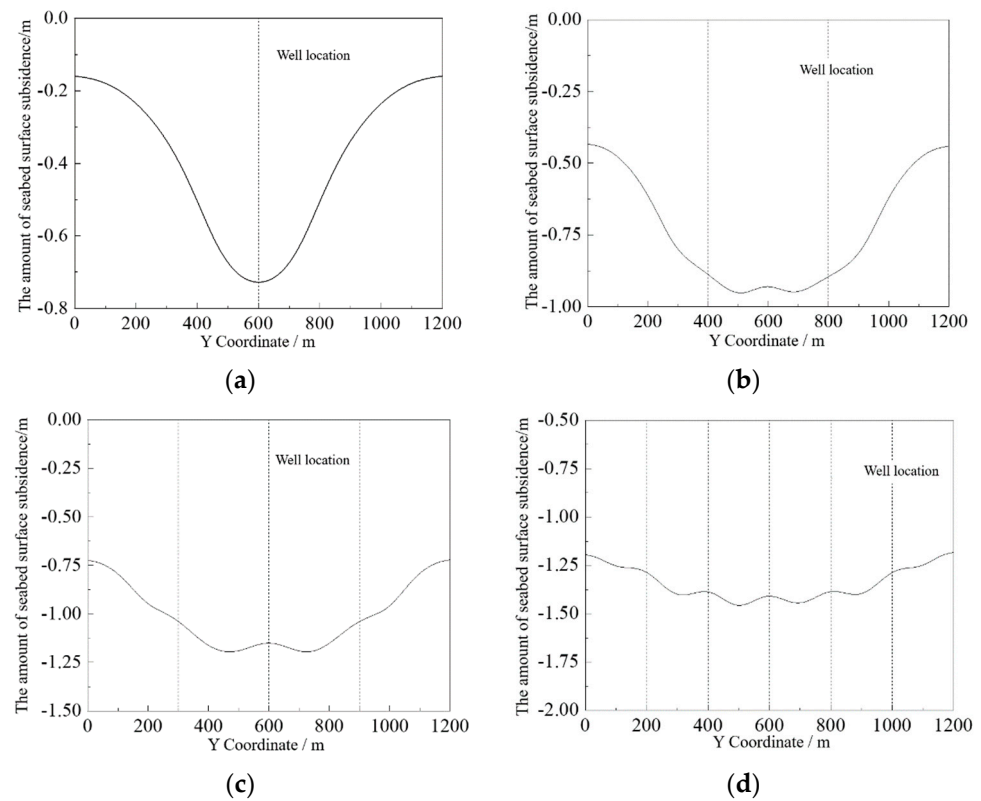


Figure 22. Seabed surface subsidence curves of each scheme. (a) Y1. (b) Y2. (c) Y3. (d) Y5.

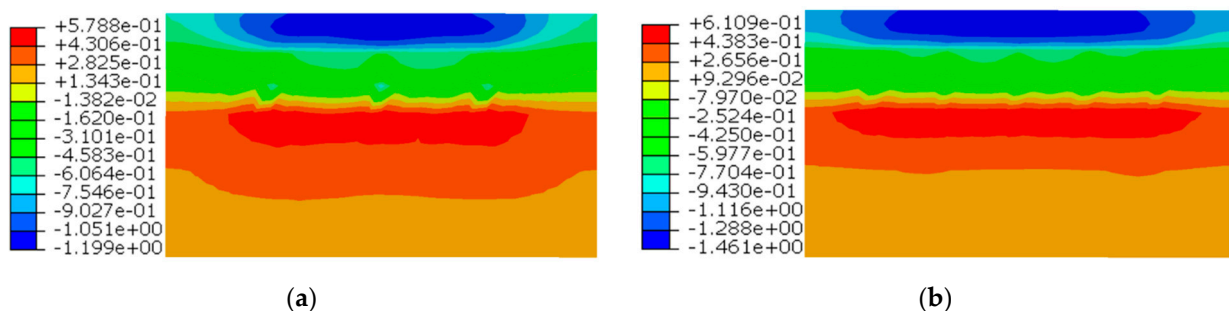


Figure 23. Vertical displacement contour maps along Section 2. (a) Y3. (b) Y5.

Figure 24a compares the maximum settlement of the seabed surface when arranging wells along and perpendicular to the slope dip direction. It can be seen that the range of large settlements is wider when arranging wells perpendicular to the slope dip direction under conditions of the same well spacing. Seabed settlement is more serious when arranging wells perpendicular to the slope, which may induce a greater risk of submarine landslides. Figure 24b illustrates the safety factors of the slope after production for 720 d under various schemes when arranging wells perpendicular to the slope dip direction, and the schemes are listed in descending order of the safety factor as Y1, Y2, Y3, and Y5. The slope safety factor decreases as the well spacing is narrowed, which leads to a gradual increase in the landslide risk of submarine slopes. The safety factor must be larger than 1.2 in engineering, and the safety factor of scheme Y5 is less than this value, so there is a risk of failure. By comparing the safety factors of schemes with the same well spacing and different well directions, it is found that the slope is more stable when wells are arranged along the slope dip direction.

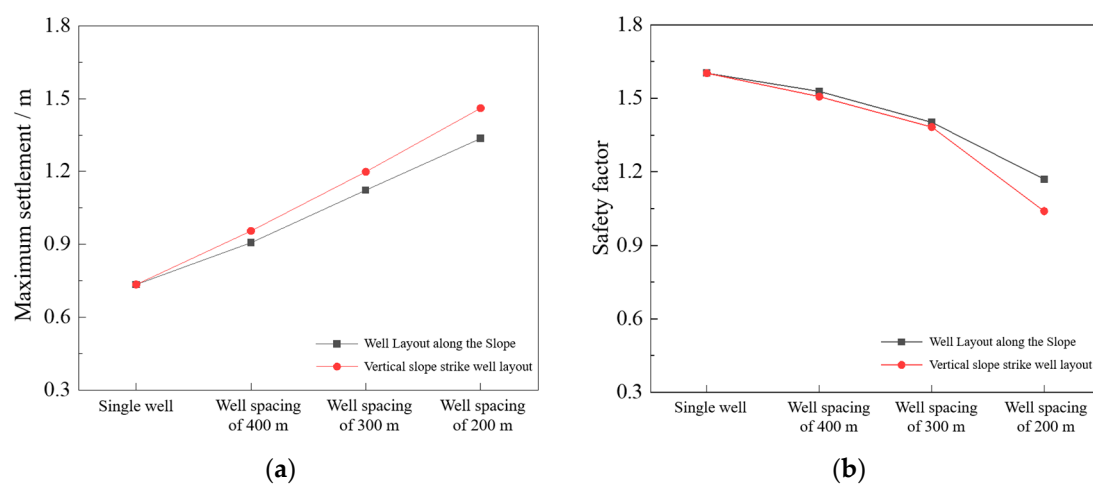


Figure 24. Comparison of the maximum settlement and safety factor of each scheme. (a) Maximum settlement. (b) Safety factor.

3.3.3. Arranging Well Patterns

When viewed from above, the NGH layer in the slope model is shown as a square of 1200 m $\times$ 1200 m. The square NGH exploitation region is subjected to $n \times n$ equal-area grid division, and a well is arranged at the midpoint of each grid [32]. Slopes with dip angles of 12°, 15°, and 18° are selected, in which the NGH layer is divided into 1 $\times$ 1, 2 $\times$ 2, 3 $\times$ 3, and 4 $\times$ 4 grids. A well is arranged at the midpoint of each grid to exploit NGHs for 720 d under a production pressure of 6 MPa. The corresponding schemes are termed V1 $\times$ 1, V2 $\times$ 2, V3 $\times$ 3, and V4 $\times$ 4.

Taking the slope with a dip angle of 12° as an example, Figure 25 shows contour maps of the pore pressure when the NGH reservoir is viewed from above and Figure 26 illustrates the pore pressure curves at different times corresponding to the dotted lines in the contour maps. The propagation range of the production pressure of each well is basically the same. In the initial stage of production, the pore pressure propagates fast, while the propagation velocity decreases in the late stage. The high-pressure-drop region is still limited to a small cylindrical range of 50 m around the wellbore after production for 720 d. With the increase in the well spacing density, the superimposed effect of the pressure drops of the production wells is enhanced, and the pore pressure in the regions between wells reduces significantly.

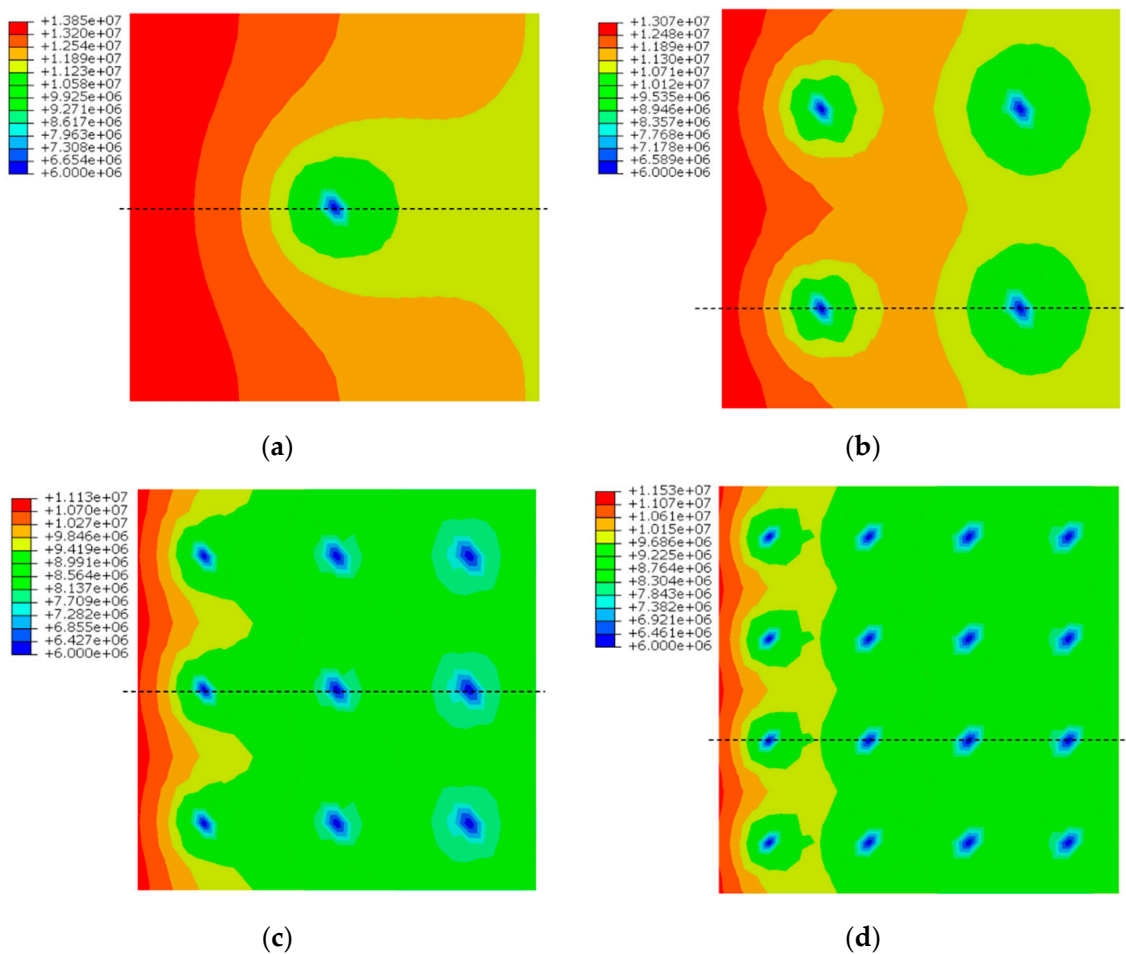


Figure 25. Pore pressure contour map of different well patterns. (a) $V1 \times 1$. (b) $V2 \times 2$. (c) $V3 \times 3$. (d) $V4 \times 4$.

According to geometric symmetry, the settlement curves of the seabed surface on the section of wells parallel to the XOZ plane are the same. Figure 27 illustrates the settlement curves of the seabed surface on the section of wells parallel to the XOZ plane under various schemes. When the well spacing density is the same, the settlement increases with increasing slope dip. Under the same slope dip, the settlement increases with increasing well spacing density. The maximum settlement is 0.735, 1.059, 1.688, and 2.206 m under schemes $V1 \times 1$, $V2 \times 2$, $V3 \times 3$, and $V4 \times 4$, respectively, when the slope dip is 18° . Influenced by the slope dip, the maximum settlement occurs slightly above the locations of the wells. As the slope dip increases, the deviation from the location of the maximum settlement to the locations of the wells grows, and the increase in the settlement in the upper part of the slope is more obvious than that in the lower part. Therefore, the exploitation of NGHs should fully consider the geological characteristics of the target area and prioritize the arrangement of wells in the upper part of the slope.

With the increase in the well spacing density, the superimposed effect of production pressure drops is gradually enhanced, and the NGH decomposition degree at the lower boundary of the NGH reservoir is improved. Depressurizing production causes the lifting of the formation in a certain range below the production wells. Influenced by the compression and deformation degree of the NGH reservoir and the drop in total vertical stress in the upper strata, the settlement at the well locations is slightly lower than that between wells in Figure 27d.

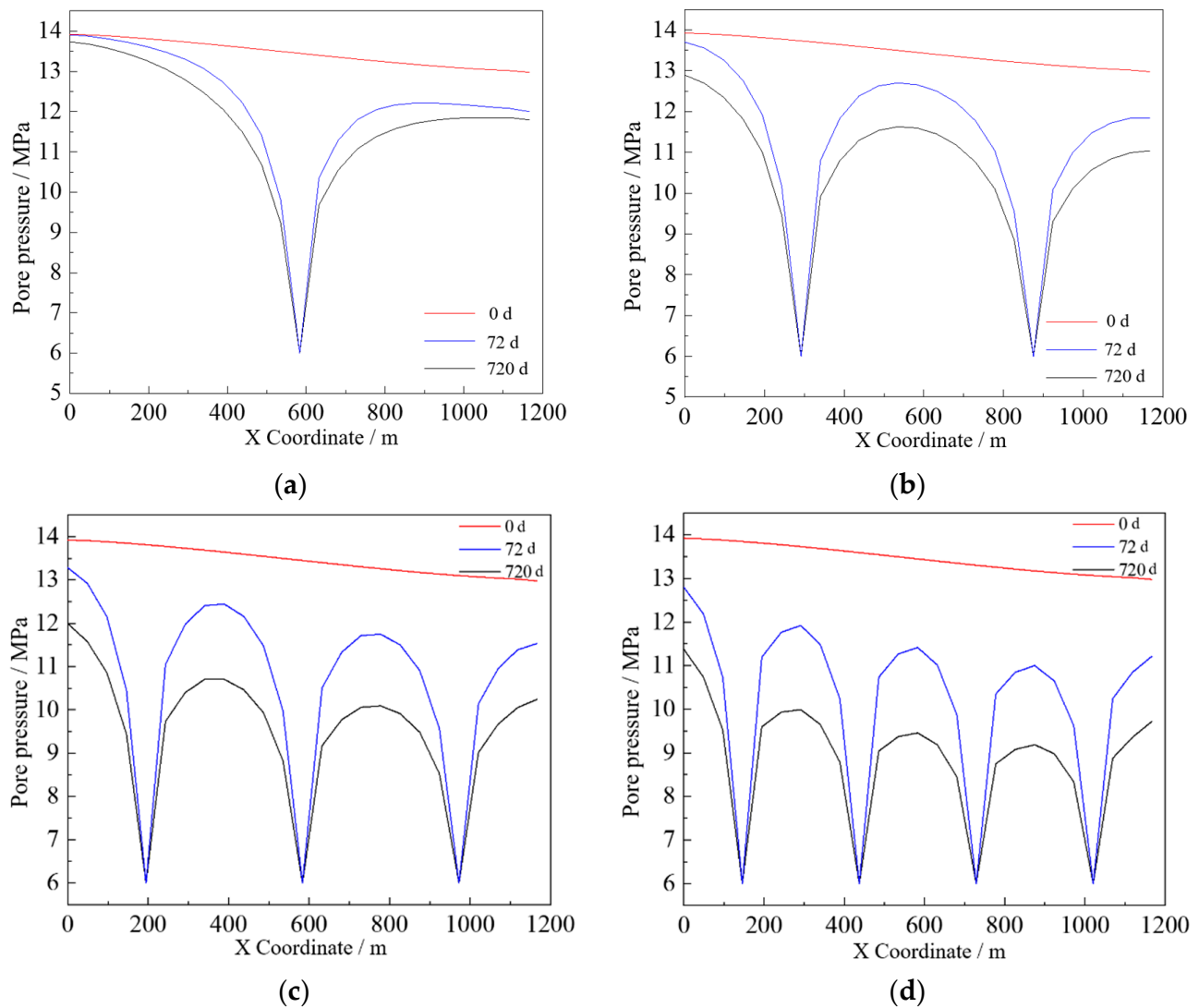


Figure 26. Pore pressure curve of different well patterns. (a) $V1 \times 1$. (b) $V2 \times 2$. (c) $V3 \times 3$. (d) $V4 \times 4$.

Figure 28 compares the safety factors under various schemes, and a slope model with the 5×5 well pattern is added. The results show that the slope dip has a large influence on the slope stability. The slopes with angles of 18° and 15° show the risk of failure after production for 720 d with well spacing densities larger than 2×2 and 4×4 , respectively; the slope with a dip angle of 12° still remains stable after production with a well spacing density of 5×5 for 720 d.

Contour maps of the total displacement of the slope with a dip angle of 18° after finishing production using the 4×4 well pattern are shown in Figure 29. Different from the well layout along a certain section, the depressurizing production of well patterns causes the upper part of the NGH reservoir to show a trend of overall settlement, and an obvious funnel-shaped depression area does not appear on the seabed surface.

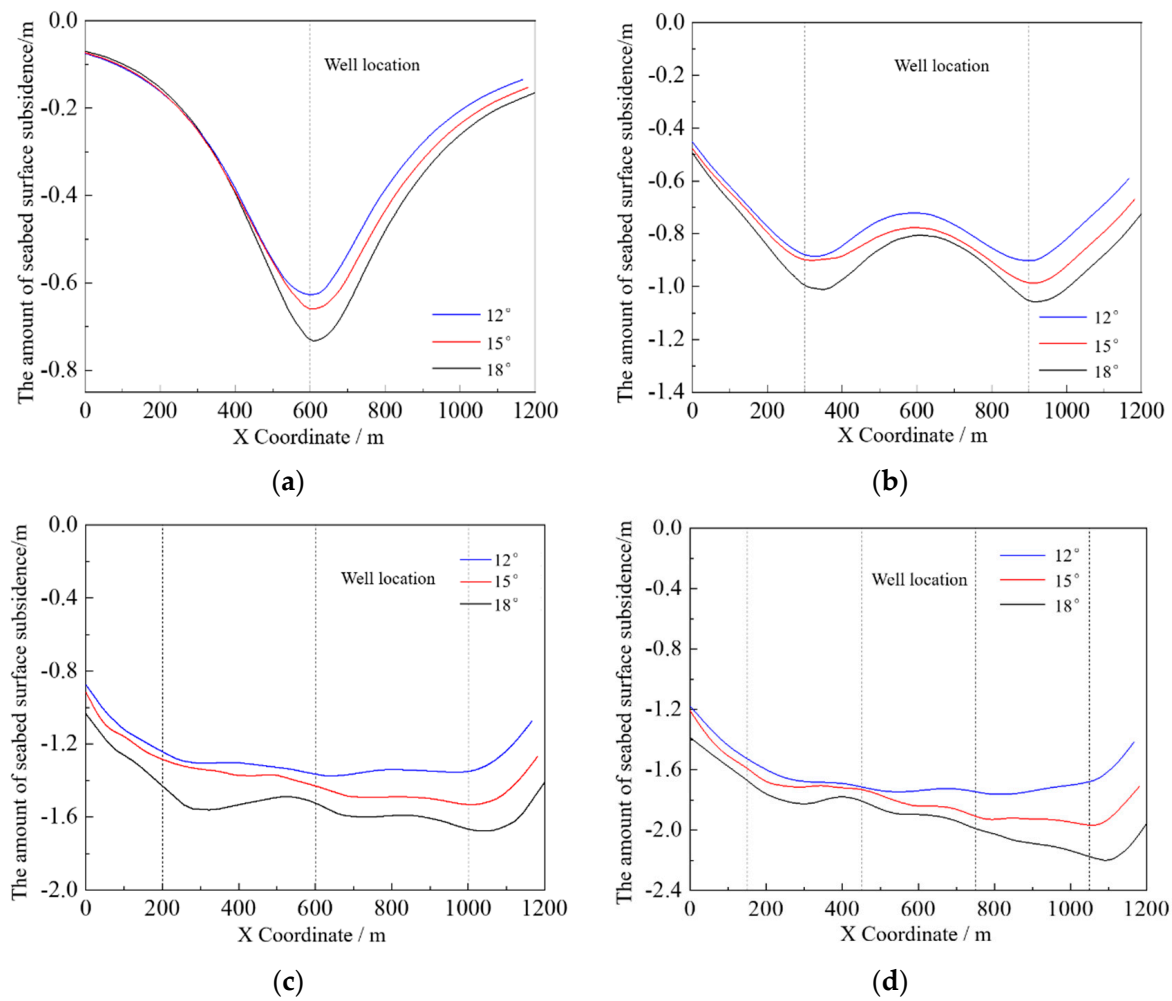


Figure 27. Seabed surface subsidence curves of each scheme. (a) $V1 \times 1$. (b) $V2 \times 2$. (c) $V3 \times 3$. (d) $V4 \times 4$.

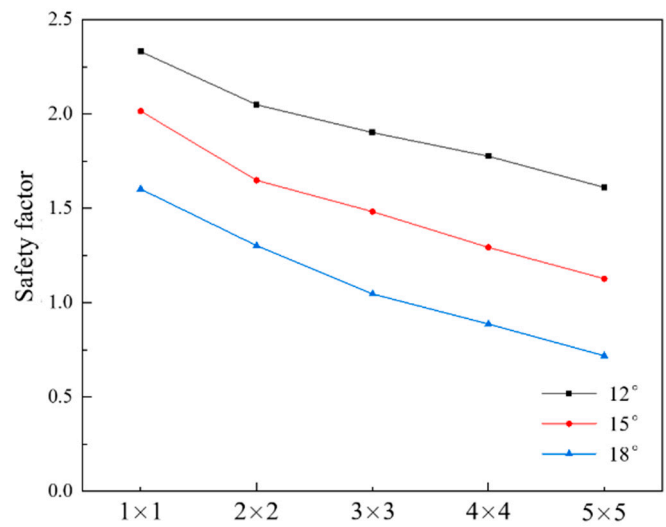


Figure 28. Safety factor of different well pattern scheme.

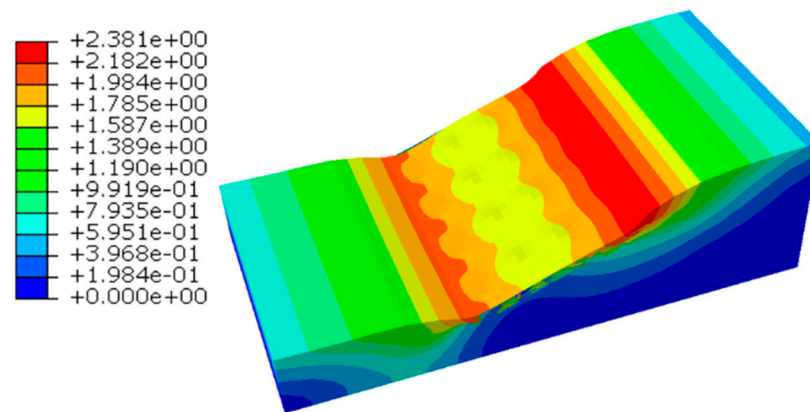


Figure 29. Contour maps of the total displacement of the slope with a dip angle of 18° using the 4×4 well pattern.

3.4. Influence of Well Spacing on Slope Stability under a Fixed Number of Wells

Taking the double-well exploitation model as an example, the influence of only the well spacing on slope stability is considered and the influence of the number of production wells is eliminated. The two wells in the NGH reservoir are shown in Section 1. The right well is fixed at the location of $X = 800$ m, while the location of the left well is determined based on the well spacing, which is set to 100, 200, 300, and 400 m. In addition, a single-well model (the well is located at $X = 800$ m) is set as the control group for 720 d of NGH production under a production pressure of 6 MPa.

Figure 30 shows contour maps of the NGH saturation along the section after production for 720 d under the various schemes. Under the influence of the geothermal gradient, the NGH decomposition zone has a triangular shape. In the research range, the smaller the well spacing is, the stronger the superimposed effect of pressure drops and the higher the decomposition degree in regions between wells. The NGH decomposition degree in regions between wells rises obviously as the well spacing narrows. The strength reduction of the reservoir caused by NGH decomposition is one of the causes of failure of submarine slopes, and the higher the decomposition degree is, the easier the failure of the slope.

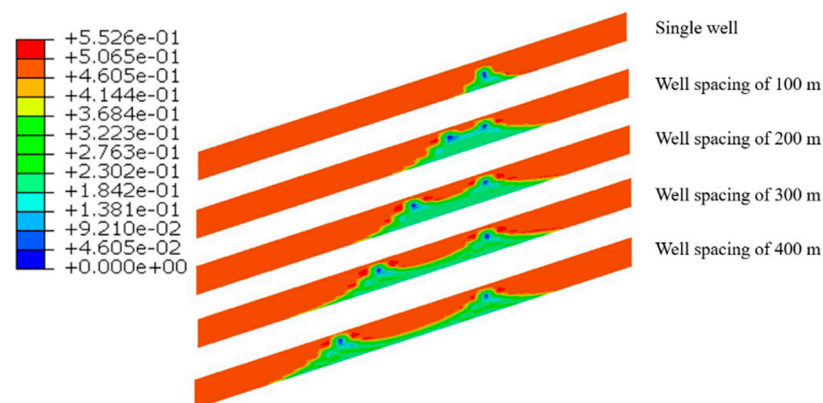


Figure 30. Hydrate saturation contour diagram.

Figure 31 shows the safety factors of the slope under various schemes. Under different well spacings, the safety factors under the double-well production scheme differ slightly. Within the range of 100~400 m, the larger the well spacing is, the greater the safety factor of the slope and the more stable the slope. The safety factor of the single-well model is 1.6023, which indicates that it is more stable than the double-well model. This is because production is influenced by the number of production wells: the NGH decomposition range under single-well production is smaller than that under double-well production.

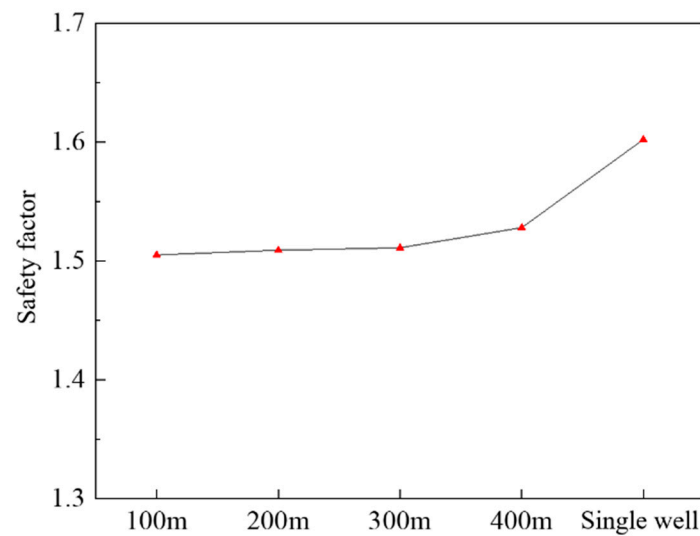


Figure 31. Safety factor corresponding to different well spacings.

The settlement curves of the seabed surface under various schemes after production for 720 d are illustrated in Figure 32. The maximum settlement under single-well production, which is 0.691 m, is the smallest among the tested schemes. The maximum settlement is 0.952, 0.986, 0.933, and 0.913 m when the well spacing is 100, 200, 300, and 400 m. With the widening of the well spacing, the maximum seabed settlement first enlarges and then reduces. This is because the high-pressure-drop range of a single well is 50 m and, influenced by the superimposed effect of pressure drops and the lifting of underlying strata in the highly decomposed zone, the settlement is maximum when the well spacing is 200 m.

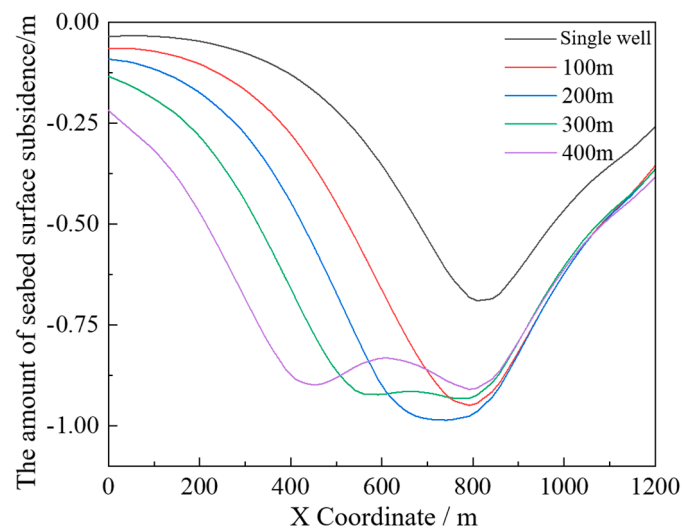


Figure 32. Subsidence curve of the seabed surface for each scheme.

4. Conclusions

In this paper, a multifield coupling model that describes the exploitation of NGHs was established. Based on the finite element analysis method, a slope stability evaluation model in the development process of NGHs was built. The influences of the well layout on the stability of submarine slopes in the exploitation of NGHs with the depressurization method were studied, and the conclusions are as follows:

- (1) When exploiting NGHs, the decomposition degree of the NGHs around wells increases with increasing burial depth under the influence of the geothermal gradient. Affected by the difference in permeability among formations, the production pressure

shows anisotropic propagation in formations, and finally, a cylindrical high-pressure-drop region with the wellbore as the axis and a radius of 50 m is formed. The process is independent of the number of wells and the well spacing density.

- (2) Because the NGH decomposition reduces the reservoir strength, the reservoir is compressed as a whole, accompanied by the settlement of overlying strata and the lifting of underlying strata. Influenced by gravity, plastic zones first appear in the NGH decomposition zone and the slope toe. With the further reduction in the strength of the formations, the plastic yield zone finally propagates throughout the slope. The yield zone does not pass through the NGH layer because the NGH decomposition zone is relatively small relative to the whole slope.
- (3) When adopting a linear well layout to exploit NGHs, arranging wells along the slope dip direction is more conducive to slope stability than arranging wells perpendicular to the slope dip direction under conditions of the same well spacing. When wells are arranged in the same direction, the slope stability is gradually enhanced with the widening of the well spacing.
- (4) If NGHs are exploited using a multiwell pattern, a larger scope of formations is influenced within the same exploitation time. Under these conditions, the slope exhibits a serious risk of failure when the slope dip is too large. The slope stability is improved with a reduction in the slope dip. Different from the well layout along a certain section, the depressurizing production of well patterns causes the upper part of the NGH reservoir to show a trend of overall settlement. With the increase in the well spacing density, the safety factor decreases.

The slope instability under the condition of production was investigated with the depressurization method and the basis for the well layout of NGH development was provided. In the future, a variety of methods, such as thermal and chemical methods, can be considered to comprehensively analyze the influence of NGH exploitation on the stability of submarine slopes, so as to achieve safe and efficient NGH development.

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