Quantitative analysis of slope stability of drilling sites with complex topography in the Qiongdongnan continental slope

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Abstract. Due to the large slope angle and the weak strength of submarine soils, Qiongdongnan deepwater continental slopes face great instability problems. In continental slope area, evaluating the stability of the slope before drilling is important as slope instability threatens the drilling safety. Taking the Lingshui deepwater well site as an example, 2D and 3D submarine slope stability calculation models, which consider the vertical heterogeneity of soil strength, were established based on the strength reduction method and Flac3D. The vertical profile of the soil shear strength was obtained via cone penetration and geotechnical tests. The effect of returned cuttings and drilling disturbance on slope stability were analyzed, and the safety factor of the slope was calculated. In addition, the position of potential slip surfaces and the possible slip directions were analyzed. Based on this, the location of the well was determined. The results indicate that the minimum safety factor of slope, which crosses the well, is 1.32. Moreover, the risk of submarine landslide is low. One potential landslide mass exists. However, the slope near the well is stable, and the slip direction of the landslide mass does not point to the well. The returned cuttings from the borehole decrease the safety factor and increase the risk of slope instability near the well.

1. Introduction

Submarine landslide is a geological phenomenon in which the seabed rocks or sediments lose stability due to various triggering factors and move downward under their own gravity [1-3]. This phenomenon generally occurs on or below the continental slope break zone due to the complex topography. Such areas are prone to slope stability problems. Generalized landslides include various movements, such as sliding, slumping, creeping, debris flow, and turbidity flow [4,5], which are not only an important mechanism for submarine sediment transport but also a major type of marine geological disaster. Therefore, submarine landslides have always been a research hotspot in the field of marine geological disasters.

Deepwater submarine soils are mostly soft clays with high water content and low strength [6,7], thus causing the submarine slope to exhibit high risks of instability. Compared to landslides that occur in land, the average angle of the submarine slope at failure is relatively smaller. Booth [8] analyzed the distribution of the average angle of the slope at failure and found that the angle of the submarine slope at failure is between 2° and 10°. Sometimes, failure even occurs on slopes that are flatter than 1°, which greatly increases the risk of submarine landslides in the continental slope area. In the
continental slope area in the northern South China Sea, oil and gas resources are extremely abundant. This area is also a key exploration and development area for natural gas hydrates [9,10]. However, compared with deepwater basins, the slope angle in the continental slope area is larger, and the shallow geological conditions are more complex. These features are prone to slope stability problems. The resulting submarine landslide may greatly damage the underwater engineering structures, such as submarine wellheads, submarine pipelines, and communication cables [11,12]. Therefore, submarine landslides must be considered when drilling in the continental slope area. A detailed geological survey is an important means to prevent submarine landslides. At present, multibeam bathymetry, submarine soil sampling, in situ testing of the geotechnical properties of soils, high-resolution seismic and sub-bottom profile surveying, etc., are mainly investigated [13-17]. In evaluating the stability of a submarine slope, comprehensively using the above data is important. Existing landslides can be identified using bathymetric, sub-bottom profile, and seismic data, whereas submarine slope stability can be quantitatively evaluated using soil mechanics. At present, the quantitative evaluation and analysis of slope stability mainly include three methods [18-23]: the limit equilibrium, numerical simulation, and probability methods. These methods have been widely used in land slope stability analysis and can be used in submarine slope stability analysis. The advantages and disadvantages of each of these methods are discussed as follows. The limit equilibrium method is the most widely used quantitative analysis method in engineering practice owing to its simple calculation process. However, it ignores the internal deformation of the landslide body [24]. In addition, when using this method, the shape of the sliding surface needs to be assumed before analysis. Thus, it is only suitable for simple slope analysis. The probability method uses reliability theory to analyze the probability of landslide occurrence within a specific time. However, it cannot afford the shape of the sliding surface or reveal the mechanical nature of the landslide [25]. The numerical analysis method is based on the soil constitutive model. Thus, the deformation and stability of the submarine slope can be obtained [26]. The safety factor can be obtained in conjunction with the strength reduction method. The influence of various factors on submarine slope stability is suitable for evaluating the stability of slopes with complex topography. At present, although numerous studies have been conducted on slope stability evaluation, research on the evaluation of the stability of the deepwater well sites in deepwater continental slope areas is scarce. In this paper, the submarine slope stability of the Lingshui well site, which is located in the Qiongdongnan continental slope area, was analyzed. Combined with the strength reduction method, 2D and 3D numerical models, which consider the effect of vertical heterogeneity and returned cuttings from the borehole, were created. The safety factor of the slope was calculated. In addition, the position of potential slip surfaces and the possible slip directions were analyzed. Based on this, the well site was determined.

2. Overview of the Lingshui deepwater well site
The Lingshui well site is located in the deepwater continental slope area of the Qiongdongnan Basin. Its seabed topography is complex, and the submarine slope greatly varies, thus causing this site to exhibit a high risk of landslide. To evaluate the risk of submarine landslide, a detailed survey on the well site was conducted before drilling, including water depth survey, sub-bottom profile survey, gravity sampling, geotechnical experiments, and cone penetration test (CPT).

2.1 Submarine topography of the Lingshui well site
An autonomous underwater vehicle (AUV) was used to conduct a refined multibeam bathymetry survey in the Lingshui well site within a range of 3 × 3 km². The contour of the water depth is presented in Figure 1. The water depth in the deepwater well site varied between 232.3 and 652.9 m. The figure shows that the submarine topography is extremely complex. The overall well site slopes to the southeast direction, and multiple NW–SE submarine canyons can be observed. To reduce the effect of the turbidity current in the canyons on the wellhead during drilling, the area near the ridge of the submarine canyon (indicated by the red dot in Figure 1) was selected as the well site, where the water depth is about 529.4 m.
Figure 1. Submarine topography of the Baodao deepwater well site (3 × 3 km²).

Figure 2 presents the slope angle diagram of the well site. The figure shows that the slope of the seafloor is between 0° and 37° and that the seafloor is extremely rugged. In most areas, the seafloor slope is greater than 5°. Some steep cliffs can also be observed. However, as the water depth increases, the seafloor gets flatter. The slope of the seabed at the selected well site is about 3.8°. Therefore, there is a certain risk of submarine landslide.

Figure 2. Slope angle diagram of the well site.

2.2 Shallow geological conditions
Figure 3(a) presents the sub-bottom profile along the NW–SE direction through the well site. The curve of CPT is superimposed on the sub-bottom profile to identify the formation interface. The figure shows that the well is located near a small slope toe. Moreover, an evident continuous interface (indicated by the red line in Figure 3) is present at a depth of 22.0 m. Furthermore, from the curves of CPT, we can observe a sharp change of excess pore pressure, tip resistance, and sleeve friction at a depth of 22.0 m, which are in good agreement. The bedding of the formation above the red line is clear and continuous, indicating that the overlying formation is a normal deposition stratum. Contrarily, the formation below the red line is mostly blank or weakly reflective, and the bedding is unclear and discontinuous. This demonstrates that the formation below the red line indicates landslide masses that
have slid down from the upslope. Thus, special attention should be paid to the changes in the formation properties above and below this interface during the analysis of submarine slope stability.

![Sub-bottom profile near the well](image)

**Figure 3.** Sub-bottom profile near the well.

### 2.3 Geotechnical parameters of soils

#### 2.3.1 Geotechnical parameters of submarine soils

A total of seven submarine soil samples were obtained near the selected well site, whose length is between 4.20 and 4.65 m. Submarine soils are mostly soft clays with a specific weight between 14.0 and 15.8 kN/m³. Geotechnical experiments show that the undrained shear strength is between 1 and 5 kPa.

#### 2.3.2 Variation of undrained shear strength versus the depth

Undrained shear strength is a significant mechanical parameter for the evaluation of submarine slope stability. Due to the limitations of the sampling depth, gravity sampling can only obtain the geotechnical parameters of submarine soils that are within a very shallow depth. This is insufficient for the accurate evaluation of submarine slope stability. As an *in situ* test method, the penetration depth of CPT can reach tens of meters beneath the seafloor; thus, it can be used to estimate the soil type and strength parameters of shallow submarine soils. CPT was conducted near the well during the well site survey. The maximum penetration depth of CPT was 38.5 m. According to the results of the CPT, the undrained shear strength of the subsea soil at different depths is explained in Figure 4.
Figure 4 demonstrates that when the depth is less than 22.0 m, the undrained shear strength of the submarine soil linearly increases with the depth. The undrained shear strength is between 1 and 30 kPa within 22.0 m. When the depth is between 22.0 and 27.4 m, the strength rapidly changes. Furthermore, when the depth is greater than 27.4 m, the undrained shear strength linearly increases with the depth. At 38.5 m, the undrained shear strength increases to 134.8 kPa.

2.3.3 Estimate of the undrained shear strength of soils below 38.5 m. The CPT obtained the undrained shear strength of the shallow soils above 38.5 m. However, this depth is still insufficient to calculate submarine slope stability. In this paper, we used the CPT data from other deep sea to estimate the undrained shear strength of the shallow soils in the Lingshui well site. Figure 5 presents the average undrained shear strength of soils from the Gulf of Mexico [27], Ormen Lange [28], Liwan 3-1 [29], Lingshui 17-2, and Songtao. The figure shows that the undrained shear strength is different due to the difference in the sedimentary environment and geological conditions in different areas. There is approximately a linear or piecewise linear relation between the undrained shear strength and depth. In numerous sea areas (such as Songtao and the Gulf of Mexico), the strength of the soil exhibits a sharp change at certain depths, which may be related to landslides, sedimentary conditions, or other factors. By comprehensively analyzing the undrained shear strength of the shallow soils from the above sea areas, the lower limit of the undrained shear strength of the seabed soil with depth can be obtained using the following linear formula:

\[ q_u = 1.0z \]  

where \( q_u \) denotes the undrained shear strength (kPa), and \( z \) denotes the depth beneath the seafloor (m).

Due to the differences in the sedimentary environment and geological conditions, certain differences are present in soil strength in different areas. Thus, accurately determining the shallow soil strength profiles without actual test data is difficult. To overestimate the safety factor of the submarine slope, this paper considers the worst case, that is, the use of the lower limit of the undrained shear strength of

![Figure 4. Variation of the undrained shear strength of soils versus the depth.](image-url)
the shallow soil to calculate the safety factor when CPT data is unavailable in some depths (deeper than 38.5 m). A calculated safety factor that is greater than 1.0 can effectively ensure that there is no risk of submarine landslide. Equation (1) shows that the slope of the undrained shear strength of the soils with a depth below 38.5 m is 1.0 kPa/m. Therefore, when the depth is greater than 38.5 m, the estimation formula of the undrained shear strength can be expressed as follows:

\[ q_u = 134.8 + 1.0(z - 38.5) \]  

(2)

**Figure 5.** Variation of the undrained shear strength of submarine soils versus the depth from different areas.

### 3. Two-dimensional numerical simulation of submarine slope stability in the deepwater well site

#### 3.1 Effect of drilling on the stability of the submarine slope

Deepwater drilling is an engineering disturbance to the submarine slopes. It affects the submarine stability through 1) additional gravity load of returned cuttings and underwater wellhead devices and 2) vibration load due to drilling.

1) Additional gravity load of returned cuttings and underwater wellhead devices

The underwater wellhead devices in deepwater drilling mainly include anti-sinking plate, high-pressure wellhead, and subsea blowout preventer. Their weight can reach up to tens of tons. However, the gravity of the wellhead devices, such as the high-pressure wellhead and subsea blowout preventer, does not directly act on the seabed surface, but acts on the surface conduits, which are lowered to a depth of tens of meters below the seabed through jet drilling. Thus, the weights of these devices can be supported by the interaction between the surface conduit and the shallow sediments. This effect is similar to those of the piles used to stabilize the slopes. Therefore, the gravity of the underwater wellhead has little effect on the stability of the submarine slope.

For the surface casing section, seawater is generally used as the drilling fluid, and the returned cuttings from the wellbore are directly deposited on the seabed [30]. Thus, compared with the underwater wellhead device, the returned cuttings more significantly affect slope stability. To evaluate the effect
of the returned cuttings on slope stability, the weight of the returned cuttings must be calculated as follows:

\[ W_s = \rho_s \left( \frac{\pi D_1^2 H_1}{4} + \frac{\pi D_2^2 H_2}{4} \right) \]  

where \( W_s \) denotes the weight of the returned cuttings from the wellbore (t); \( \rho_s \) is the density of the soils (t/m³); \( D_1 \) and \( D_2 \) are the well diameter of conduit and surface casing section, respectively; and \( H_1 \) and \( H_2 \) denote the well depth of conduit and surface casing section, respectively.

Hundreds of tons of the returned cuttings generate additional gravity loads on the seabed surface. This increases the normal and shear loads on the seabed (see Figure 6). As a result, the submarine slope near the well may become instable.

\[ \begin{align*}
\sigma_n &= \frac{F_n}{A} = \frac{W_s \cos \beta}{A}, \\
\sigma_t &= \frac{F_t}{A} = \frac{W_s \sin \beta}{A}
\end{align*} \]

where \( \beta \) denotes the slope angle; \( F_n \) and \( F_t \) denote the normal and shear force caused by the gravity load (N), respectively; \( \sigma_n \) and \( \sigma_t \) denote the normal stress and shear stress caused by the gravity load (Pa), respectively; and \( A \) denotes the distributed area of the deposited returned cuttings (m²).

2) Vibration load due to drilling

During deepwater drilling, the surface conduit is run through jet drilling. The crushing effect of the high-pressure jet on the shallow soil generates dynamic loads near the borehole, which may cause slope instability.

In this paper, the strength reduction method based on Flac3D was used to analyze the submarine slope stability of the Lingshui deepwater well site. The effect of the additional load on the seabed surface caused by the returned cuttings was considered, whereas the effect of vibration load due to drilling was disregarded.

3.2 Two-dimensional modeling of submarine slope stability

3.2.1 Geometric models. Select the AA’ with the largest slope angle at the well site as the 2D modeling section. For comparison, the BB’ and CC’ profile are also selected. The locations of these three profiles are presented in Figure 7.
The resulting 2D Flac3D geometric models are presented in Figure 8.

**Figure 8.** Geometric model of submarine slopes.

### 3.2.2 Vertical profile of soil strength

Based on the CPT results and Equation (2), a vertical profile of the undrained shear strength of soils can be established (taking AA’ as an example; see Figure 9).

**Figure 9.** Vertical profile of the undrained shear strength of soils.
3.2.3 Boundary and initial conditions. In the numerical simulation, the plane strain model is used. The bottom of the model is fixed, and the normal displacement of the left and right sides of the model is constrained. Moreover, the slope surface is set to be free. For fluid boundary conditions, the pore pressure at the slope surface is equal to the seabed hydrostatic pressure, and the pore pressure at the left and right sides of the model is also equal to the hydrostatic pressure. The bottom of the model is impermeable. For the load conditions, seawater pressure is applied on the slope surface.

3.2.4 Model parameters. The model parameters are presented in Table 1.

| Parameter                  | Value  | Parameter                  | Value  |
|----------------------------|--------|----------------------------|--------|
| Density of soil (g/m³)     | 2.0    | Diameter of the surface conduit (in) | 36     |
| Diameter of surface casing (in) | 20     | Depth of the surface conduit section (m) | 100    |
| Depth of surface casing section (m) | 800    | Weight of the returned cuttings (t) | 474.7  |
| Density of water (g/m³)    | 1.03   | Viscosity of pore water (Pa.s) | 0.001  |
| Elastic modulus (MPa)      | 10     | Poisson’s ratio             | 0.35   |

3.2.5 Plastic zone and potential slip surface. In Figure 10, the state of shear plastic yield of the submarine slope when losing stability (the area where shear plastic yield is currently occurring is indicated by red in the figure) is presented. For the AA’ profile, when slope instability occurs, different degrees of plastic yield occur near the wellhead and at the upper slope. This indicates that these two areas exhibit high risk of landslide. The plastic yield near the wellhead is due to the additional loads caused by the returned cuttings, whereas the plastic yield of the upper slope is caused by the large slope angle. For the BB’ profile, the plastic yield occurs near the wellhead and at the lower upper. The CC’ profile has four large plastic yield areas at the slopes with large angles. In addition, the returned cuttings cause a small plastic yield near the well.

Figure 10. State of shear plastic yield of the submarine slope when losing stability.

The triaxial experiments reveal that the fracture surface of the soil is consistent with the shear strain failure zone [31]. Thus, the shear strain increment can be used to identify the shear zone and determine the potential slip surface. In Figure 11, the shear strain increment when the submarine slope loses stability is presented. For the AA’ profile, the shear strain near the wellhead and the upper slope is extremely large, indicating that a slip tendency exists at these two locations. A very evident slip surface is formed at the upper slope, with a maximum depth of about 20 m. For the BB’ profile, the maximum shear strain increment appears near the wellhead and at the two lower slopes. Moreover, for
the CC' profile, five large shear failure zones are present, which are consistent with the plastic yield area presented in Figure 10.

**Figure 11.** Maximum shear strain increment of the submarine slope when losing stability.
The calculated safety factors of slope stability of the AA', BB', and CC' profiles are 1.32, 1.67, and 1.41, respectively. Thus, the risk of landslide is low.

4. Three-dimensional numerical simulation of the submarine slope stability in the deepwater well site

The topography of the Lingshui well site is complex, and the slope angles vary greatly. Thus, the risk of landslide varies in different areas. The instability of the slopes around the well may influence the wellhead stability. Thus, the use of 3D numerical simulation is recommended to identify the potential sliding masses and analyze the influence of the surrounding slopes on the wellhead according to the position and sliding direction of the sliding masses.

4.1 Three-dimensional model

Figure 12 presents the 3D model, which has a width of 2 km and a length of 3 km. The parameters of this model are set to be equal to those of the 2D model described above. During the calculation, the displacement of the bottom surface and the normal displacement around the model are fixed. The initial in situ stress caused by the weight of soils is applied on the entire model. The undrained shear strength, which was obtained via CPT and using Equation (2), is used to calculate the variation of shallow soil strength versus depth. However, establishing the lateral heterogeneity of the strength of soils is difficult due to the insufficient number of CPT and sampling points; thus, the variation of soil parameters in the plane are not considered.

![Figure 12. 3D model and its top view.](image)

4.2 Results and discussion

The safety factor calculated using the 3D model is 1.61. When the slopes lose stability, a large-scale plastic yield failure occurs in the submarine slope (indicated by red in Figure 13). This indicates that these areas may become unstable under external disturbance. However, on the slopes near the wellhead, no large-scale plastic failure occurs, indicating that the seabed near the wellhead is more stable and that the selection of the well site is reasonable.
Figure 13. State of shear plastic region of the submarine slope when losing stability.
In Figure 14, the maximum shear strain increment when the slopes lose stability is presented. The location of the maximum shear strain increment denotes the potential slip surface, and the formation above the slip surface indicates the potential landslide bodies. As shown in Figure 14, only one large potential landslide mass is present. The well site is not located in the potential landslide mass, indicating that the risk of landslide is low. The displacement magnitude can also be used to determine the possible position of the landslide body. Moreover, the velocity vector can predict the sliding direction of the landslide mass. Figure 15 presents the displacement and velocity vector diagram, and in this figure, only one area exhibits increased displacement in the well site. Compared with Figure 14, Figure 15 shows that this area is consistent with the potential landslide mass. The slope slides downward, which has little impact on the safety of the wellhead.

Figure 14. Maximum shear strain increment and potential landslide mass of the submarine slope when losing stability.
5. Conclusions

1) The calculated safety factor of the Lingshui deepwater well site is greater than 1.32, indicating that the risk of landslide is low. The results of the 3D calculation show that the selected well site is not inside the potential landslide and that the sliding of the surrounding slopes has little effect on the wellhead.

2) The additional load caused by the returned cuttings reduces the safety factor of the submarine slope and increases the risk of instability of the submarine slope near the wellhead.

3) The strength of the submarine soil has a significant impact on submarine slope stability. To improve the accuracy of safety factor calculation, the spatial variation of the soil strength should be considered.

4) Scientific assessment methods for evaluating the strength of the shallow soil with a large burial depth is still lacking. Thus, more research should be conducted in the future on the prediction of the spatial distribution of the physical and mechanical parameters of the shallow soils.

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