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Drilling- and Reservoir-Constrained First-Order Probabilistic Assessment of Gas Hydrate Stability and Slope Sensitivity in the Shenhu Production Area, Northern South China Sea

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Abstract

This study develops a MATLAB-based (MathWorks, Natick, MA, USA; version R2024b) first-order probabilistic screening framework for the Shenhu gas hydrate production area, northern South China Sea, to separate the roles of bottom-water warming, geothermal and fluid perturbation, hydrate saturation, excess pore pressure, and slope geometry. The framework integrates methane hydrate phase equilibrium, geothermal profiles, transient heat diffusion, base of gas hydrate stability zone (BGHSZ) migration, conceptual reservoir phase layering, and infinite-slope factor-of-safety (FoS) analysis. The modeled present-day BGHSZ (~271 mbsf) is broadly consistent with reported bottom-simulating-reflector depths. At the baseline thermal diffusivity, conductive potential dissociation thickness stays below 4 m even for +3.0 °C over 1000 years; across the full tested diffusivity–warming–time matrix it ranges 0–19.5 m; geological tests, reported as equilibrium BGHSZ offsets, give larger responses. Monte Carlo analysis under three parallel slope-angle assumptions shows that absolute FoS depends strongly on the slope distribution. Conductive warming reduces the median FoS by about 5.5%, with about 9% of realizations exceeding a 10% reduction, yet low-FoS outcomes remain absent within the tested ranges. Within the adopted parameterization, modeled FoS variability is controlled primarily by slope angle, friction angle, and the prescribed excess pore-pressure ratio, while conductive thermal forcing produces a comparatively modest reduction in relative stability margin.

Keywords: gas hydrate; Shenhu; BGHSZ; BSR; slope stability; factor of safety; excess pore pressure; South China Sea



Academic Editor: Mianmo Meng

Received: 2 June 2026

Revised: 23 June 2026

Accepted: 30 June 2026

Published: 16 July 2026

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1. Introduction

Natural gas hydrates are crystalline compounds in which gas molecules, predominantly methane, are trapped within water cages under low-temperature and high-pressure conditions. They occur widely in marine continental-margin sediments and permafrost regions and are recognized as potential unconventional energy resources, geohazard factors, and components of the global carbon cycle [1–4]. In marine settings, hydrate occurrence is controlled by pressure–temperature conditions, methane supply, sediment properties, gas-migration pathways, and geological evolution [5,6]. The base of the gas hydrate stability zone (BGHSZ) is commonly associated with bottom-simulating reflectors (BSRs); however, BSRs do not necessarily mark the exact hydrate stability boundary because they may also reflect free-gas accumulation, lithological contrasts, mixed gas composition, or changes in

hydrate phase structure [7–9]. Recent borehole evidence even documents hydrate persisting and slowly dissociating tens of meters beneath the regional BGHSZ, underscoring that the stability boundary is a dynamic, kinetically modulated interface [10].

A central concern for hydrate-bearing continental slopes is whether hydrate destabilization can reduce sediment strength, generate excess pore pressure, and contribute to submarine slope failure. Previous work has shown that hydrate dissociation may weaken sediments and promote slope instability under specific conditions, particularly where dissociation coincides with pore-pressure buildup, rapid sedimentation, weak layers, steep slope angles, or external triggers such as earthquakes [11–13]. Recent studies, however, emphasize that hydrate dissociation alone does not necessarily trigger large-scale submarine landslides; rather, the mechanical consequence of destabilization depends on coupled thermal, hydraulic, and geomechanical conditions [14,15]. Hydrate-related slope stability should therefore be evaluated within a coupled framework that jointly considers hydrate stability, pore-pressure response, sediment strength, and slope geometry.

The Shenhu area on the northern continental slope of the South China Sea is among the most intensively studied marine gas hydrate provinces in China. Drilling expeditions GMGS1, GMGS3, and GMGS4 have identified hydrate-bearing fine-grained sediments, high-saturation hydrate intervals, pressure-core evidence, logging anomalies, and complex reservoir architecture [16–20]. GMGS3 and GMGS4 results indicate that hydrate concentration in hydrate-bearing intervals commonly ranges from 20% to 60% of pore volume, with interval thicknesses from approximately 10 m to more than 80 m [18]. Dynamic accumulation studies further suggest that channel–levee migration, sediment erosion and deposition, gas chimneys, localized thermal-fluid input, and geothermal-gradient variation may influence BSR migration, double-BSR formation, and hydrate accumulation patterns in Shenhu [19]. Three-dimensional reservoir modeling indicates that the production-test reservoir is not a homogeneous hydrate layer but comprises hydrate-bearing layers, three-phase mixed layers, and free-gas or gas–water intervals [20]. At these deep-water sites, bottom-water temperatures of approximately 3–4 °C are maintained by regional deep circulation and exchange between the South China Sea and the western Pacific through the Luzon Strait [21].

Despite these advances, a quantitative and probabilistic framework linking BGHSZ migration, bottom-water warming, exploratory geological stress tests, hydrate saturation, excess pore pressure, and slope stability remains limited for Shenhu. Most prior studies have emphasized hydrate accumulation, reservoir characterization, production potential, or BSR interpretation, whereas the propagation of parameter uncertainty into FoS response has not been fully explored. Accordingly, this study develops a MATLAB-based probabilistic assessment framework with five objectives: (1) estimate the present-day BGHSZ and compare it with reported BSR depths; (2) quantify BGHSZ shoaling under bottom-water warming scenarios; (3) evaluate exploratory geological stress-test scenarios involving high geothermal gradient, localized thermal-fluid input, and high hydrate saturation; (4) link BGHSZ migration to excess pore pressure, strength degradation, and FoS response; and (5) identify the dominant controls on hydrate-related slope sensitivity using Monte Carlo simulation and sensitivity analysis.

2. Materials and Methods

2.1. Geological Setting and Data Constraints

The Shenhu gas hydrate production area lies on the northern continental slope of the South China Sea, within the deep-water Pearl River Mouth Basin. It is characterized by canyon–ridge morphology, fine-grained marine sediments, channel–levee systems, and locally focused fluid migration. Hydrate-bearing sediments are mainly clayey silt, fine-

grained silt, and clay-rich silt, with hydrate occurring predominantly as pore-filling or disseminated hydrate [16–20].

Published drilling and logging data provide the principal constraints for model parameterization (Table 1). Reported water depths in the drilling area generally fall within ~1000–1700 m. Bottom-water temperatures are low, commonly ~3–4 °C, whereas geothermal gradients are relatively high (~44–67 °C/km) [16,19]. Hydrate-bearing intervals range from tens of meters to more than 80 m. Hydrate saturation commonly ranges from 20% to 60%, with locally higher values reported in GMGS3/4 boreholes [18,19]. The low bottom-water temperature in the Shenhu area reflects regional deep-water circulation and exchange with the western Pacific through the Luzon Strait, which help maintain seafloor temperatures of approximately 3–4 °C at hydrate-bearing water depths of about 1000–1700 m [21].

Table 1. Model input parameters and literature constraints used in the Shenhu BGHSZ–FoS probabilistic framework.

Parameter	Symbol	Baseline	Range/Scenario	Unit
Water depth	H_w	1300	1000–1700; site values 1105–1262	m
Bottom-water temperature	T_b	4.0	3.3–5.6	°C
Geothermal gradient	G	47	44–67	°C km ^{−1}
Reported BSR depth	z_{BSR}	site-dependent	184–237; broader ~150–350	mbsf
Hydrate saturation	S_h	0.34	0.20–0.60; high case 0.40–0.76	fraction
Porosity	ϕ	0.55	0.45–0.65	fraction
Thermal diffusivity	κ	3.0×10^{-7}	tested $1.0\text{--}8.0 \times 10^{-7}$	m ² s ^{−1}
Slope angle	θ	three structural-uncertainty cases	Triangular (0.5, 2.5, 6.0°); Triangular (0.5, 0.8, 2.0°); Uniform (2–15°)	degree
Effective cohesion	c'	10	5–20	kPa
Effective friction angle	ϕ'	26	20–32	degree
Excess pore-pressure ratio	r_u	0.3	0–0.5; response surface 0–0.6	dimensionless
Failure-plane depth	z_f	50	30–100	mbsf

Note: This table lists the core parameters used in the main analyses. The complete parameter set, including density, salinity, grid spacing, phase-layer depths, diagnostic indices, degradation coefficients, thermal-fluid anomaly, and Monte Carlo settings, is provided in Supplementary Table S1. The baseline thermal diffusivity ($\kappa = 3.0 \times 10^{-7}$ m² s^{−1}) is treated as an explicit uncertain parameter and tested in Supplementary Figure S2.

Gas geochemistry indicates that hydrate-bound gas in Shenhu is methane-dominated but includes minor C2+ hydrocarbons; carbon and hydrogen isotopes suggest mixed microbial and thermogenic contributions in some intervals [22]. A pure methane hydrate phase-equilibrium curve is therefore adopted as a first-order approximation, with the uncertainty related to mixed gas and possible structure-II hydrates addressed in the Discussion.

Recent 3D reservoir modeling suggests that the production-test reservoir can be simplified into hydrate-bearing layers, three-phase mixed intervals, and free-gas/gas–water layers [20]. This phase architecture is incorporated conceptually to interpret how BGHSZ migration may interact with different reservoir intervals and produce different pore-pressure and strength responses.

2.2. Modeling Workflow

The model comprises five modules: (1) present-day BGHSZ estimation from geothermal and hydrate phase-equilibrium profiles; (2) transient one-dimensional heat diffusion of bottom-water warming into sediments; (3) calculation of conductive potential dissociation thickness and equilibrium BGHSZ offsets; (4) parameterized excess pore pressure and strength degradation linked to hydrate dissociation; and (5) infinite-slope FoS calculation with Monte Carlo uncertainty propagation.

The model is intended as a regional first-order screening and sensitivity-analysis tool. It does not explicitly solve hydrate dissociation kinetics, gas–water multiphase migration, pressure diffusion, sediment deformation, or three-dimensional slope failure. Instead, it

compares the relative contributions of thermal forcing, reservoir architecture, pore pressure, and geomechanical parameters to slope stability. The processes that are and are not represented in this first-order framework are summarized in Table 2.

Table 2. Model scope: processes included in the first-order framework and processes not solved, with their interpretation.

Process	Treatment	Interpretation
Hydrate phase equilibrium	Included: equilibrium intersection	Present-day and perturbed BGHSZ proxy
Conductive heat diffusion	Included: 1D semi-infinite erfc solution	Conductive warming sensitivity only
Hydrate dissociation kinetics	Not solved	D _{diss} is not dissociated mass or rate
Multiphase gas-water flow	Not solved	No gas migration or saturation evolution prediction
Advective heat transport	Not solved	Focused thermal-fluid cases are imposed end-members
Pore-pressure diffusion	Not solved	r _u is parameterized rather than dynamically predicted
Sedimentation/erosion history	Not solved	No stratigraphic evolution forecast
3D slope geometry	Not solved	FoS is a relative infinite-slope indicator
Progressive/strain-softening failure	Not solved	No failure timing or runout prediction
Earthquake dynamic response	Not solved; pseudo-static kh stress test only	No ground-motion time history or cyclic degradation
Production depressurization	Supplementary mechanism-isolation stress test; no well-scale flow model	Separates drawdown, pore pressure, strength loss, and kh effects

2.3. Present-Day BGHSZ Estimation

The sediment temperature profile is expressed as

$$T(z) = T_b + G z \quad (1)$$

where T_b is the bottom-water temperature, G is the geothermal gradient, and z is depth below seafloor. Pore-fluid pressure is taken as hydrostatic over the combined water and sediment column. The BGHSZ is defined by the intersection of the geothermal profile and the methane hydrate phase-equilibrium curve,

$$T(z) = T_{eq}(P) \quad (2)$$

Methane hydrate three-phase equilibrium follows the Dickens & Quinby-Hunt (1994) seawater relation [23], valid over the 0.1–100 MPa oceanic range, with a linear salinity correction. The modeled BGHSZ is compared with reported BSR depths as a first-order consistency check. Because BSRs need not coincide exactly with the BGHSZ in Shenhu, the comparison is not treated as strict calibration.

2.4. Bottom-Water Warming and Thermal Diffusion

Downward propagation of bottom-water warming is simulated with a one-dimensional heat-diffusion equation,

$$\partial T / \partial t = \kappa \partial^2 T / \partial z^2 \quad (3)$$

where κ is sediment thermal diffusivity. The total perturbed temperature field is the background geotherm plus the diffused surface anomaly, $T(z,t) = T_b + Gz + \Delta T \cdot \text{erfc}[z / (2\sqrt{\kappa t})]$. This closed-form erfc solution corresponds to a semi-infinite sediment column with a step increase ΔT imposed at the seafloor ($z = 0$) at $t = 0$, an unperturbed background geotherm

at $t < 0$, and the far-field condition that the temperature anomaly decays to zero at depth ($z \rightarrow \infty$). Four idealized warming anomalies (+0.5, +1.0, +2.0, +3.0 °C) are evaluated after 50, 100, 500, and 1000 years.

2.5. Conductive Potential Hydrate Dissociation Thickness and Equilibrium BGHSZ Offset

BGHSZ shoaling is converted into a potential hydrate dissociation thickness,

$$D_{diss} = z_{BGHSZ,0} - z_{BGHSZ,t} \quad (4)$$

where $z_{BGHSZ,0}$ and $z_{BGHSZ,t}$ are the present-day and perturbed BGHSZ depths. D_{diss} is interpreted as a potential—not actual—dissociation thickness, because multiphase flow and reaction kinetics are not explicitly modeled. Equation (4) is used as a conductive potential dissociation-thickness proxy only for transient bottom-water-warming simulations. For high-geothermal-gradient, localized-temperature, and artificial combined tests, the same boundary-depth difference is reported as an equilibrium BGHSZ offset relative to the reference state and is not interpreted as a dissociation thickness.

2.6. Infinite-Slope FoS Model

Slope stability is evaluated with a simplified infinite-slope model, an approach also adopted in recent probabilistic assessments of hydrate-bearing continental slopes [24,25],

$$\text{FoS} = [c' + (\gamma' z_f \cos^2 \theta - u_{ex}) \tan \phi'] / (\gamma' z_f \sin \theta \cos \theta) \quad (5)$$

where c' is effective cohesion, γ' is effective unit weight, z_f is failure-plane depth, θ is slope angle, u_{ex} is excess pore pressure, and ϕ' is effective friction angle. Excess pore pressure is expressed through the ratio $r_u = u_{ex} / \sigma'_v$. Hydrate saturation is coupled to pore-pressure generation and strength degradation in the dissociation scenarios, so that hydrate-rich sediments can mechanically amplify destabilization. The infinite-slope formulation is adopted only as a first-order screening tool; it assumes a laterally continuous slope with a prescribed planar failure depth, an idealized excess-pore-pressure ratio, and homogeneous, isotropic strength parameters. It does not capture three-dimensional slope geometry, strain-softening or progressive failure, cyclic earthquake loading, sediment anisotropy, or spatially variable weak layers. The resulting FoS values should therefore be interpreted only as relative sensitivity indicators rather than as deterministic measures of slope safety.

2.7. Scenario Design and Monte Carlo Analysis

Three groups of scenario and mechanism-isolation tests are evaluated. The first represents climate-only bottom-water warming. The second represents exploratory geological stress-test scenarios—high hydrate saturation, high geothermal gradient, localized thermal-fluid input, and a combined geological end-member. The third separates hydrate-related mechanical mechanisms: GHSZ retreat only; GHSZ retreat plus excess pore pressure; and GHSZ retreat plus both excess pore pressure and strength degradation.

Monte Carlo simulation (Latin hypercube sampling, $N = 10,000$) propagates uncertainty in slope angle, friction angle, cohesion, hydrate saturation, porosity, geothermal gradient, bottom-water temperature, and excess pore-pressure ratio. This combination of an infinite-slope FoS model with Monte Carlo propagation of geotechnical and thermal parameter uncertainty follows the strategy used in recent probabilistic landslide-susceptibility frameworks for hydrate-rich slopes, including applications in the South China Sea [24–26]. Outputs include FoS probability distributions, $P(\text{FoS} < 1.0)$, $P(\text{FoS} < 1.2)$, and standardized rank regression coefficients (SRRCs). Additional outputs include the relative FoS reduction and its percentiles, slope-angle-conditioned statistics, analytical critical excess-

pore-pressure ratios for target FoS values of 1.0 and 1.2, and the sample-wise pore-pressure margin $M_{ru} = r_{u,crit} - r_u$. The probability distribution assigned to each uncertain input, together with its distribution type and defining parameters, is specified explicitly in Table 3. Geothermal gradient and hydrate saturation use triangular distributions over their literature/GMGS ranges; bottom-water temperature, porosity, and effective friction angle use truncated normal distributions bounded by the stated literature ranges; effective cohesion and the excess-pore-pressure ratio use uniform distributions over their tested ranges; and slope angle is treated as a structural-uncertainty case under three parallel assumptions (Section 2.8). No single distribution is defined as the true Shenhu parameter distribution; the table therefore reports the exact sampling assumptions and their constraint basis rather than calibrated field statistics. The scenario groups propagated through this analysis are defined in Table 4.

Table 3. Exact Monte Carlo input distributions, units, and constraint basis used in the uncertainty analysis. Slope angle is treated under three parallel assumptions (Section 2.8); no distribution is presented as the true Shenhu parameter distribution.

Parameter	Distribution	Unit	Constraint Basis
Geothermal gradient	Triangular (43, 47, 68)	$^{\circ}\text{C km}^{-1}$	Literature range; uncertainty input
Bottom-water temperature	TruncatedNormal (4.0, 0.4; 3.3–5.6)	$^{\circ}\text{C}$	Literature/site range; uncertainty input
Hydrate saturation	Triangular (0.20, 0.34, 0.48)	-	GMGS range; uncertainty input
Porosity	TruncatedNormal (0.55, 0.04; 0.45–0.65)	-	Logging/core range; uncertainty input
Effective cohesion	Uniform (5, 20)	kPa	Literature range; uncertainty input
Effective friction angle	TruncatedNormal (26, 3; 23–29)	deg	Literature range; uncertainty input
Excess pore-pressure ratio	Uniform (0, 0.5)	-	Screening range, weakly constrained
Slope angle: Assumption A	Triangular (0.5, 2.5, 6.0)	deg	Transparent Assumption A for detailed diagnostics, not field-derived
Slope angle: very-gentle bound	Triangular (0.5, 0.8, 2.0)	deg	Very-gentle sensitivity bound; not field-derived
Slope angle: broad stress test	Uniform (2, 15)	deg	Conservative stress-test assumption

Table 4. Definition of the scenario groups evaluated in the probabilistic framework. Scenarios are grouped into idealized climate-warming sensitivity cases, literature-bounded sensitivity cases, and exploratory end-member stress tests; the local thermal-fluid, combined end-member, empirical strength-degradation, and uncalibrated pore-pressure-coupling cases are exploratory stress tests and are not reconstructions or forecasts of Shenhu field behavior. Here, "+" denotes the cumulative addition of the indicated mechanism to the preceding case in the mechanism-isolation rows, and a positive temperature increment elsewhere.

Group	Scenario	Forcing/Parameter Changes	Purpose
Idealized climate-warming sensitivity case	Bottom-water warming	$\Delta T_b = +0.5/+1.0/+2.0/+3.0\text{ }^{\circ}\text{C}$; $t = 50/100/500/1000\text{ yr}$	Test BGHSZ response to ocean warming alone
Literature-bounded sensitivity case	High saturation	Sh up to 0.40–0.76	Test amplification of FoS reduction by hydrate-rich sediments
Literature-bounded sensitivity case	High geothermal gradient	$G = 47/55/67\text{ }^{\circ}\text{C/km}$	Represent higher regional/local heat flow
Exploratory end-member stress test	Local thermal-fluid	$\Delta T_{local} = 0/1/2\text{ }^{\circ}\text{C}$ near BGHSZ	Proxy for gas-chimney/focused-fluid heating
Exploratory end-member stress test	Combined end-member	High G + local heat + high Sh + elevated ru + strength loss	Conservative upper-bound sensitivity test (not a forecast of expected conditions)
Mechanism	A: GHSZ retreat only	No excess pore pressure, no strength loss	Isolate purely thermodynamic boundary shift
Mechanism	B: + excess pore pressure	Add ru	Quantify pore-pressure contribution to FoS
Mechanism	C: + strength degradation	Add cohesion/friction loss (α, β)	Quantify combined mechanical weakening

2.8. Robustness Tests for Input Distributions

Because the infinite-slope FoS is highly sensitive to slope geometry, three slope-angle assumptions are carried in parallel as structural-uncertainty cases rather than as competing estimates of a single true distribution. Assumption A is a transparent low-gradient triangular distribution ($0.5, 2.5, 6.0^\circ$) used as the primary case for detailed diagnostics; an explicit very-gentle-slope boundary assumption (triangular distribution with parameters $0.5, 0.8, 2.0^\circ$) is retained as a very-gentle-slope bound; and a broad uniform distribution ($2\text{--}15^\circ$) is retained as a conservative stress test. None of these is presented as the measured Shenhu slope-angle distribution, and none requires multibeam bathymetry. These cases are used to quantify how strongly the absolute FoS and the low-FoS probabilities depend on the slope-angle assumption, and to separate that dependence from the relative FoS reduction caused by warming; the resulting comparison is reported as Supplementary Figure S1.

3. Results

3.1. Conceptual Phase-Layer Framework

Figure 1 summarizes the conceptual phase-layer architecture that organizes the Shenhu reservoir into a hydrate-bearing layer, a three-phase mixed layer, and a free-gas/gas–water layer. The present-day modeled BGHSZ at ~ 271 mbsf lies near the transition between the three-phase mixed layer and the free-gas/gas–water layer. Under a combined exploratory end-member stress test (high geothermal gradient, localized thermal-fluid input, and elevated hydrate saturation), the BGHSZ migrates upward to ~ 176 mbsf, crossing into the hydrate-bearing layer. The mechanical consequence of BGHSZ migration depends on the reservoir interval affected: if the boundary intersects hydrate-bearing intervals, gas generation, pore-pressure change, and strength degradation may become relevant. These processes are represented only as parameterized mechanism tests and are not dynamically simulated here.

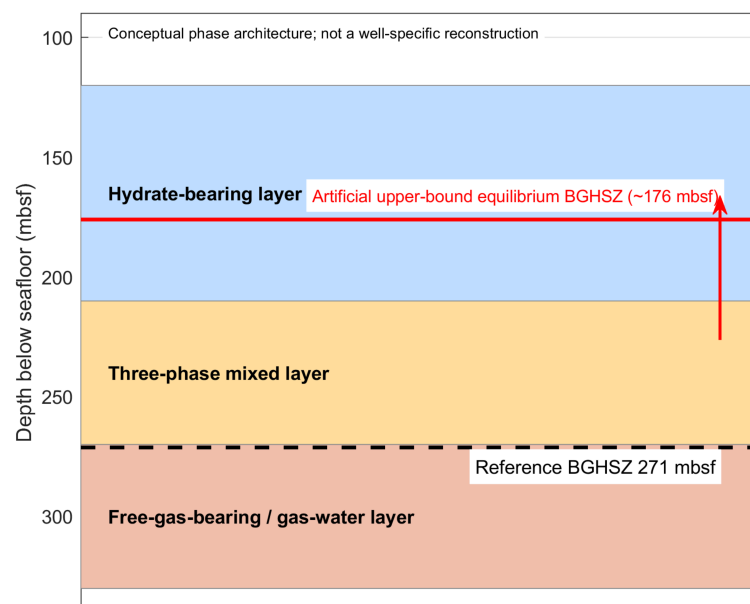


Figure 1. Conceptual phase-layer model and BGHSZ migration in the Shenhu area. The reservoir is simplified into a hydrate-bearing layer ($\sim 120\text{--}210$ mbsf), a three-phase mixed layer ($\sim 210\text{--}270$ mbsf), and a free-gas/gas–water layer ($\sim 270\text{--}330$ mbsf). The dashed line marks the present-day modeled BGHSZ at 271 mbsf; the red line denotes the artificial upper-bound equilibrium BGHSZ at ~ 176 mbsf produced by the combined exploratory end-member stress test, illustrating how upward migration shifts the controlling interface into the hydrate-bearing layer where dissociation may generate excess pore pressure and strength loss. The red upward arrow indicates the direction of BGHSZ migration (upward shoaling of the controlling interface) under the exploratory end-member stress test.

3.2. Thermal Structure, Model–BSR Comparison, and Modeled Hydrate-Stability Response

Figure 2 summarizes the present-day thermal structure, the model–BSR comparison, and the modeled hydrate-stability response to bottom-water warming. The intersection of the geothermal profile with the methane hydrate phase-equilibrium curve defines a present-day BGHSZ of ~271 mbsf, which falls within the deeper part of the reported Shenhu GHSZ/BSR range (Figure 2a). Comparison of modeled BGHSZ depths with reported BSR depths at five comparison sites (Figure 2b) yields MAE = 16.3 m and RMSE = 19.8 m. This mismatch provides an order-of-magnitude consistency check but should not be interpreted as formal calibration or validation, because BSR depth may differ from the thermodynamic BGHSZ owing to spatial variations in geothermal gradient, sedimentation, gas composition, reservoir architecture, and kinetic effects. The downward propagation of a +2.0 °C anomaly (Figure 2c) is slow: within 50–100 years, the warming is largely confined to shallow sediments and attenuates rapidly with depth; after 500 years, it penetrates deeper; and after 1000 years it becomes evident near the lower hydrate stability zone. The corresponding BGHSZ shoaling and potential dissociation thickness (Figure 2d) remain negligible within 50–100 years across all tested anomalies; at 1000 years, D_{diss} reaches approximately 0.6, 1.2, 2.5, and 3.9 m for +0.5, +1.0, +2.0, and +3.0 °C, respectively. Bottom-water warming alone thus produces only meter-scale potential dissociation even under millennial forcing.

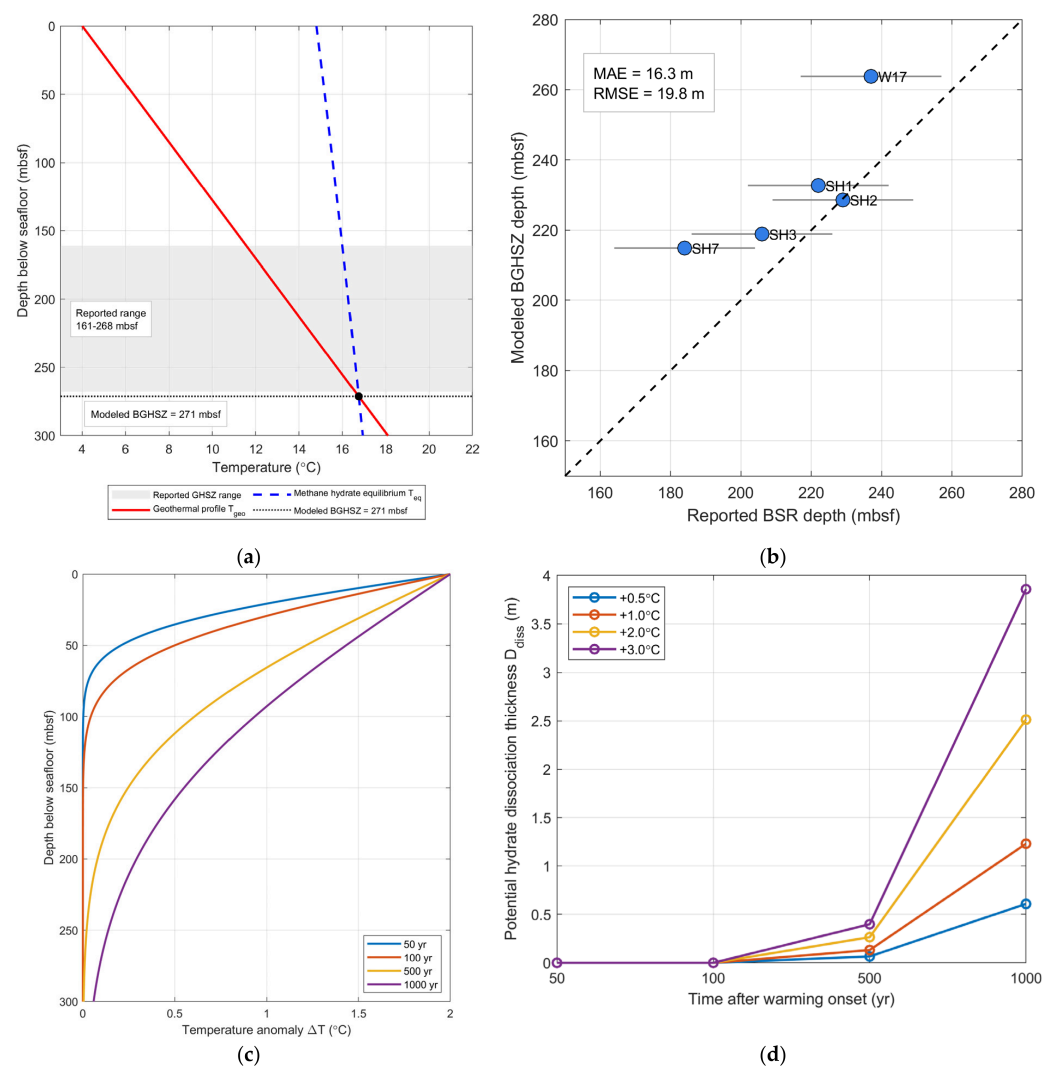


Figure 2. Thermal structure, model–BSR comparison, and modeled hydrate-stability response in the Shenhu area. (a) Present-day geothermal profile (T_{geo} , red solid line) and methane hydrate phase-equilibrium curve (T_{eq} , blue dashed line); their intersection defines the modeled BGHSZ at 271 mbsf;

the grey band marks the reported GHSZ/BSR range. (b) Modeled BGHSZ versus reported BSR depth at the SH1, SH2, SH3, SH7, and W17 comparison sites; the dashed line is the 1:1 relation; MAE = 16.3 m and RMSE = 19.8 m. (c) Downward diffusion of a +2.0 °C bottom-water warming anomaly at 50, 100, 500, and 1000 years after onset. (d) Potential hydrate dissociation thickness D_{diss} as a function of time after warming onset for +0.5, +1.0, +2.0, and +3.0 °C anomalies.

3.3. Exploratory Geological Stress-Test Scenarios

Exploratory geological stress-test scenarios produce stronger responses than bottom-water warming alone (Figure 3). The bottom-warming-only case yields a small D_{diss} and a high FoS. The high-saturation case does not alter the thermal boundary shift directly, but lowers FoS by amplifying the prescribed pore-pressure and strength-degradation response. The high-geothermal-gradient case produces an equilibrium BGHSZ offset of ~90 m relative to the reference state and substantially lowers FoS; the localized thermal-fluid case yields an equilibrium BGHSZ offset of ~37 m with a comparable FoS reduction; and the artificial combined upper-bound test produces the largest equilibrium BGHSZ offset (~95 m) and the lowest FoS of all tested cases. These geological cases are reported as equilibrium BGHSZ offsets relative to the present-day reference state, not as conductive dissociation thicknesses, and are not interpreted as actual hydrate dissociation thicknesses. Among these, the high-saturation case is the most directly field-constrained, because GMGS3/GMGS4 boreholes report local hydrate saturations up to 0.40–0.76; the high-geothermal-gradient case is bounded by the reported regional range (~44–67 °C/km), whereas the localized thermal-fluid and combined end-member cases are deliberately conservative, hypothetical stress tests that are not constrained by a specific Shenhu observation and are used only to separate mechanisms and bound the response.

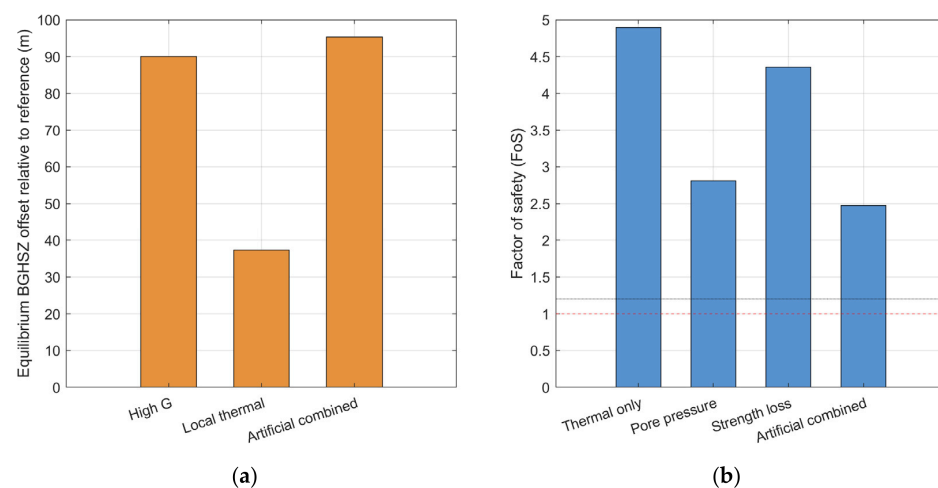


Figure 3. Decoupled geological stress tests and mechanism isolation. (a) equilibrium BGHSZ offset relative to the present-day reference state for the high-geothermal-gradient (High G), localized thermal-fluid (Local thermal), and artificial combined upper-bound tests; these are equilibrium boundary-depth offsets, not conductive dissociation thicknesses. (b) factor of safety (FoS) for the isolated mechanism tests—thermal forcing only, added excess pore pressure, added strength loss, and the artificial combined upper-bound test; dashed lines mark FoS = 1.0 (red) and FoS = 1.2 (black). The localized thermal-fluid and artificial combined cases are hypothetical conservative stress tests and are not forecasts of expected Shenhu conditions.

3.4. Geomechanical Response and Uncertainty Analysis

Figure 4 summarizes the geomechanical and uncertainty responses of hydrate-related slope stability. The FoS response surface (Figure 4a) shows that slope angle and excess

pore-pressure ratio $ru = u_{ex}/\sigma'_v$ jointly control stability; low slope angles and low ru yield high FoS, whereas simultaneous increases push the system toward the $FoS = 1.2$ and $FoS = 1.0$ thresholds. The three-mechanism comparison (Figure 4b) shows $FoS = 4.90$ for GHSZ-retreat-only (A), 3.49 with added excess pore pressure (B), and 3.40 with additional strength degradation (C); excess pore pressure accounts for most of the modeled FoS reduction. For the Monte Carlo distribution (Figure 4c), the three slope-angle assumptions in Table 1 are treated in parallel as structural-uncertainty cases rather than as competing estimates of a true Shenhu slope-angle distribution: a transparent low-gradient triangular assumption used for detailed diagnostics, an explicit very-gentle-slope boundary assumption (triangular 0.5, 0.8, 2.0°), and a broad uniform (2–15°) conservative stress test. The absolute FoS depends strongly on which assumption is adopted, confirming that the infinite-slope FoS is not a calibrated stability value. Under the illustrative triangular assumption, the baseline distribution has a mean FoS of 11.08 and a median of 9.56, and the +2.0 °C, 1000-year warming case shifts it toward lower values (mean 10.42, median 8.98). The corresponding median relative FoS reduction is approximately 5.50% (5th–95th percentile range 2.52–11.20%); about 9.23% of realizations show a reduction exceeding 10%, whereas only about 0.01% exceed a 20% reduction. Crucially, low-FoS outcomes remain absent: $P(FoS < 1.0) = P(FoS < 1.2) = 0$ under all three slope-angle assumptions within the tested static parameter ranges (Supplementary Figure S1, Table S2). To provide a more interpretable engineering threshold than the large absolute FoS values at low slope angle, we additionally compute the critical excess-pore-pressure ratio ru_{crit} required to reach target FoS values and the corresponding pore-pressure margin $M_{ru} = ru_{crit} - ru$ (Figure 5). For the reference slope and friction angle, $ru_{crit} \approx 0.839$ for $FoS = 1.0$ and ≈ 0.796 for $FoS = 1.2$. For the $FoS = 1.2$ target, a valid critical ratio is obtained for about 90.3% of Monte Carlo samples, with a conditional median pore-pressure margin of about 0.823; the remaining ~9.7% have $ru_{crit} > 1$ and are reported separately as unreachable within the $0 \leq ru \leq 1$ screening interval (full distributions in Supplementary Materials). The Monte Carlo and pore-pressure-margin results should therefore be read as a reduction in relative stability margin under conductive warming rather than as an increased probability of slope failure, and absolute FoS values should not be over-interpreted as literal safety margins. The SRRC tornado (Figure 4d) identifies slope angle as the strongest negative control on FoS and friction angle as the strongest positive control; excess pore-pressure ratio is the second most important destabilizing factor; and hydrate saturation acts as a secondary negative factor, indicating that hydrate-rich sediments can amplify pore-pressure buildup and strength degradation. Bottom-water temperature and geothermal gradient have relatively weak direct effects on FoS under the reference warming scenario.

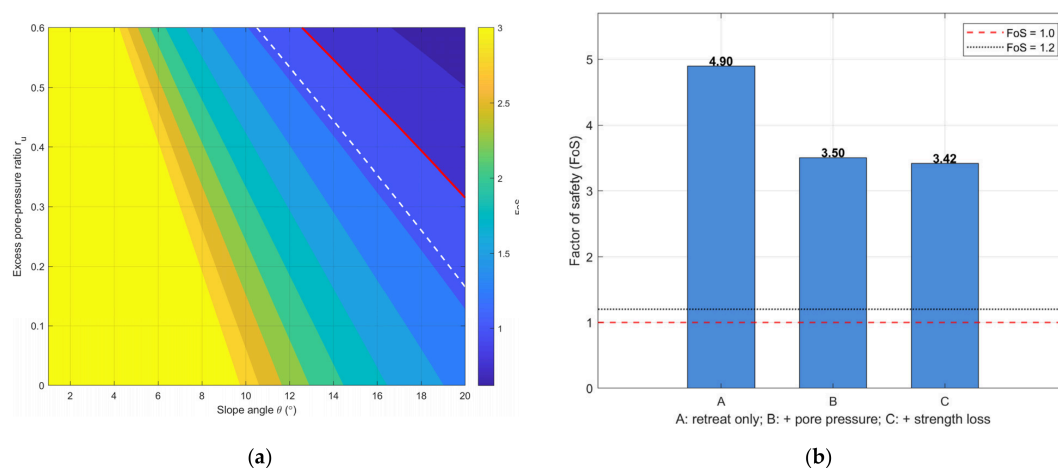


Figure 4. Cont.

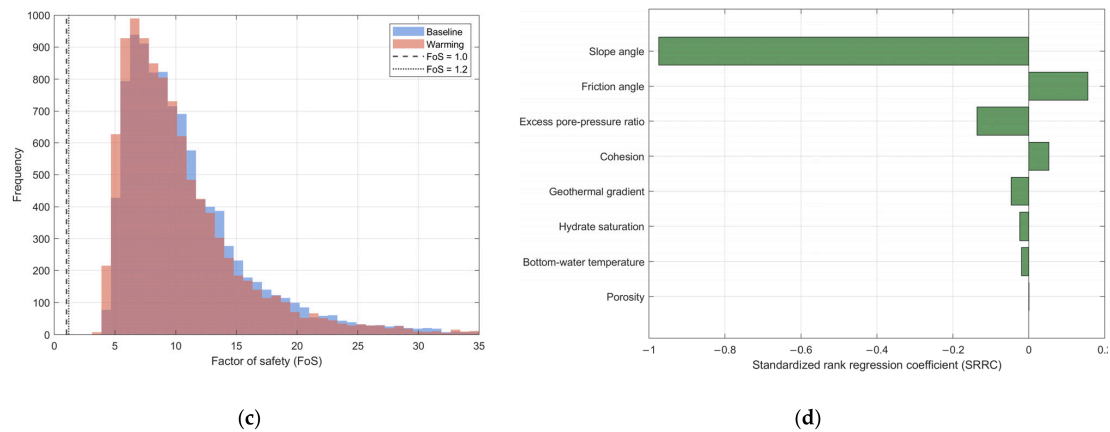


Figure 4. Geomechanical response and uncertainty analysis of hydrate-related slope stability. (a) FoS response surface as a function of slope angle θ and excess pore-pressure ratio r_u ; the red solid contour marks FoS = 1.0 and the white dashed contour marks FoS = 1.2. (b) FoS under three hydrate-related mechanism scenarios: A, GHSZ retreat only (4.90); B, + excess pore pressure (3.49); C, + excess pore pressure and strength degradation (3.40). (c) Monte Carlo probability distribution of FoS under baseline and warming (+2.0 °C, 1000 yr) scenarios, computed under the illustrative low-gradient triangular slope-angle assumption (Assumption A); the warming case shifts the distribution toward lower values (median relative reduction $\approx 5.5\%$) but does not generate low-FoS conditions under any of the three tested slope-angle assumptions (Supplementary Figure S1 and Table S2). In panel (c), the baseline distribution is shown in blue and the warming distribution in red; their overlap appears as a brownish tone. (d) Standardized rank regression coefficients (SRRCs) quantifying the relative influence of uncertain inputs on FoS.

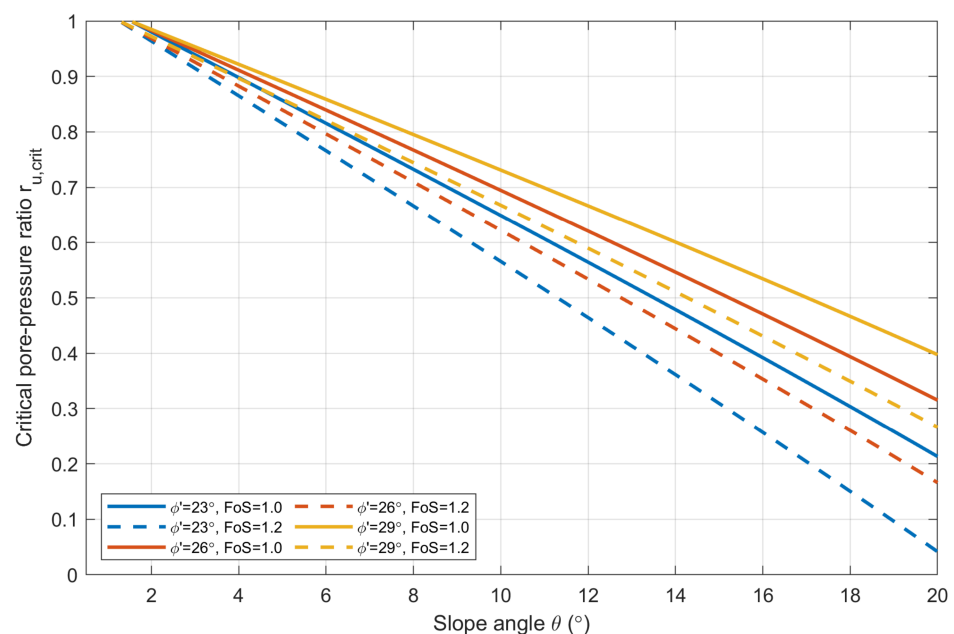


Figure 5. Critical excess-pore-pressure ratio $r_{u,crit}$ required to reach target factors of safety (FoS = 1.0 and FoS = 1.2) as a function of slope angle, shown for effective friction angles of 23°, 26°, and 29°. The critical ratio provides an engineering-oriented relative stability threshold that is less sensitive to the high absolute FoS values obtained at very low slope angles. For the reference slope and friction angle, $r_{u,crit} \approx 0.839$ for FoS = 1.0 and ≈ 0.796 for FoS = 1.2.

4. Discussion

4.1. Limited Influence of Bottom-Water Warming

The results indicate that bottom-water warming alone has limited influence on the Shenhu BGHSZ over centennial timescales. Even under a +3.0 °C anomaly sustained for 1000 years, the conductive potential dissociation thickness remains below 4 m at the baseline thermal diffusivity; across the full tested diffusivity–warming–time matrix it ranges to about 19.5 m (Supplementary Figure S2, Table S4). This reflects slow downward heat diffusion and the relatively deep present-day BGHSZ, consistent with global modeling showing that only a small fraction of the marine hydrate inventory responds to warming on centennial-to-millennial timescales [27] and with field cases where non-thermal forcings such as isostatic rebound or sea-level change dominate dissociation [15,28]. In particular, a basin-scale simulation of Last Deglaciation forcing (a ~120 m sea-level rise and a ~2.5 °C bottom-water temperature increase) found that hydrate dissociated in the Dongsha, Xisha, and Qiongdongnan areas but not in the Shenhu area, because its greater water depth and lower bottom-water temperature kept the reservoir within the stability field [29]; this provides independent, site-specific support for the limited sensitivity of the Shenhu BGHSZ to bottom-water warming alone. By analogy, hydrate-stability responses in high-latitude and permafrost-associated settings are likewise paced by slow thermal diffusion [30]. We note that the adopted thermal diffusivity ($\kappa = 3.0 \times 10^{-7} \text{ m}^2 \text{ s}^{-1}$) lies at the lower end of typical marine values ($\sim 10^{-6} \text{ m}^2 \text{ s}^{-1}$) and thus tends to amplify the modeled thermal-delay effect. To quantify this effect, an explicit κ sensitivity test is reported in Supplementary Figure S2: for a +2.0 °C bottom-water warming sustained for 1000 years, D_{diss} increases approximately monotonically with κ , from essentially zero at $\kappa = 1.0 \times 10^{-7} \text{ m}^2 \text{ s}^{-1}$ to ~12 m at $\kappa = 8.0 \times 10^{-7} \text{ m}^2 \text{ s}^{-1}$. Crucially, even at the upper end of the tested κ range, the warming-driven conductive potential dissociation thickness remains smaller than the equilibrium BGHSZ offsets produced by the exploratory geological tests, which range from approximately 37 to 95 m in the evaluated cases. The absolute magnitude of warming-driven BGHSZ shoaling is therefore κ -dependent, but the leading-order conclusion that conductive bottom-water warming produces a smaller boundary response than the imposed high-geothermal-gradient and localized-temperature equilibrium tests is robust across the tested κ range. Shenhu should therefore not be interpreted as a hydrate system in which bottom-water warming alone rapidly causes large-scale dissociation; the precise magnitude of warming-driven shoaling should nevertheless be revisited as higher-resolution thermal-property data become available. This conclusion applies specifically to the conductive, one-dimensional heat-diffusion framework and the parameter ranges tested here; it does not account for advective heat transport by fluid flow, hydrate dissociation kinetics, gas migration, or changes in sediment thermal properties, any of which could modify the warming response.

4.2. Dominant Role of Geological Perturbations

High geothermal gradient and localized thermal-fluid input produce much larger BGHSZ shoaling and FoS reduction than bottom-water warming alone. This is consistent with geological interpretations that gas chimneys, channel–levee migration, focused fluid flow, local thermal anomalies, and sediment erosion/deposition influence BSR migration and hydrate accumulation in Shenhu and adjacent provinces, where fault- and chimney-controlled fluid pathways and source-rock–geothermal coupling govern accumulation [19,31]. Persistent methane seepage documented at nearby cold-seep systems further attests to sustained focused fluid flux on this margin [32]. The BGHSZ should thus be regarded as a dynamic interface controlled by both regional thermal structure and localized fluid-flow processes.

4.3. From BGHSZ Migration to Slope Sensitivity: Reservoir Architecture, Pore Pressure, and Mechanical Limits

The phase-layer model highlights that BGHSZ migration carries different implications depending on whether it affects hydrate-bearing layers, three-phase mixed layers, or free-gas intervals. Hydrate saturation becomes mechanically important when migration intersects hydrate-rich, low-permeability, weakly cemented sediments, where dissociation can promote excess pore pressure and strength loss. This explains why hydrate saturation appears as a secondary but physically meaningful destabilizing factor in the sensitivity analysis. We emphasize that the three-layer subdivision is a conceptual simplification: the layer-boundary depths are constrained by published three-dimensional reservoir-architecture and logging interpretations for the production-test region rather than by a single well profile, and the actual Shenhu reservoir is laterally heterogeneous, so the phase layering should be read as a representative conceptual model rather than a site-specific stratigraphy.

The FoS and Monte Carlo results show that hydrate destabilization does not automatically cause slope failure. Instability requires an unfavorable combination of high slope angle, high excess pore pressure, weak sediment strength, high hydrate saturation, and potentially external triggers. Hydrate-related geohazard assessment should therefore avoid deterministic assumptions that dissociation directly causes failure; a coupled, probabilistic sensitivity framework is more appropriate, in agreement with recent susceptibility analyses that resolve failure-prone zones only where unfavorable factors coincide [24,25]. The numerical values of the exploratory geological stress-test scenarios should be interpreted as stress tests for mechanism separation rather than calibrated forecasts of expected Shenhu conditions.

4.4. Implications, Limitations, and Future Work

Because the absolute FoS depends strongly on the assumed slope-angle distribution and the model is not constrained by measured bathymetry, we do not present a regional hazard classification or a terrain-resolved geohazard map. Any operational use of the framework should be preceded by acquisition of measured multibeam bathymetry and site-specific geotechnical data, after which the relative controls identified here could be re-evaluated against real terrain.

For the production area, monitoring should not focus solely on bottom-water temperature. Subsurface thermal anomalies, gas chimneys, fluid pathways, pore-pressure evolution, gas-bearing layers, hydrate saturation, and local slope morphology should also be considered. Because excess pore pressure accounts for most of the modeled FoS reduction, pore-pressure monitoring and permeability characterization are particularly important for production safety and geohazard assessment. This emphasis is consistent with Shenhu-specific coupled modeling showing that depressurization production generates excess pore pressure, weakened layers, and seafloor subsidence that can drive slope instability [33] and that geothermal gradient strongly modulates multiphase-flow behavior and engineering safety during exploitation [34].

This study uses a simplified MATLAB-based probabilistic framework rather than a fully coupled multiphase flow–geomechanical simulator. Hydrate dissociation kinetics, gas–water migration, pressure diffusion, sediment deformation, and three-dimensional progressive failure are not explicitly simulated. In particular, bottom-water temperature is prescribed as a fixed upper boundary condition, so the model does not represent the thermal feedback by which endothermic hydrate dissociation can locally cool the surrounding sediment and bottom water; neglecting this negative feedback is conservative, because it would otherwise act to slow further dissociation. Seismic loading, which is widely regarded as one of the most common external triggers of submarine slope failure and can

promote hydrate dissociation and excess-pore-pressure generation through cyclic shear and transient stress changes [35], is likewise not included; on this tectonically active margin, earthquake ground motion should therefore be considered an additional destabilizing factor in any site-specific follow-up assessment. The phase-layer model is conceptual and based on published reservoir architecture rather than a specific well profile, and the exploratory geological stress-test scenarios should be interpreted as sensitivity tests and end-members, not deterministic predictions. Despite these limitations, the framework provides a transparent, reproducible first-order tool for comparing the relative effects of bottom-water warming, geothermal forcing, localized thermal-fluid input, hydrate saturation, excess pore pressure, and slope geometry and can guide more detailed coupled thermal-hydraulic-mechanical modeling.

5. Conclusions

This study developed a drilling- and reservoir-constrained first-order probabilistic framework for evaluating gas hydrate stability and slope sensitivity in the Shenhu production area. The main conclusions are:

- The modeled present-day BGHSZ is approximately 271 mbsf and is consistent at first order with reported BSR depths (MAE = 16.3 m; RMSE = 19.8 m).
- Bottom-water warming alone produces limited BGHSZ shoaling; even under +3.0 °C sustained for 1000 years, the conductive-potential hydrate dissociation thickness remains below 4 m at the baseline thermal diffusivity (0–19.5 m across the full tested diffusivity–warming–time matrix).
- Exploratory geological stress-test scenarios—particularly high geothermal gradient and localized thermal-fluid input—generate much larger equilibrium BGHSZ offsets and stronger FoS reduction than climate-only conductive warming.
- FoS is controlled primarily by slope angle, friction angle, and excess pore-pressure ratio, with hydrate saturation acting as a secondary destabilizing factor by amplifying pore-pressure generation and strength degradation; consequently, hydrate dissociation does not inevitably cause slope failure in Shenhu, and significant slope sensitivity requires the spatial overlap of hydrate destabilization, excess pore pressure, weak sediment strength, high hydrate saturation, and unfavorable slope geometry. In the Monte Carlo analysis, conductive warming reduces the modeled relative stability margin (median FoS reduction $\approx$ 5.5% under the illustrative triangular assumption, with $\sim$ 9.2% of realizations exceeding 10% and only $\sim$ 0.01% exceeding 20%) but does not generate low-FoS conditions within the tested static parameter ranges; production-depressurization, pseudo-static seismic, latent-heat, and multiphase-flow effects are addressed only as Supplementary stress tests or as explicit model-scope limitations.
- The absolute factor of safety is strongly dependent on the assumed slope-angle distribution, so relative stability-margin reduction—rather than absolute FoS or any regional hazard classification—is the appropriate model output; across the three parallel slope-angle assumptions, the dominant control ranking (slope angle, friction angle, excess pore-pressure ratio) remains stable.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/jmse14141306/s1>, Figure S1: Slope-angle structural-uncertainty comparison; Figure S2: Thermal-diffusivity–warming–time conductive matrix; Figure S3: Localized cooling-proxy sensitivity; Figures S4 and S5: Production/depressurization and pseudo-static seismic mechanism-isolation tests; Tables S1–S8: Full parameter list, slope-angle diagnostics, conductive matrix, pore-pressure-margin statistics, cooling proxy, production/seismic tests, and BSR-target uncertainty.

Author Contributions: Conceptualization, H.L. and J.L.; methodology, H.L.; software, H.L.; validation, H.L., Q.H. and Z.C.; formal analysis, H.L.; investigation, H.L.; resources, Q.H. and J.L.; data curation, H.L. and X.G.; writing—original draft preparation, H.L.; writing—review and editing, H.L., J.L. and Y.P.; visualization, H.L.; supervision, J.L.; project administration, J.L.; funding acquisition, Q.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Open Fund Project of the State Key Laboratory of Natural Gas Hydrate, titled “Sequence Stratigraphy and Tectonic Setting of Gas Hydrate Enrichment Areas”, grant number CCL2024RCPS0270KQN.

Data Availability Statement: The data presented in this study are available within the article and its Supplementary Materials. The MATLAB code, parameter set, and fixed random seed used to generate all results are available from the corresponding author upon reasonable request. All drilling, logging, and reservoir-characterization data used for parameterization are from previously published sources cited in the manuscript; no new field data were generated in this study.

Acknowledgments: During the preparation of this manuscript, the authors used a generative artificial intelligence tool (Anthropic Claude Opus 4.8) for the purposes of language polishing, editing, and manuscript formatting assistance. The authors have reviewed and edited the output and take full responsibility for the content of this publication. The authors also gratefully acknowledge the support of the Deep Earth Probe and Mineral Resources Exploration—National Science and Technology Major Project (Nos. 2025ZD1006601 and 2025ZD1006600).

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

BGHSZ	Base of the gas hydrate stability zone
BSR	Bottom-simulating reflector
FoS	Factor of safety
GHSZ	Gas hydrate stability zone
GMGS	Guangzhou Marine Geological Survey
MAE	Mean absolute error
mbsf	Meters below seafloor
RMSE	Root mean square error
SRRC	Standardized rank regression coefficient

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