

Article

Instability Risk of Submarine Hydrate-Bearing Slopes Under Thermal Disturbances

Xiaolong Song ^{1,*}, Jiuhui Cheng ¹, Bin Zhu ²  and Hao Zhang ³¹ State Key Laboratory of Digital Intelligent Technology for Unmanned Coal Mining, Anhui University of Science and Technology, Huainan 232001, China; cheng_jiuhui@aust.edu.cn² School of Mechanics and Civil Engineering, China University of Mining and Technology, Xuzhou 221116, China; binzhu@cumt.edu.cn³ State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian 116024, China; haoz@mail.dlut.edu.cn

* Correspondence: songxiaolongyt@163.com

Abstract

Thermal disturbance can destabilize submarine hydrate-bearing sediments by reducing hydrate stability, promoting dissociation, weakening hydrate-derived cementation, and increasing excess pore pressure. This study develops a probabilistic framework coupling a one-dimensional thermal–hydrate evolution model with an infinite slope stability formulation. Hydrate system degradation is represented by a hydrate degradation risk index (RI_{hyd}), whereas mechanical stability is evaluated using the minimum factor of safety (FS_{min}). The reference simulation places hydrate mainly at 140–200 m below the seafloor, with a peak initial saturation of approximately 0.45. Over 10 ka, the hydrate occurrence zone contracts by approximately 66.7%. The minimum factor of safety, FS_{min} , decreases from approximately 6.2, crosses the warning threshold of 1.30, and first reaches the critical threshold of 1.00 at approximately 4.6 ka after substantial hydrate system degradation. Monte Carlo simulations ($n=800$) yield a terminal median FS_{min} of approximately 2.8 and a 5th–95th percentile range of 1.1–11.4; the corresponding median RI_{hyd} is approximately 31. The terminal probabilities of warning and critical states are approximately 0.16 and 0.08, respectively. Sensitivity analysis identifies slope angle and total temperature rise as the principal controls on FS_{min} , while total temperature rise dominates the coupled risk response. The framework provides an uncertainty-aware screening tool for comparing hydrate degradation and slope stability responses.

Keywords: gas hydrate; thermal disturbance; submarine slope stability; risk index; uncertainty analysis



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1. Introduction

Natural gas hydrate is an ice-like crystalline compound in which gas molecules, predominantly methane, are enclosed within a crystalline water lattice [1]. They are widely distributed in continental-margin sediments and are relevant to marine geohazards and the global carbon cycle [2]. Their stability is controlled by pressure–temperature conditions, pore-fluid composition, sediment properties, and gas supply [3,4]. Sustained ocean warming can modify bottom-water temperatures and shift hydrate stability boundaries. The response is strongly conditioned by water depth, sediment thermal properties, fluid pathways, and geological history [5–14]. Thermal disturbances may also arise from drilling,

wellbore heat transfer, thermal stimulation, fluid injection, depressurization, and hydrate-production operations [15–19]. Although climate-driven and engineering-induced heating differ in scale and boundary conditions, both can be characterized by the total temperature rise and warming duration, which respectively describe disturbance intensity and the timescale of heat input.

Hydrate dissociation may affect slope stability through coupled thermal, hydraulic, and mechanical pathways. Hydrates can enhance sediment stiffness and shear resistance by cementing grain contacts, filling pores, or contributing to the load-bearing skeleton [20,21]. The magnitude of this contribution depends on hydrate saturation, morphology, and spatial distribution [22,23], while the resulting mechanical response is further controlled by porosity, fines content, effective stress, drainage condition, and strain rate [24–31]. Dissociation therefore weakens the sediment not only by reducing hydrate-derived cohesion and frictional resistance but also by releasing gas and water. Where drainage is inefficient, excess pore pressure can reduce effective normal stress and accelerate stability loss [32–38]. Consequently, the mechanical effect of a given degree of hydrate loss cannot be inferred from saturation change alone; it depends on the initial sediment state, stress conditions, and hydraulic response.

Submarine slope failure is inherently multi-causal. Slope geometry, weak layers, sedimentation history, fluid migration, pore-pressure evolution, and geological heterogeneity may be as important as hydrate dissociation [39–41]. Engineering operations may further couple reservoir deformation with slope response [42–45]. Hydrate dissociation should therefore be regarded as a potential weakening mechanism rather than direct evidence of failure. However, existing studies commonly emphasize either hydrate system evolution—such as temperature propagation, saturation loss, and changes in the hydrate-bearing interval—or the resulting mechanical response, including strength degradation, deformation, and factor-of-safety reduction. These two responses are related but not equivalent: substantial hydrate degradation may occur without immediate failure where drainage and residual strength are sufficient, whereas limited dissociation may cause pronounced stability loss in a steep, weak, or poorly drained slope. A framework that quantifies hydrate degradation and mechanical stability separately and then evaluates their relationship is therefore required.

Uncertainty further complicates this relationship. Hydrate system response depends on initial saturation, reservoir thickness, sediment thermal properties, disturbance intensity, and warming duration, whereas slope stability is affected by geometry, pore-pressure response, hydrate cementation, residual cohesion, and friction angle. Previous reliability, subsidence, and reservoir-scale studies demonstrate that uncertain reservoir and sediment properties can produce markedly different deformation and failure responses [46–48]. Nevertheless, the manner in which these uncertainties propagate simultaneously into time-dependent hydrate degradation and slope stability limit states remains insufficiently quantified. The specific problem addressed here is therefore how to link these two responses under thermal disturbance while accounting for uncertainty in the governing thermal, hydrate-related, hydraulic, geometric, and mechanical parameters.

To address this problem, this study develops a probabilistic framework that links a one-dimensional thermal-hydrate model with an infinite slope stability formulation. The framework tracks thermal propagation, hydrate dissociation, contraction of the hydrate-bearing interval, equivalent strength degradation, and pore-pressure weakening. Hydrate system degradation and mechanical stability are evaluated separately using RI_{hyd} and FS_{min} , while RI_{coupled} provides an integrated indicator for scenario comparison rather than a direct failure probability. Monte Carlo simulation propagates uncertain input parameters into the distributions of the risk indices, factor of safety, and warning- and critical limit-state

probabilities. Spearman's rank correlation is used to screen the dominant controls, and a two-dimensional parameter sweep examines the distinct roles of total temperature rise and warming duration. The novelty of the study lies in separating the precursor degradation state from the mechanical stability response within a unified probabilistic framework, thereby avoiding the assumption that hydrate dissociation necessarily implies slope failure. The framework is intended for relative risk assessment and parameter screening rather than site-specific failure prediction.

2. Materials and Methods

2.1. Conceptual Model and Parameterization

The Shenhu area in the northern South China Sea provides the geological basis for the present study, where hydrate-bearing fine-grained sediments, variable hydrate saturation, drilling evidence, and offshore production-test data have been extensively documented [49–51]. Based on these regional geological characteristics, a Shenhu-inspired conceptual slope model was developed to investigate the coupled effects of thermal disturbance, hydrate degradation, and slope stability under parameter uncertainty, as shown in Figure 1. The model consists of a vertically resolved sediment column beneath a submarine slope, including an upper low-permeability layer, a hydrate-bearing interval, and an underlying sedimentary layer.

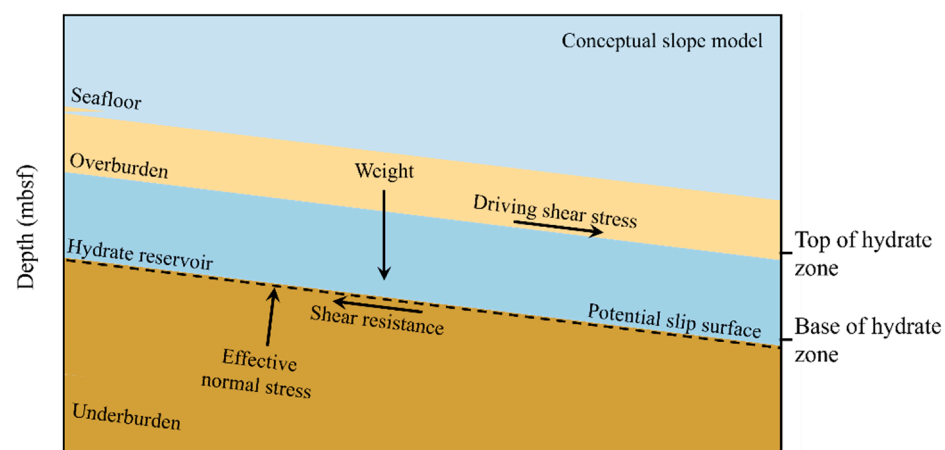


Figure 1. Conceptual infinite slope model.

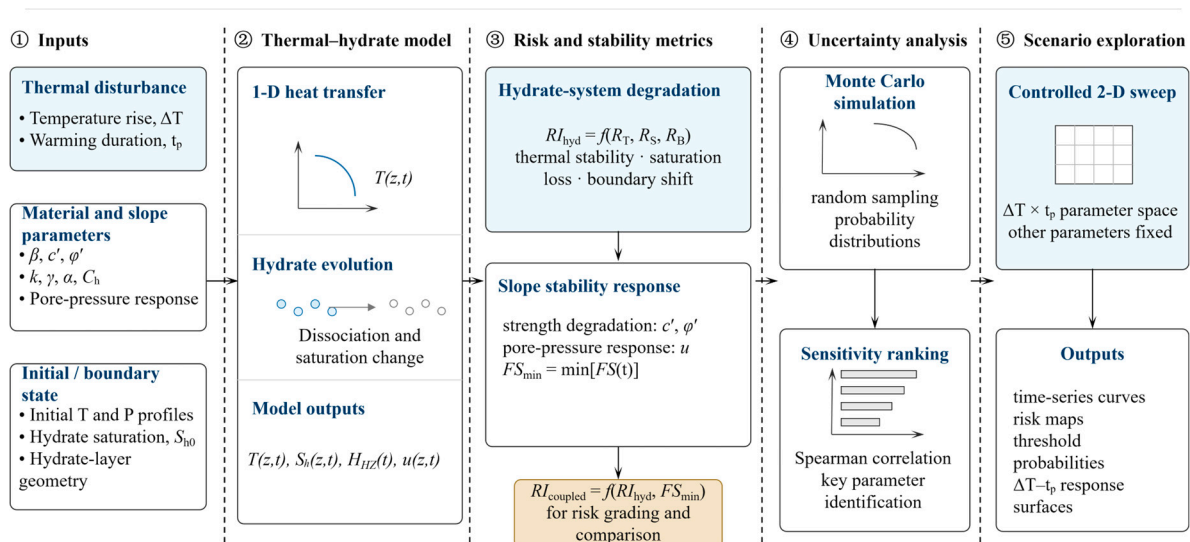
Comparable geological evidence is also available from the adjacent Dongsha area, where drilling and sediment analyses have identified both shallow seepage-dominated and deep diffusion-dominated hydrate reservoirs. Variations in mineral composition, specific surface area, permeability, and sealing conditions were shown to influence hydrate accumulation and vertical reservoir architecture [52].

The initial hydrate occurrence is determined using a coupled thermodynamic and methane supply calculation following the analytical framework previously proposed by Song et al. [36]. The reference configuration adopts a water depth of 1274 m, an initial seafloor temperature of 4 K, a 1000 m sediment domain, and a vertical grid spacing of 10 m. Slope stability is evaluated using an infinite slope approximation, which captures the coupling effect between hydrate dissociation, strength degradation, pore-pressure-related weakening, and mechanical stability. However, the model does not explicitly resolve three-dimensional slip-surface geometry, gas migration, multiphase flow, or transient pore-pressure diffusion. Table 1 summarizes the reference parameter values adopted for the deterministic reference case and the parameter ranges used in the uncertainty analysis.

Table 1. Parameter values for the reference case.

Parameter	Symbol	Reference Value	Unit
Water depth	z_w	1274	m
Initial seafloor temperature	T_0	4.0	K
Porosity	θ	0.30	–
Permeability	k	5.5×10^{-15}	m^2
Thermal diffusivity	κ	4.5×10^{-7}	m^2/s
Total temperature rise	ΔT	7.5	K
Warming duration	t_p	300	yr
Slope angle	β	5	°
Residual cohesion	c_0	2	kPa
Hydrate cementation	$c_{\text{hyd,max}}$	25	kPa
Initial friction angle	φ'_0	28	°
Maximum friction-angle loss	$\Delta\varphi_{\text{max}}$	3	°

To quantitatively evaluate the stability risk of hydrate-bearing submarine slopes under different thermal disturbances, this paper constructs a probabilistic framework consisting of “deterministic hydrate decomposition simulation–risk index conversion–limit state discrimination–Monte Carlo uncertainty analysis”. Firstly, this framework uses the hydrate thermal decomposition model to obtain the dynamic changes in temperature, hydrate saturation, and occurrence boundaries; secondly, it converts the hydrate decomposition results into relative risk indices; thirdly, based on the infinite slope safety factor, it defines stable, warning, and critical states; finally, through the Monte Carlo simulation, it quantifies the impact of key parameter uncertainties on the safety factor, risk index, and probability of critical state. The technical route is shown in Figure 2.

**Figure 2.** Workflow of thermal disturbance-driven hydrate degradation and slope stability risk assessment.

The one-dimensional framework adopted in this study is an extension of a previous hydrate thermal-response model [36]. In the present work, this framework is further coupled with slope stability analysis and probabilistic uncertainty quantification to evaluate the long-term response of hydrate-bearing submarine slopes.

2.2. Thermal Disturbance and Hydrate Evolution

At $t = 0$, the sediment column is specified by its initial temperature $T_i(z)$, pressure $P_i(z)$, and hydrate saturation $S_{h0}(z)$. A thermal disturbance is applied at the seafloor boundary as follows:

$$T_s(t) = \begin{cases} T_0 + \Delta T \frac{t}{t_p}, & 0 \leq t \leq t_p \\ T_0 + \Delta T, & t > t_p \end{cases} \quad (1)$$

Here, ΔT denotes the prescribed total increase in the seafloor boundary temperature, and t_p is the duration over which the temperature increases linearly from T_0 to $T_0 + \Delta T$. After t_p , the seafloor boundary temperature is maintained at $T_0 + \Delta T$. Under boundary warming, the resulting temperature evolution within the sediment column is described by the following heat conduction equation:

$$\frac{\partial T(z, t)}{\partial t} = \kappa \frac{\partial^2 T(z, t)}{\partial z^2} + s(z, t) \quad (2)$$

Here, $s(z, t)$ is a term accounting for possible heat sources/sinks, and κ is the effective thermal diffusivity (in m^2/s). The model tracks the resulting temperature evolution, hydrate saturation $S_h(z, t)$, and occurrence-zone boundaries.

The transient heat equation is solved using a finite-difference scheme. Hydrate begins to dissociate when the local temperature reaches the dissociation temperature corresponding to the local pressure. During dissociation, heat is consumed by latent heat. After considering the latent heat consumption, the hydrate saturation can be expressed as

$$\begin{cases} S_h(z, t) = S_{h0}(z) \left[1 - \frac{Q_{acc}(z, t)}{L} \right], & 0 \leq Q_{acc}(z, t) < L \\ 0, & Q_{acc}(z, t) < L \end{cases} \quad (3)$$

where Q_{acc} is the cumulative heat available for hydrate dissociation, and L is the latent heat required per unit volume of hydrate for complete decomposition.

2.3. Hydrate Degradation and Slope Stability Indices

The comprehensive risk index is constructed from three complementary components representing different stages of hydrate system evolution: (1) thermal stability condition as the triggering factor, (2) hydrate saturation loss as the material degradation process, and (3) hydrate stability zone thickness shrinkage as the spatial structural response.

The normalized thermal stability risk is defined as follows:

$$\overline{R}_T(t) = \min \left[\max \left(\frac{\Delta T_b - M_T(z, t)}{\Delta T}, 0 \right), 1 \right] \quad (4)$$

where ΔT_b is the normalized temperature buffering scale. $M_T(z, t)$ represents the thermal stability reserve and can be determined by Formula (5):

$$M_T(z, t) = T_{diss}(P(z, t)) - T(z, t) \quad (5)$$

To convert the process of hydrate decomposition into a risk assessment indicator, the following is defined as the rate of hydrate saturation loss.

$$R_s(z, t) = \frac{S_{h0}(z) - S_h(z, t)}{S_{h0}(z)} \quad (6)$$

The overall saturation loss risk within the hydrate reservoir zone can be defined as follows:

$$\overline{R_s}(t) = \frac{\sum_{z \in HZ_0} R_s(z, t) S_{h0}(z)}{\sum_{z \in HZ_0} S_{h0}(z)} \quad (7)$$

The thickness variation risk of hydrate reservoirs, denoted by $R_B(t)$, is used to characterize the degree of contraction of the hydrate storage space under thermal disturbance.

$$\overline{R_B}(t) = 1 - \frac{H_{HZ}(t)}{H_{HZ}(0)} \quad (8)$$

Combining Formulas (4)–(8), the spatially averaged components are used as follows:

$$RI_{hyd}(t) = 100[w_T \overline{R_T}(t) + w_S \overline{R_S}(t) + w_B \overline{R_B}(t)] \quad (9)$$

$$w_T + w_S + w_B = 1 \quad (10)$$

where RI_{hyd} is a relative indicator of hydrate system degradation, and $w_T = 0.35$, $w_S = 0.40$, and $w_B = 0.25$ denote the respective weights of each component. The saturation loss component was assigned the highest weight because it directly represents the actual loss of solid hydrate and the associated reduction in hydrate-derived cementation. The thermal-stability component represents the thermodynamic driver and an early precursor of dissociation. The occurrence-zone contraction component provides complementary spatial information but partly overlaps with the information contained in hydrate saturation loss and was therefore assigned a lower weight. The weight-sensitivity analysis is provided in Appendix A.

To quantitatively evaluate slope stability, the limit equilibrium method (LEM) based on the infinite slope sliding mode is adopted, which is widely used for submarine slope stability analysis [53–55]. The slope stability coefficient can be derived as follows:

$$FS(t) = \frac{c'(t) + [\sigma_n(t) - u(t)] \tan \varphi'}{\tau(t)} \quad (11)$$

where $\sigma_n(t)$ represents the normal stress, $u(t)$ represents the excess pore pressure, φ' represents the effective internal friction angle, $\tau(t)$ represents the shear stress, and $c'(t)$ represents the effective cohesion.

To quantify the effect of excess pore pressure, a dimensionless pore-pressure response coefficient, α_u , is defined as

$$\alpha_u = \frac{\Delta u(t)}{\sigma'_{n,0}(z) \overline{R_S}(t)} \quad (12)$$

Considering the attenuation of the bonding strength caused by the decomposition of hydrates, the effective cohesion and friction angle are expressed as follows:

$$c'(t) = c_0 + c_{hyd,max} [1 - \overline{R_S}(t)] \quad (13)$$

$$\varphi'(t) = \varphi'_0 - \Delta \varphi'_{max} \overline{R_S}(t) \quad (14)$$

Among them, c_0 represents the residual cohesion after the complete decomposition of the hydrate, $c_{hyd,max}$ represents the maximum bonding strength provided by the hydrate, φ'_0 is the initial effective friction angle, and $\Delta \varphi'_{max}$ is the maximum friction-angle loss associated with complete local hydrate removal.

This paper employs a dual-threshold method to classify the stable state of the slope as follows:

$$\begin{cases} FS > 1.3, & \text{stable state} \\ 1.0 < FS \leq 1.3, & \text{warning state} \\ FS \leq 1.0, & \text{critical state} \end{cases} \quad (15)$$

$FS = 1.00$ represents limiting equilibrium, at which the available shear resistance equals the driving shear stress. $FS = 1.30$ is adopted as a warning threshold [51].

The hydrate degradation index (RI_{hyd}) characterizes the thermal stability degradation, water saturation loss, and spatial occurrence structure changes in the hydrate system under thermal disturbance. Its essence reflects the “degree of driving degradation” of the system. The slope safety factor (FS) represents the anti-sliding stability state of the slope under given mechanical conditions. There is no direct equivalence relationship between the two, but RI_{hyd} indirectly controls the evolution process of FS by changing the hydrate cementation strength and pore-pressure state. Therefore, RI_{hyd} can be regarded as a precursor driving indicator for FS changes, while FS is a result indicator of the system’s mechanical response.

To provide an integrated representation of hydrate degradation and mechanical instability for risk classification and scenario comparison, a hydrate–slope coupled risk index, $RI_{coupled}$, is further introduced. The purpose of this index is not to replace either RI_{hyd} or FS , but to identify whether hydrate degradation has been translated into an appreciable mechanical instability risk. The coupled risk index is defined as

$$RI_{coupled}(t) = 100[w_{hyd}RI_{hyd} + w_{FS}R_{FS}] \quad (16)$$

where $w_{hyd} = 0.7$ and $w_{FS} = 0.3$ denote the respective weights of each component. The hydrate degradation group accounts for 70% of the coupled index so that the index remains sensitive to the preceding thermal and hydrate degradation processes. The FS -derived component accounts for 30%, allowing the index to respond clearly when the slope enters the warning-to-critical range without causing $RI_{coupled}$ to become merely a normalized representation of FS . The weight-sensitivity analysis is in Appendix A.

To quantify the effects of parameter uncertainty on hydrate system degradation and slope stability evaluation, the Monte Carlo method was adopted to randomly sample thermal disturbance, slope geometry, hydrate cementation, and sediment mechanical parameters. The random input variables included the total temperature increase ΔT , warming duration t_p , slope angle β , pore-pressure response coefficient α_u , residual cohesion c_0 , effective internal friction angle φ_0 , maximum hydrate-induced cohesion $c_{hyd,max}$, and thermal diffusivity κ . The Monte Carlo realization was performed, which was sufficient to capture the statistical characteristics of the model responses, including the median trends and uncertainty ranges, for the present screening-level probabilistic assessment. The selected sample size provides an effective balance between uncertainty representation and computational efficiency. The input vector for the Monte Carlo realization is expressed as Equation (17). The complete distributions are reported in Table 2.

$$X = [\Delta T, t_p, \beta, \alpha_u, c_0, \varphi'_0, c_{hyd,max}, \kappa, \Delta\varphi'_{max}] \quad (17)$$

For each Monte Carlo sampling, the deterministic hydrate dissociation–slope stability model is run once, and the outputs of $RI_i(t)$ and $FS_i(t)$ are obtained. The probability of the warning state and the critical state are, respectively, defined as follows:

$$P_w(t) = \frac{1}{N} \sum_{i=1}^N I[FS_i(t) \leq 1.3] \quad (18)$$

$$P_c(t) = \frac{1}{N} \sum_{i=1}^N I[FS_i(t) \leq 1.0] \quad (19)$$

Here, N represents the number of Monte Carlo simulations, and $I[\cdot]$ is an indicator function.

Table 2. Probability distributions for the Monte Carlo input parameters.

Input Parameter	Distribution and Parameters	Selection Rationale
ΔT	U(2, 10) K	Plausible thermal disturbance bounds; no unique most likely value [36].
t_p	U(100, 1000) yr	Covers relatively rapid to gradual warming scenarios [36].
β	U(2, 15)°	Covers gentle to moderately inclined submarine slopes [36].
α_u	Tri(0.10, 0.40, 0.90)	Represents weak, moderate, and strong pore-pressure responses [34,36].
$c_{\text{hyd,max}}$	Tri(10, 25, 45) kPa	Covers low to high hydrate cementation contributions [24,30].
φ'_0	Tri(20, 28, 34)°	Based on representative strength ranges of hydrate-bearing sediments [31].
c_0	Tri(0.10, 2.00, 5.00) kPa	Covers very weak to moderately cohesive marine sediments [34,36].
κ	Tri(2.5×10^{-7} , 4.5×10^{-7} , 8.0×10^{-7}) m ² /s	Represents uncertainty in sediment thermal properties [36].
$\Delta\varphi'_{\text{max}}$	Tri(1, 3, 6)°	Represents mild to pronounced frictional-strength degradation [31].

Note: U(a,b) denotes a uniform distribution between the lower and upper bounds. Tri(a,m,b) denotes a triangular distribution with lower bound a, mode m, and upper bound b.

The parameter sensitivity is evaluated using the Spearman rank correlation coefficient:

$$\rho_s(X_k, Y) = \text{corr}[\text{rank}(X_k), \text{rank}(Y)] \quad (20)$$

Here, X_k represents the k th input parameter, and Y is the output indicator. The larger the value of $|\rho_s|$, the stronger the influence of this parameter on the output result; the sign of ρ_s is used to determine the direction in which increasing the parameter will enhance the stability or risk of the slope.

2.4. Monte Carlo Convergence Assessment

A cumulative convergence assessment was conducted using the same reproducible random sequence with valid sample sizes of $N = 100, 200, 300, 500, 800$, and 1000. The $N = 1000$ results were used as the reference. At each checkpoint, the maximum relative change in the selected statistical outputs and the maximum absolute difference in the time-dependent limit-state probability curves were calculated, as shown in Figure 3.

Convergence was considered satisfactory when the maximum relative statistical change was below 5%, and the maximum probability-curve difference was below 0.01. At $N = 500$, both deviations remained slightly above the prescribed criteria. At $N = 800$, the statistical deviation decreased to below 1%, while the probability-curve difference decreased to approximately 0.009, satisfying both criteria. The deviations at $N = 1000$ were zero by definition because this sample size was used as the reference.

Therefore, $N = 800$ was adopted for the final Monte Carlo analysis, providing an appropriate balance between numerical convergence and computational efficiency.

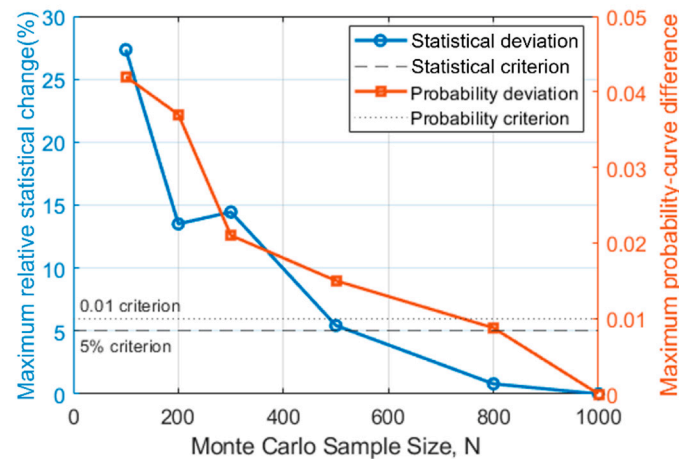


Figure 3. Monte Carlo convergence assessment based on cumulative valid realizations.

3. Results

3.1. Hydrate System Degradation and Reference Slope Response

Figure 4 presents the evolution of the initial hydrate occurrence, relative hydrate degradation risk, minimum factor of safety, and hydrate occurrence-zone boundaries under the reference thermal disturbance scenario. As shown in Figure 4a, hydrate is primarily distributed within the shallow sedimentary section, with the main interval of elevated hydrate saturation located at approximately 130–200 mbsf and a maximum initial saturation of approximately 0.45. Based on the hydrate occurrence-zone boundaries shown in Figure 4d, the initial effective hydrate-bearing interval extends from approximately 140 to 200 mbsf, corresponding to an initial effective thickness of approximately 60 m. This initial occurrence structure provides the basis for subsequent changes in hydrate stability and slope mechanical response under thermal disturbance.

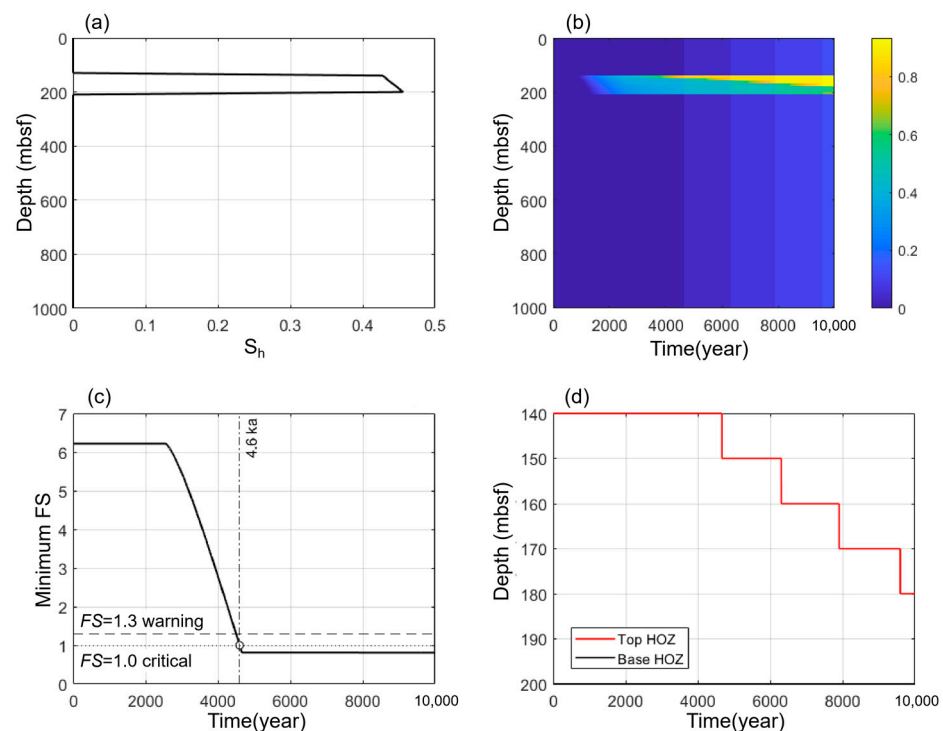


Figure 4. Spatial and temporal responses of the reference case to thermal disturbance. (a) Initial hydrate saturation profile. (b) Relative hydrate degradation risk map. (c) Temporal evolution of FS_{min} . (d) Migration of the hydrate occurrence-zone boundaries.

Figure 4b shows that the relative hydrate degradation risk is mainly concentrated within the hydrate-bearing interval at approximately 150–200 mbsf and increases progressively with time. During the early stages of the simulation, risk values remain generally low, with only localized weak responses. As the thermal disturbance persists, the risk zone expands and its intensity increases. By the end of the simulation, relatively high risk is concentrated at depths of approximately 180–200 mbsf, where the relative risk reaches about 0.9 and coincides with the interval of maximum hydrate saturation loss. Notably, the risk evolution exhibits a depth-dependent and spatially heterogeneous response within the hydrate-bearing layer.

Consistent with the risk evolution, Figure 4d indicates that the upper boundary of the hydrate occurrence zone progressively migrates downward during the simulation, whereas the lower boundary remains approximately constant at about 200 mbsf. The upper boundary shifts from an initial depth of approximately 140 mbsf to approximately 150, 160, 170, and 180 mbsf, respectively. Consequently, the effective thickness of the hydrate occurrence zone decreases from approximately 60 m to approximately 20 m, representing an overall reduction of about 66.7%. These results indicate that, under the baseline thermal disturbance condition, contraction of the hydrate occurrence zone is mainly associated with the progressive loss of the upper stable hydrate-bearing interval. The reduction in hydrate-bearing thickness also implies a progressive narrowing of the sediment interval capable of providing hydrate-related cementation and structural support.

Figure 4c presents the temporal evolution of the minimum factor of safety, $FS_{\min}$, for the reference case. At the beginning of the simulation, $FS_{\min}$ is approximately 6.2 and remains nearly constant until approximately 2.5 ka, indicating that the slope maintains a high level of stability during the early stages. Subsequently, as hydrate degradation accumulates, $FS_{\min}$ declines rapidly, crossing the warning threshold of 1.30 and then reaching the critical threshold of 1.00. At approximately 4.6 ka, $FS_{\min}$ first reaches 1.00, indicating that the slope enters the critical stability state.

3.2. Coupling Between Hydrate Degradation Risk and Slope Stability

Figure 5 compares RI_{hyd} , RI_{coupled} , and $FS_{\min}$ for the same reference case presented in Figure 4c. By approximately 2.5 ka, RI_{hyd} reaches about 30, whereas $FS_{\min}$ still exceeds 6. This temporal offset shows that loss of thermal stability and the onset of hydrate degradation precede a material mechanical response.

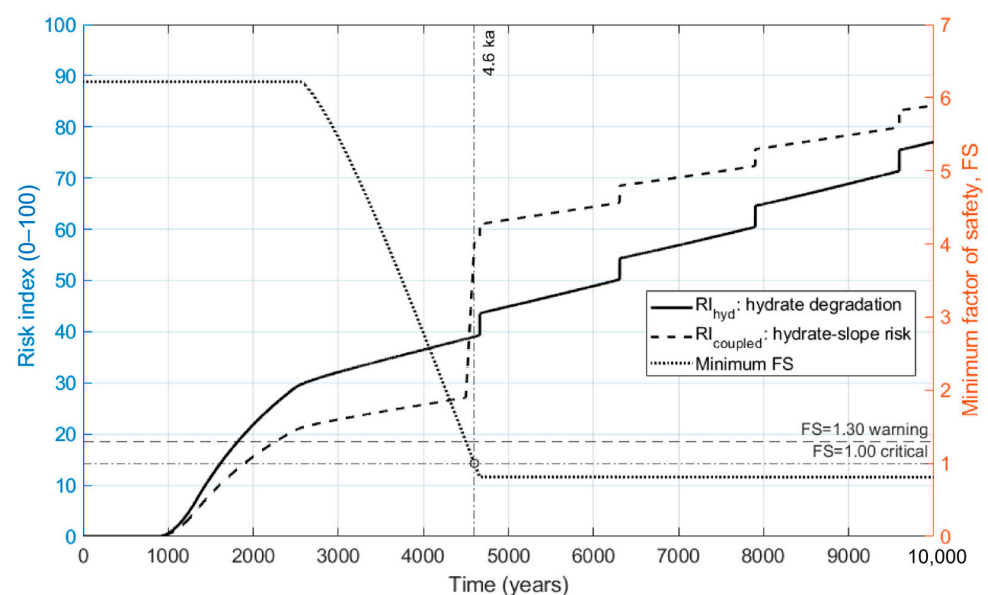


Figure 5. Coupling between hydrate degradation and slope stability in the reference case.

Between approximately 2.5 and 4.6 ka, RI_{hyd} rises more gradually from about 30 to about 38 as hydrate saturation loss and occurrence-zone contraction accumulate. Over the same interval, FS_{min} falls steeply from more than six to the critical threshold. The reference case preserves the initial FS_{min} of approximately 6.2 and first reaches the critical threshold of 1.00 at 4.6 ka. Thus, the critical state is reached only after a substantial prior buildup of hydrate system degradation.

$RI_{coupled}$ follows the early increase in RI_{hyd} but exhibits a marked jump from approximately 27 to approximately 60 when FS approaches the warning-to-critical range. This behavior is expected because $RI_{coupled}$ includes an FS-derived instability component. It subsequently increases to approximately 85 by 10 ka, whereas RI_{hyd} reaches approximately 77. RI_{hyd} should therefore be interpreted as the pre-mechanical degradation indicator, and $RI_{coupled}$ as an integrated state descriptor. Although RI_{hyd} and FS_{min} are negatively associated in time, they are not interchangeable quantities. A similar RI_{hyd} can produce different FS_{min} values when slope angle, residual cohesion, friction angle, hydrate cementation, or pore-pressure sensitivity differ.

3.3. Terminal Relationship Between Hydrate Degradation Risk and Slope Stability

Figure 6 evaluates the terminal relationship between the hydrate degradation risk index RI_{hyd} and the minimum factor of safety FS_{min} across the Monte Carlo realizations. To maintain a consistent temporal basis, each point combines RI_{hyd} and FS_{min} extracted at the same simulation end time (10 ka). The scatter indicates that high hydrate degradation risk generally increases the likelihood of reduced slope stability, but the relationship is not single-valued. At RI_{hyd} close to zero, FS_{min} spans a wide range, from approximately 2 to more than 17. This spread shows that, even when terminal hydrate degradation is limited, the mechanical state remains strongly controlled by slope angle, residual cohesion, friction angle, hydrate-derived cohesion, and the pore-pressure response.

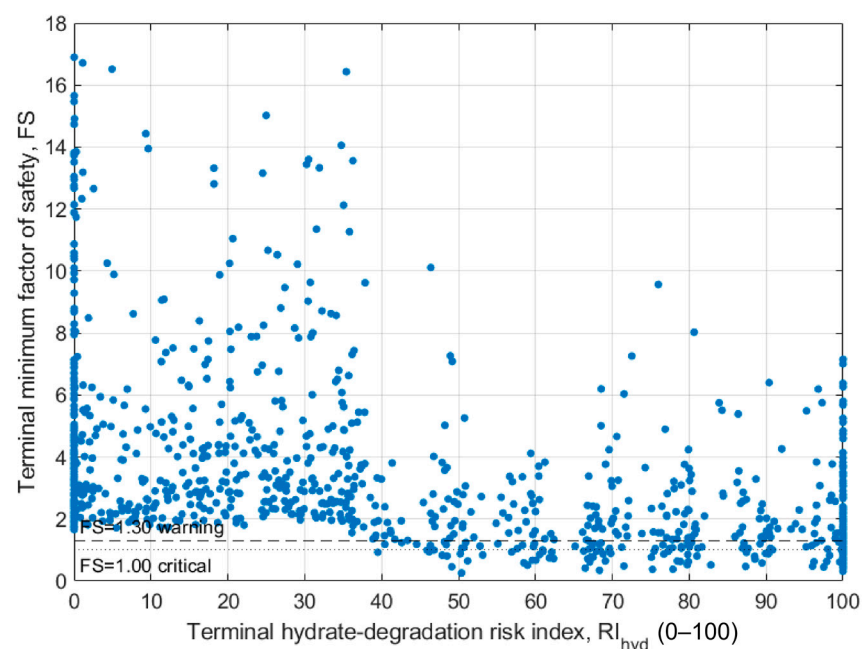


Figure 6. Terminal relationship between hydrate degradation risk index RI_{hyd} and minimum factor of safety FS_{min} across Monte Carlo realizations.

As RI_{hyd} increases into the moderate-to-high range, the cloud shifts toward lower FS_{min} values. Most realizations that approach or fall below the warning threshold ($FS_{\text{min}} = 1.30$) and the critical threshold ($FS_{\text{min}} = 1.00$) occur at RI_{hyd} values above approximately 50. This pattern is physically consistent with stronger hydrate saturation loss and occurrence-zone contraction progressively weakening hydrate cementation and amplifying the pore-pressure proxy. Nevertheless, some high- RI_{hyd} realizations remain mechanically stable, confirming that hydrate system degradation alone is not sufficient to determine failure. Two vertical accumulations of points occur near $RI_{\text{hyd}} = 0$ and $RI_{\text{hyd}} = 100$. These concentrations arise from the bounded construction of RI_{hyd} : realizations with negligible thermal-margin loss, saturation loss, and occurrence-zone contraction are truncated at zero, whereas realizations in which the component risks approach their upper limits are capped at 100.

Overall, Figure 6 reinforces the distinction adopted in this study. RI_{hyd} is an early indicator of hydrate system degradation, whereas FS_{min} represents the mechanical response of the slope. Combining both indicators is therefore necessary for risk interpretation: high RI_{hyd} identifies conditions that warrant attention, while the FS thresholds determine whether the associated mechanical state remains stable, has entered a warning state, or has reached the critical domain.

4. Discussion

4.1. Probabilistic Evolution of RI_{hyd} and FS_{min}

Figure 7 shows the temporal uncertainty in slope stability and hydrate degradation obtained from the Monte Carlo simulations. The shaded areas represent the 5th–95th percentile ranges, whereas the black lines indicate the median responses. The reference case is included for comparison, and the vertical line at 4.6 ka marks the time at which it first reaches the critical threshold of $FS_{\text{min}} = 1.00$. As shown in Figure 7a, FS_{min} exhibits a broad uncertainty range throughout the simulation, demonstrating that the mechanical stability response is strongly influenced by variability in slope angle, strength parameters, and pore-pressure response. Under mechanically unfavorable parameter combinations, the lower-percentile trajectories approach or cross the warning and critical thresholds earlier than the median trajectory. The widening separation among the trajectories after substantial hydrate degradation indicates that differences in material strength and hydraulic weakening become increasingly important as the system evolves.

Figure 7b shows that RI_{hyd} generally increases with time, while its uncertainty range expands as hydrate degradation progresses. This dispersion reflects variations in the magnitude and duration of thermal disturbance, thermal diffusivity, and the initial hydrate state. In contrast, FS_{min} is controlled not only by hydrate degradation but also by slope geometry and the mechanical parameters entering the infinite slope formulation. Hydrate saturation loss reduces hydrate-derived cohesion and effective frictional resistance, while the excess pore pressure term in Equation (11) further lowers the effective normal stress. Consequently, RI_{hyd} characterizes the extent of hydrate system degradation, whereas FS_{min} represents the resulting mechanical response under a specific combination of geometric, strength, and pore-pressure conditions. The two indicators should therefore be interpreted jointly when evaluating thermally induced slope-instability risk.

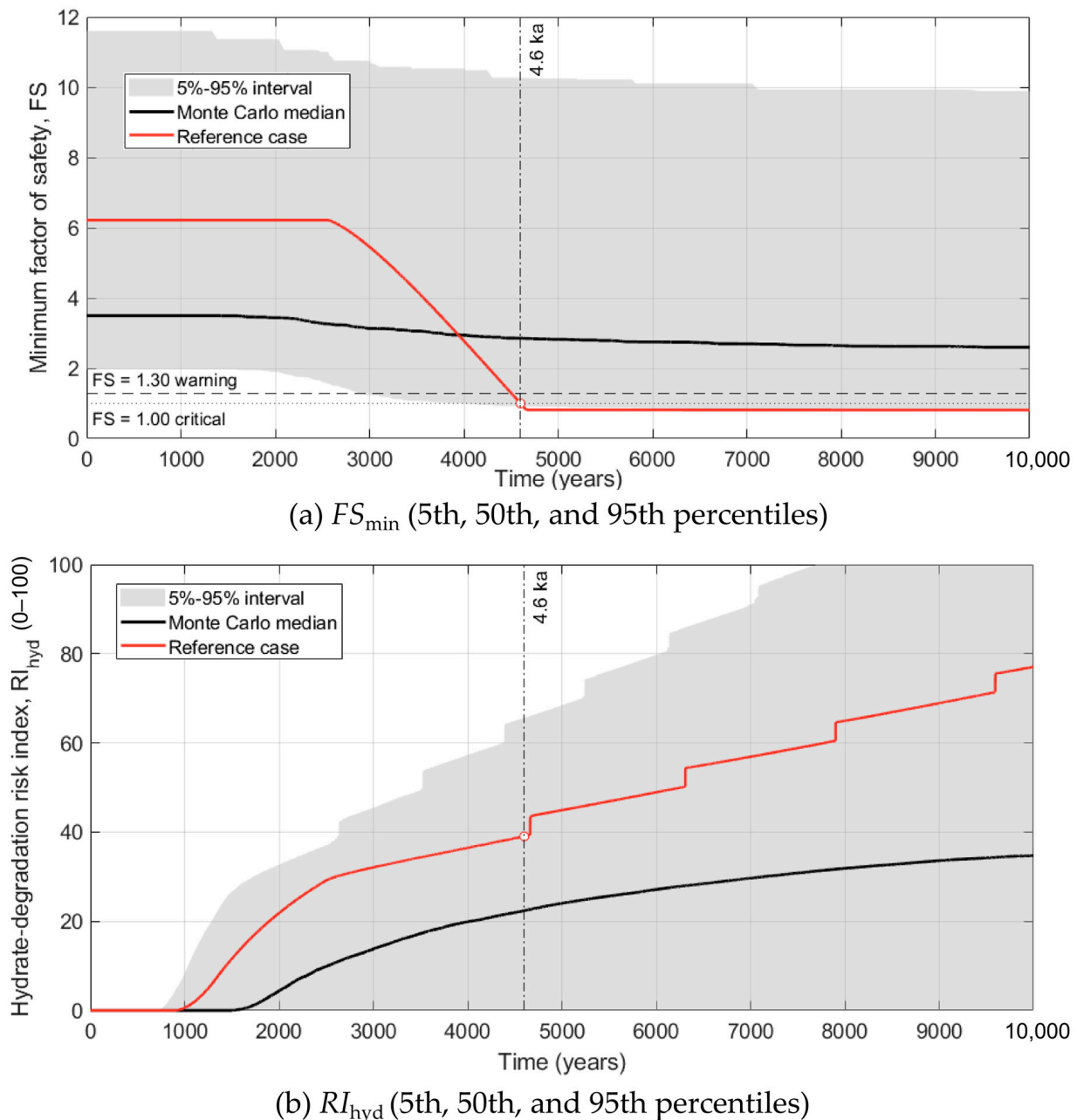


Figure 7. Monte Carlo uncertainty envelopes ($N = 800$).

4.2. Limit State Probabilities and Sensitivity Controls

Figure 8 shows the model-based conditional probabilities of entering the warning and critical states. The warning probability $P(FS_{min} \leq 1.30)$ first becomes non-zero at approximately 1.7 ka and increases progressively to approximately 0.16 at 10 ka. The critical probability $P(FS_{min} \leq 1.00)$ emerges later, at approximately 2.3 ka, and reaches approximately 0.08 at the end of the simulation. The delayed onset of the critical probability indicates that critical behavior requires a more unfavorable combination of thermal degradation, pore-pressure response, and mechanical parameters than warning-state behavior.

These probabilities are conditional on the assumed model structure and input distributions. They should therefore not be interpreted as observed landslide frequencies. Instead, they quantify the fraction of sampled parameter combinations that cross specified FS thresholds under the imposed thermal disturbance scenario.

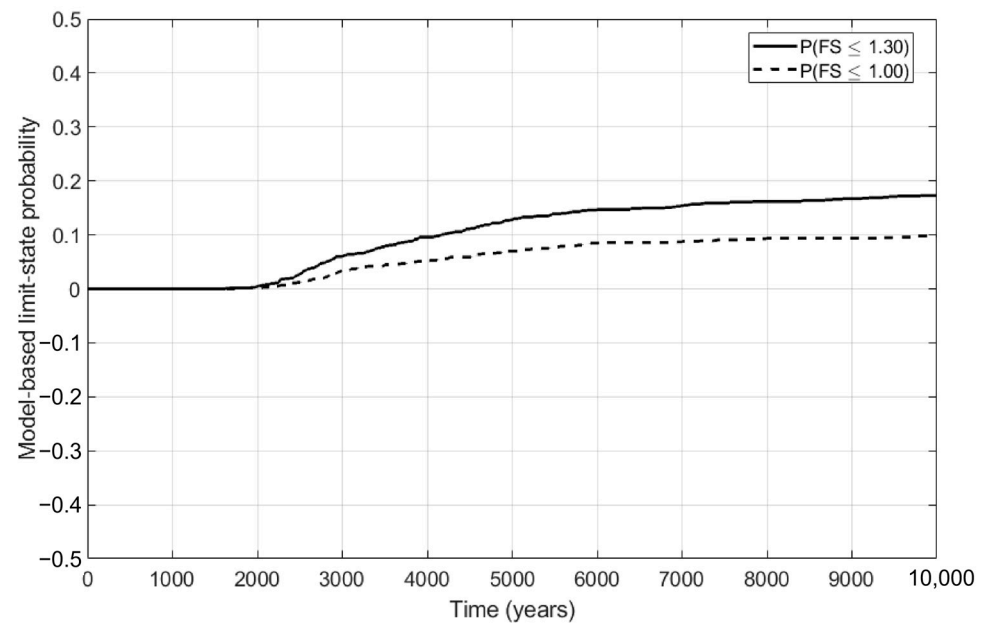


Figure 8. Model-based limit-state probabilities under thermal disturbance.

Figure 9a identifies slope angle as the dominant control on $FS_{\min}$ (Spearman $\rho_s = -0.74$), followed by total temperature rise ($\rho_s \approx -0.56$). The initial friction angle has a positive relationship with $FS_{\min}$ ($\rho_s = 0.17$), whereas the pore-pressure factor has a negative relationship ($\rho_s = -0.13$). These signs agree with the governing mechanics: steeper slopes increase driving stress, greater heating accelerates hydrate loss, higher friction increases resistance, and stronger pore-pressure response reduces effective stress.

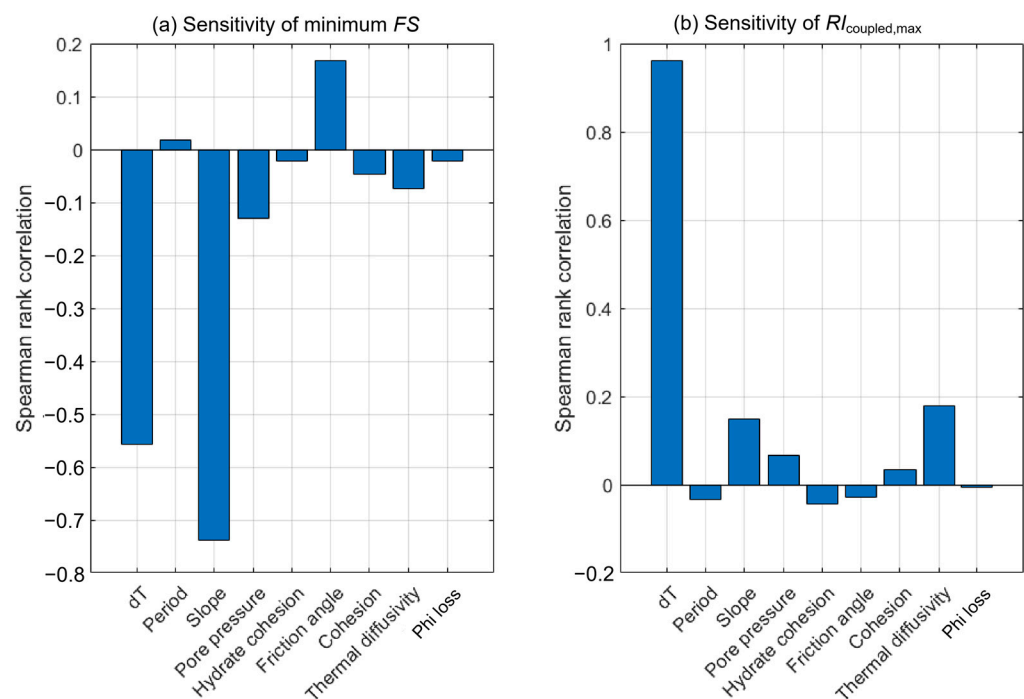


Figure 9. Spearman's rank correlation sensitivity analysis.

Figure 9b displays the sensitivity of the maximum coupled risk index $RI_{\text{coupled,max}}$. The total temperature rise is overwhelmingly dominant ($\rho_s \approx 0.96$). Thermal diffusivity ($\rho_s \approx 0.18$), slope angle ($\rho_s \approx 0.15$), and the pore-pressure factor ($\rho_s \approx 0.12$) provide secondary contributions. The use of $RI_{\text{coupled,max}}$ is important here: unlike RI_{hyd} , it con-

tains the FS-derived instability component and can therefore respond to geometric and pore-pressure variables.

4.3. Effects of Thermal Disturbance Intensity and Warming Duration

To isolate the effects of thermal disturbance intensity and thermal-input timescale on hydrate system degradation and slope stability, a controlled two-dimensional parameter sweep was performed. Only the total temperature increase, ΔT , and warming duration, t_p , were varied, whereas the hydrate occurrence conditions, slope geometry, sediment strength parameters, pore-pressure response coefficient, and thermal properties were fixed at their baseline values. The total temperature increase ranged from 2 to 10 K, and the warming duration ranged from 100 to 1000 yr, resulting in 21×21 deterministic thermal disturbance scenarios. Unlike the Monte Carlo analysis, this parameter sweep was designed to directly identify the independent effects of ΔT and t_p on the risk response.

Figure 10a presents the response surface of the maximum hydrate degradation risk index, $RI_{hyd,max}$, under different combinations of thermal disturbance parameters. Overall, $RI_{hyd,max}$ increases with increasing ΔT . A larger temperature increase further reduces the hydrate thermal-stability margin, causing a greater proportion of the hydrate-bearing interval to approach or exceed equilibrium conditions. This process expands the hydrate dissociation zone and enhances both hydrate saturation loss and contraction of the hydrate occurrence zone. For a given ΔT , a shorter warming duration corresponds to a higher average warming rate, $\Delta T/t_p$, which promotes the earlier onset of thermal-stability degradation and hydrate dissociation.

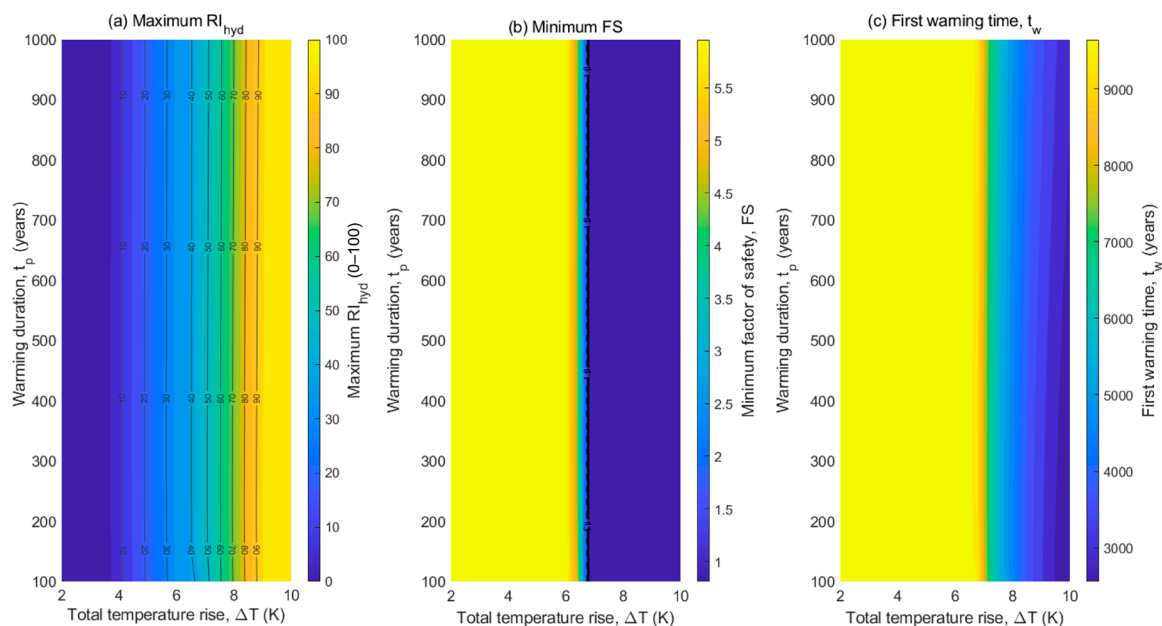


Figure 10. Controlled response surfaces for thermal disturbance intensity and duration.

Figure 10b shows the response of the minimum factor of safety, FS_{min} , to ΔT and t_p . In general, FS_{min} decreases as ΔT increases. Stronger thermal disturbance induces more substantial hydrate saturation loss, thereby weakening hydrate-related cementation and reducing effective cohesion and frictional resistance. Meanwhile, increased hydrate loss enhances the pore-pressure proxy effect and further reduces the effective normal stress. The $FS = 1.30$ contour represents the warning-state boundary, whereas the $FS = 1.00$ contour represents the critical-state boundary. Parameter combinations characterized by larger ΔT and shorter t_p are therefore more likely to enter warning or critical stability states.

Compared with ΔT , the influence of t_p on $FS_{\min}$ and $RI_{\text{hyd,max}}$ is primarily associated with the timescale of thermal loading. Because all scenarios eventually reach the same final boundary temperature for a given ΔT , and because the total simulation duration is much longer than the warming period, t_p mainly controls the rate of thermal input and the timing of risk development. In contrast, ΔT more directly controls the extent to which the hydrate system departs from thermodynamic equilibrium. Thus, the total temperature increase primarily determines the overall magnitude of hydrate degradation and slope stability reduction, whereas the warming duration mainly regulates the rate and timing of the response.

Figure 10c further presents the first warning time, t_w , defined as the first time at which $FS \leq 1.30$. Larger ΔT and shorter t_p generally correspond to earlier warning times. A greater temperature increase accelerates the reduction in hydrate stability and the associated saturation loss, whereas a shorter warming duration concentrates thermal input within a shorter period, thereby promoting an earlier transition to the warning state. In contrast, under relatively small ΔT and long t_p , hydrate degradation proceeds more slowly, and the slope may not reach the warning threshold within the simulated period.

For parameter combinations that do not reach $FS = 1.30$ during the simulation, the original value of t_w is retained as missing data. For visualization purposes only, these missing values are assigned to the simulation end time to produce a continuous response surface. Accordingly, regions approaching the simulation end time in Figure 10c should be interpreted as cases that remain above the warning threshold throughout the simulated period.

Overall, Figure 10 demonstrates that thermal disturbance intensity and warming duration jointly control hydrate system degradation and slope stability response. A larger ΔT is the primary factor enhancing hydrate dissociation risk and reducing slope stability, whereas a shorter t_p increases the rate of thermal loading and causes the risk response to emerge earlier. These results suggest that thermal-risk management should consider not only the total thermal input but also the duration and rate of thermal loading.

5. Conclusions

In this paper, we construct a probabilistic framework for evaluating the decomposition of hydrates, slope stability, and probabilistic risk under thermal disturbance conditions and obtain the following main conclusions:

- (1) Thermal disturbance can promote the evolution of the hydrate system from a stable state to a degraded state by reducing the thermal stability margin of hydrates, causing the loss of hydrate saturation, and shrinking the hydrate occurrence zone. RI_{hyd} , constructed based on thermal stability risk, saturation loss risk, and occurrence-zone change risk, can reflect the degree of degradation driving the hydrate system.
- (2) The risk of hydrate degradation indirectly controls the safety factor of the slope through the attenuation of bonding strength, the decrease in internal friction angle, and the proxy effect of excess pore pressure. RI_{hyd} can be regarded as a pre-driving indicator for FS changes, while $FS_{\min}$ reflects the final stability response of the slope under given geometric and mechanical conditions.
- (3) RI_{hyd} and $FS_{\min}$ have a generally negative coupling relationship, but their correspondence is not strictly one-to-one. When the degree of hydrate decomposition is similar, differences in slope angle, response coefficient of pore pressure, residual cohesion, internal friction angle, and hydrate-bonding strength can still lead to significantly different slope stability results.
- (4) The Monte Carlo simulation indicates that using the percentile interval of the safety factor, the probability of a warning state, and the probability of a critical state can more comprehensively express the uncertainty range of the stability risk of water-

containing slopes under thermal disturbance conditions. Parameter sensitivity analysis can further identify the key factors controlling the risk of hydrate degradation and slope instability.

- (5) The total temperature rise amplitude ΔT and the duration of temperature rise t_p jointly determine the degradation of the hydrate system and the change in slope stability. A shorter duration of temperature rise mainly affects the time at which the risk occurs and the response rate, while a larger total temperature rise amplitude more directly controls the degree of hydrate decomposition and the long-term degradation amplitude of slope stability.

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Appendix A. Weight-Sensitivity Analysis of the Risk Indices

The weighting coefficients used in RI_{hyd} and $RI_{coupled}$ were prescribed according to the physical roles and relative independence of the normalized risk components. Because these coefficients contain a degree of judgment, a moderate perturbation analysis was conducted to evaluate whether the principal results depend strongly on the selected weights.

A one-at-a-time perturbation procedure was adopted. For each test, one original weight was increased or decreased by 20%, while the remaining weights were initially kept unchanged. All weights were then renormalized so that their sum remained equal to unity.

Appendix A.1. Sensitivity of RI_{hyd} to w_T , w_S , and w_B

The hydrate degradation risk index was defined as follows:

$$RI_{hyd}(t) = 100[w_T \overline{R_T}(t) + w_S \overline{R_S}(t) + w_B \overline{R_B}(t)] \quad (A1)$$

where RI_{hyd} is a relative indicator of hydrate system degradation, and the original weights were $w_T = 0.35$, $w_S = 0.4$, $w_B = 0.25$.

Table A1. Normalized weighting schemes used in the sensitivity analysis of RI_{hyd} .

Weighting Scheme	w_T	w_S	w_B
Original weights	0.3500	0.4000	0.2500
$w_T - 20\%$	0.3011	0.4301	0.2688
$w_T + 20\%$	0.3925	0.3738	0.2336
$w_S - 20\%$	0.3804	0.3478	0.2717
$w_S + 20\%$	0.3241	0.4444	0.2315
$w_B - 20\%$	0.3684	0.4211	0.2105
$w_B + 20\%$	0.3333	0.3810	0.2857

The weight-sensitivity results are shown in Figure A1. Moderate variations in the weighting coefficients affected the magnitude of RI_{hyd} , but the overall temporal evolution remained essentially unchanged. Under all tested schemes, the onset of risk growth, the

main period of continuous increase, and the subsequent stepwise increases occurred at approximately the same times.

The largest response was produced by perturbations of w_T . Decreasing w_T by 20% resulted in a maximum relative change of approximately 14%, whereas increasing w_T by 20% produced a maximum change of approximately 12%. Perturbations of w_S resulted in maximum relative variations of approximately 7–9%, while perturbations of w_B produced the smallest variations, approximately 5%.

These results indicate that RI_{hyd} is most sensitive to the relative contribution of the thermal-stability component. Nevertheless, the original trajectory remained within the envelope formed by all perturbed weighting schemes, and the principal temporal characteristics of hydrate system degradation were preserved.

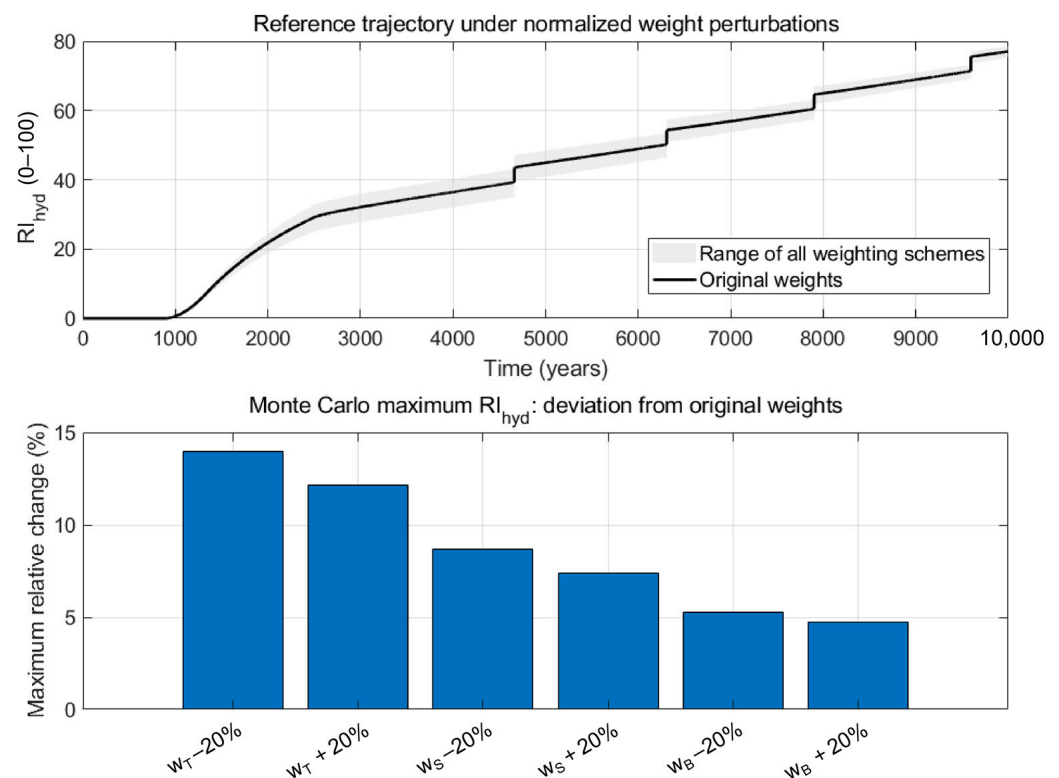


Figure A1. Sensitivity of the hydrate degradation risk index, RI_{hyd} , to moderate perturbations of w_T , w_S , and w_B .

Appendix A.2. Sensitivity of $RI_{coupled}$ to w_{hyd} , w_{FS}

The coupled risk index is defined as follows:

$$RI_{coupled}(t) = 100[w_{hyd}RI_{hyd} + w_{FS}R_{FS}] \quad (A2)$$

where the original weights were $w_{hyd} = 0.70$, $w_{FS} = 0.3$. The normalized group-weight schemes are listed in Table A2.

Table A2. Normalized weighting schemes used in the sensitivity analysis of $RI_{coupled}$.

Weighting Scheme	w_{hyd}	w_{FS}
Original weights	0.7000	0.3000
$w_{hyd} - 20\%$	0.6512	0.3488
$w_{hyd} + 20\%$	0.7368	0.2632
$w_{FS} - 20\%$	0.7447	0.2553
$w_{FS} + 20\%$	0.6604	0.3396

Figure A2 shows that the group-weight perturbations only produced a relatively narrow range around the original RI_{coupled} trajectory. The onset of risk growth, the overall temporal evolution, and the marked increase near 4.6 ka remained essentially unchanged under all tested schemes.

The maximum relative variation in the Monte Carlo maximum RI_{coupled} ranged from approximately 5.3% to 7.0%. The largest variation occurred when w_{hyd} was reduced by 20%, which correspondingly increased the normalized contribution of the FS-derived instability component. The smallest variation occurred when w_{hyd} was increased by 20%.

The limited variation indicates that the adopted group weights provide a stable balance between precursor hydrate degradation information and the mechanical-stability response. Moderate changes in the relative importance assigned to these two groups affect the absolute magnitude of RI_{coupled} , but do not alter its principal temporal characteristics or the interpretation of the risk-state transition.

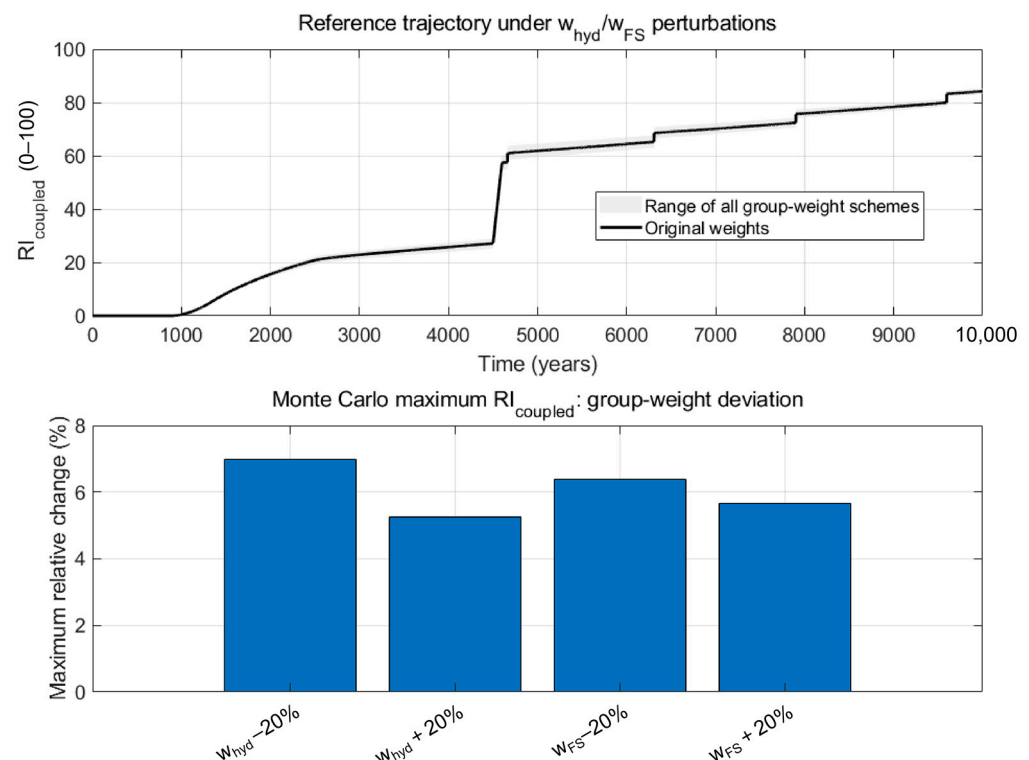


Figure A2. Sensitivity of the coupled hydrate–slope risk index, RI_{coupled} , to moderate perturbations of w_{hyd} and w_{FS} .

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