

Article

Influence of Mineral Loading Variations on the Body State of a Deep-Sea Mining Vehicle

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Abstract

Tracked deep-sea mining vehicles (DSMVs) interact strongly with soft seabed sediments during seafloor operations, which may cause excessive sinkage and vehicle instability. Variations in mineral loading and initial pitch angle are important factors affecting operational safety. In this study, the “Kunlong 500” tracked DSMV was selected as the prototype, and a coupled Eulerian–Lagrangian (CEL) numerical model was established to simulate vehicle–sediment interaction. The Drucker–Prager elastoplastic model was adopted to describe sediment yielding and plastic deformation. Different mineral loading levels and initial pitch angles were considered to investigate vehicle sinkage, local Mises stress in the track–sediment contact region, and attitude response. The results show that increasing mineral loading significantly increases body sinkage and rear-track Mises stress, causing the vehicle response to evolve from overall sinkage to rear-biased sinkage. Under the present model parameters, the reference critical loading for local rear-track sinkage was estimated to be approximately 5.8 t, with a sensitivity range of approximately 4.5–7.1 t under $\pm 10\%$ variation in the equivalent bearing term. Under the present model conditions, loading conditions of 8 t and above should therefore be treated as key risk-control cases. The initial pitch angle further aggravates asymmetric sinkage, especially under the 4 t loading and 4° pitch condition. These findings provide a reference for load control and attitude regulation of DSMVs.

Keywords: deep-sea mining; tracked vehicle; CEL method; Drucker–Prager model; mineral loading; initial pitch angle; sinkage performance

1. Introduction

Deep-sea mineral resources contain abundant critical metals, such as nickel, cobalt, copper, and manganese, and have become important strategic reserves for future resource supply [1–3]. With the development of deep-sea mining technology, the pipeline-lifting mining system has gradually become one of the main technical routes for seafloor mineral exploitation. In this system, deep-sea mining vehicles (DSMVs) are responsible for mineral collection, transportation, and seabed locomotion, and therefore play a key role in ensuring continuous mining operations. Compared with wheeled vehicles, tracked vehicles provide a larger contact area, lower ground pressure, better trafficability on soft soil, and higher overall stability, making them one of the dominant locomotion forms for DSMVs [4–6]. However, deep-sea sediments are generally characterized by high water

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content, high compressibility, low shear strength, and strong disturbance sensitivity. When a vehicle travels on such sediments, excessive sinkage may occur, seriously hindering normal vehicle motion [7,8].

The interaction between DSMVs and seabed sediments has been extensively investigated by researchers worldwide. Early studies mainly borrowed theories from terrestrial vehicle mechanics. Bekker [9] described the bearing capacity of soil under vertical loading through the pressure–sinkage relationship, while Wong [10] further developed theoretical methods for analyzing traction, slip, and trafficability of off-road vehicles. Chen et al. [11] evaluated the performance and operational safety of rack vehicles in mountainous regions under pulsating wind loads using dynamic modeling, showing that external environmental disturbances should be considered in vehicle stability and risk-control assessments. Pressure–sinkage models provide an important basis for quantitatively describing the sinkage response of vehicles under specific loading conditions and thus are fundamental for studying the interaction between DSMVs and seabed sediments. In addition, seabed shear interaction is also important for the mobility and stability of tracked DSMVs. Previous studies indicate that shear deformation, local soil failure, and sediment disturbance near the track and grousers can significantly affect traction, sinkage, and vehicle stability [12,13]. Nevertheless, deep-sea sediments usually exhibit high water content, low bearing capacity, and large-deformation behavior. Traditional empirical models are often insufficient for describing large-scale nonlinear sinkage, while conventional Lagrangian finite element simulations may suffer from severe mesh distortion under large sediment deformation [14]. To overcome these difficulties, various advanced numerical methods have been increasingly applied to track–sediment interaction problems in deep-sea mining [15–17].

Among these methods, the coupled Eulerian–Lagrangian (CEL) method has significant advantages in simulating large-deformation behavior. The CEL concept was first proposed by Noh [18] and was further developed by Benson and Okazawa [19,20]. In recent years, the CEL method has been widely used in studies of DSMV track optimization, sinkage prediction, and landing safety analysis. Sumith et al. [21] used Abaqus and the CEL method to study the traction performance at the grouser–soft seabed interface and validated the numerical model through laboratory direct shear tests. Sun et al. [22,23] established CEL-based interaction models between track plates and seabed soil, and systematically analyzed the effects of loading rate, touchdown velocity, track plate aspect ratio, grouser height, and soil mechanical parameters on pressure–sinkage curves. Their results showed that both track structural parameters and soil properties jointly affect the maximum sinkage. Gao et al. [24] investigated the sinkage and shear behavior between different grouser structures and soil based on the CEL method and the Mohr–Coulomb elastoplastic model. They found that grouser geometry significantly affects the maximum sinkage of track plates, and that soil disturbance is positively correlated with sinkage. The study by Zeng et al. [25] provided an important full-scale CEL-based framework for DSMV landing safety prediction and track design optimization. Its focus was mainly on touchdown safety and data-driven design evaluation.

Existing studies mainly focus on the local interaction mechanism between track plates and soil, static sinkage behavior, or steady-state locomotion performance. In many of these studies, the vehicle body is simplified as a constant load or a rigid upper boundary. However, relatively limited attention has been paid to attitude variation and sinkage behavior of vehicles caused by changes in mineral loading during vehicle operation. In actual mining processes, the mineral load in the storage bin changes continuously with collection progress, and the vehicle attitude may also vary with seabed terrain. Therefore, this study focuses on the full-vehicle response during the mineral loading stage. The “Kunlong 500” tracked deep-sea mining vehicle was selected as the prototype, and a ve-

hicle–sediment interaction model was established in Abaqus. The CEL method is used to simulate large-deformation contact between the track and flow-plastic sediment, while the Drucker–Prager elastoplastic model is adopted to characterize soil yielding and plastic deformation. The effects of mineral loading and initial pitch angle on sinkage displacement, Mises stress response, and attitude stability are analyzed. Moreover, a simplified rear-track local sinkage estimation is introduced to explain the onset of deep-sinkage risk, and the coupling between mineral loading and initial pitch angle is analyzed to reveal a “front-tilting–rear-loading” instability mode. The results are expected to provide theoretical support for storage bin design, load control, and safe operation of DSMVs.

2. Materials and Methods

2.1. Vehicle Model and Simplification

As shown in Figure 1, the “Kunlong 500” vehicle (Changsha Research Institute of Mining and Metallurgy, Co., Ltd., Changsha, China) was selected as the prototype in this study. A three-dimensional model was first established in SolidWorks 2022 and then further modified and simplified in Abaqus 2022 to balance computational efficiency and numerical accuracy. Small gaps and irregular geometric features that might affect mesh generation were repaired. Structural details with minor influence on the overall mechanical response, such as internal gear structures in the track system, were neglected. The track was simplified as a combination of a plate with finite thickness and groovers, while the main body of the vehicle and the storage bin were simplified as cuboid structures. Both the vehicle body and the track system were treated as rigid bodies, and their structural deformation was not considered. This rigid-body treatment neglects the structural compliance of the vehicle frame, track plates, and grousers. Therefore, the calculated results should be mainly reflected in the effects of external load redistribution and soil deformation rather than the structural deformation of the vehicle itself.

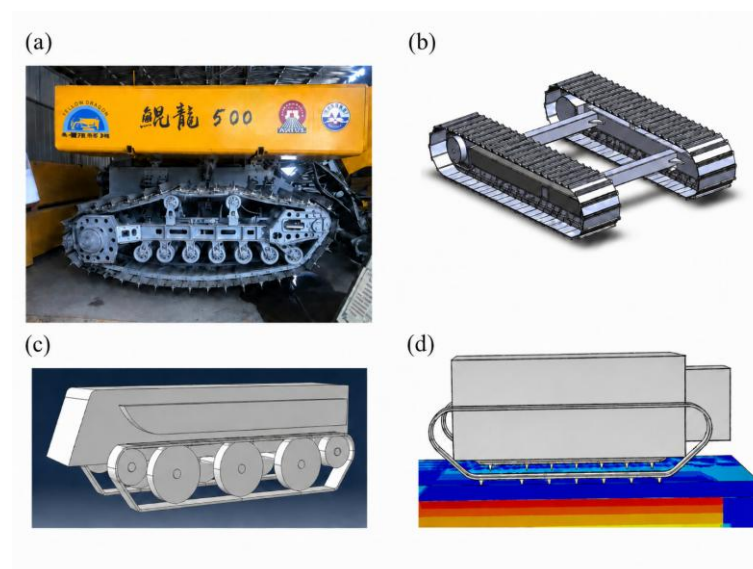


Figure 1. Prototype and simplified model of the vehicle: (a) “Kunlong 500” vehicle (non-English term means DSMV prototype); (b) track mechanism model; (c) simplified vehicle model in SolidWorks; (d) vehicle–sediment interaction model.

2.2. Mechanical Characteristics and Elastoplastic Model of Deep-Sea Sediments

Deep-sea sediments usually show obvious stratification along the depth direction. As depth increases, the sediment state gradually changes from suspension-like to flow-plastic and finally to plastic [26], as shown in Figure 2. The surface layer is close to a suspension-

like state, where the undrained shear strength is almost zero and cannot provide sufficient traction or bearing capacity [27]. In contrast, the deeper plastic-like layer exhibits a sudden increase in strength and bearing capacity, which may increase resistance and even damage the grousers [28]. Therefore, for safe vehicle operation, the track sinkage should be controlled within the intermediate flow-plastic layer, where the bearing capacity is relatively stable.

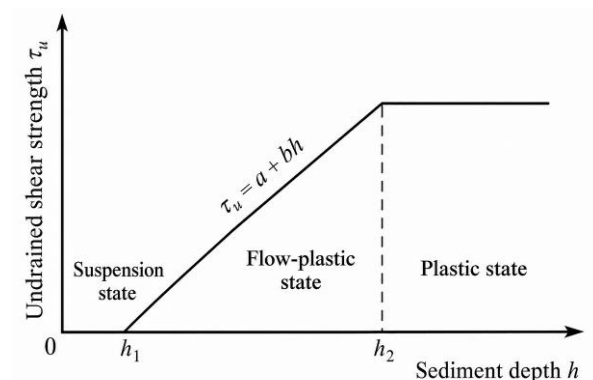


Figure 2. Relationship between undrained shear strength τ_u and sediment depth h .

In situ measurements of deep-sea sediments from the Clarion–Clipperton Zone have shown that the shear strength of flow-plastic sediments increases approximately linearly with depth [29]. This relationship can be expressed as:

$$\tau_u(h) = a + bh \quad (1)$$

When the vehicle track acts on the sediment surface, the soil does not undergo only vertical compression, but also lateral flow, shear failure, and local heave. The essence of vehicle sinkage is that the vehicle displaces flow-plastic sediments under vertical loading and gradually penetrates deeper into soil layers with higher bearing capacity. To interpret this process, the vehicle–sediment interaction can be simplified as a limiting equilibrium problem of the vehicle body penetrating into soil. When the track acts on the soil surface, the soil beneath the track is subjected to vertical pressure and forms a local failure wedge. As sinkage increases, soil shear strength and lateral pressure gradually increase until the soil resistance balances the vertical load of the vehicle, after which the sinkage tends to stabilize.

According to whether the vehicle body contacts the sediment, the sinkage state can be divided into two cases, as shown in Figure 3.

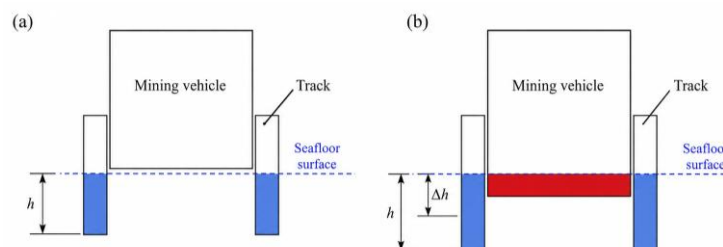


Figure 3. Two contact states between the vehicle and sediment: (a) only the tracks are in contact with the sediment; (b) both the tracks and the vehicle body are in contact with the sediment.

When $h < \Delta h$, only the tracks are in contact with the sediment, and the vertical load is mainly supported by the soil beneath the tracks. The sinkage depth is given by:

$$h = \frac{G - 2aS}{S(2b + \gamma)} \quad (2)$$

When $h > \Delta h$, the vehicle body also contacts the sediment, and the vehicle load is jointly carried by the soil beneath the tracks and the soil beneath the vehicle body. The sinkage depth is given by:

$$h = \frac{G - 2aS + (2b + \gamma)\Delta h S_2}{S(2b + \gamma)} \quad (3)$$

where h is the local sinkage depth, Δh is the height difference between the bottom of the vehicle body and the bottom of the track, G is the total weight of the vehicle and mineral load, a and b are shear-strength parameters of the sediment, γ is a sediment-related parameter, S is the track contact area, and S_2 is the contact area of the vehicle body.

In numerical simulations, the yielding and plastic deformation of sediment under complex stress states can be described by various yield criteria, such as the Mohr–Coulomb, Tresca, von Mises, and Drucker–Prager criteria. Compared with the Mohr–Coulomb model, the Drucker–Prager model accounts for the effect of the intermediate principal stress and replaces the hexagonal pyramidal yield surface with a smooth conical yield surface. This treatment improves numerical convergence and computational efficiency [30]. Although yielding, dilatancy and contractancy, and undrained shear strength of fine-grained marine sediments can be strongly affected by pore-water pressure and gas volume fraction, for fine-grained gas-bearing soil with high saturation, the effective stress principle can still be used to explain its mechanical behavior [31]. Therefore, the Drucker–Prager elastoplastic model was adopted in this study to describe the equivalent mechanical response of deep-sea sediments. The soil parameters were selected with reference to [32] and were based on in situ tests and laboratory geotechnical tests of deep-sea surface sediments in China’s polymetallic nodule mining areas.

It should be noted that the Drucker–Prager parameters used in the CEL simulations should be interpreted as equivalent elastoplastic parameters for the main flow-plastic layer rather than as drained soil parameters. Although the adopted Drucker–Prager parameters are homogeneous, the mean stress and confining pressure increase with depth; therefore, the apparent resistance predicted by the Drucker–Prager model also increases with depth. The internal friction angle of 6° was introduced as a small equivalent friction parameter to represent the weak pressure-dependent resistance of highly saturated sediment and to maintain numerical stability. The analytical relationship $\tau_u = a + bh$ and the homogeneous Drucker–Prager model is used at different modeling levels: the former supports the simplified sinkage estimation, whereas the latter provides an equivalent constitutive description for comparative CEL simulations.

2.3. Coupled Eulerian–Lagrangian Model

In the CEL method, the structure and soil are described using different formulations. The vehicle body and track system are modeled using the Lagrangian formulation, in which the mesh moves with the structure. The deep-sea sediment is modeled using the Eulerian formulation, in which the mesh remains fixed in space while the soil material flows through the mesh. This method effectively avoids mesh distortion caused by large soil deformation in traditional finite element methods and can realistically simulate sediment displacement and heave during track penetration.

For the Eulerian domain, the governing equations for soil flow can be expressed as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \quad (4)$$

$$\frac{\partial(\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v} \otimes \mathbf{v}) = \nabla \cdot \boldsymbol{\sigma} + \rho \mathbf{b} \quad (5)$$

$$\frac{\partial e}{\partial t} + \nabla \cdot (e \mathbf{v}) = \boldsymbol{\sigma} : \mathbf{D} \quad (6)$$

where ρ is the density, $\mathbf{v}$ is the material velocity, $\mathbf{v} \otimes \mathbf{v}$ is the tensor product of the velocity vector, $\boldsymbol{\sigma}$ is the Cauchy stress tensor, $\mathbf{b}$ is the body force, e is the internal energy, and $\mathbf{D}$ is the strain-rate tensor.

Displacement constraints were applied to the outer boundaries of the soil domain to limit far-field soil movement and reduce boundary effects on the sinkage results. The top surface of the soil domain was set as a free surface to allow sediment heave and flow during track penetration. The vehicle and track were subjected only to gravity and an initial downward velocity, without any additional external driving force or constraint.

2.4. Model Validation

To ensure the reliability of the subsequent full-vehicle sinkage simulations, a rectangular track-plate benchmark model with a length of 0.5 m, a width of 0.2 m, and a thickness of 0.06 m was established to evaluate the applicability of the CEL method to the track plate–sediment contact problem. This benchmark model was also used to determine the soil domain size, boundary conditions, and mesh strategy. A mesh independence analysis was conducted to balance numerical accuracy and computational efficiency. The results are shown in Figure 4a. Based on the comparison, a mesh size of 0.03 m was selected for the main computational region. The benchmark configuration was designed with reference to previous studies [24].

In addition, the simulated stress–sinkage curve shown in Figure 4b was compared with the experimental data reported by Huang et al. [33], in which a smooth rectangular plate with dimensions of 0.48 m × 0.08 m × 0.01 m was used. During the early sinkage stage, within the sinkage range of 0–0.03 m, the numerical results show a certain discrepancy from the experimental curve. As sinkage increases, the numerical results gradually agree with the experimental data. This early-stage discrepancy is probably related to the simplified assumption of the undrained shear strength of the surface suspension-like sediment layer introduced in Figure 2. Owing to the extremely low strength and unstable mechanical properties of this layer, the uncertainties of its parameters may result in relatively large errors during the initial penetration stage. However, in the subsequent vehicle–sediment interaction simulations, the vehicle sinkage generally exceeds 0.03 m and reaches the flow-plastic sediment layer. Therefore, the uncertainty in the surface-layer parameters has limited influence on the main simulation results. These results indicate that the established CEL numerical model can reasonably describe the bearing and sinkage responses of deep-sea sediment during vehicle sinking and is suitable for subsequent vehicle–sediment interaction analysis.

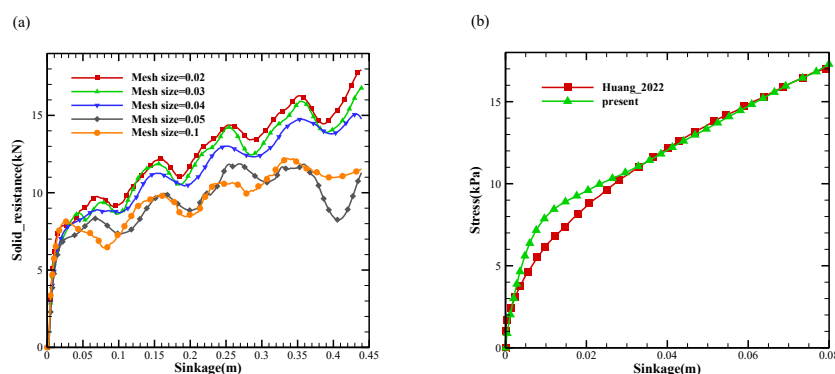


Figure 4. Model Validation: (a) Mesh independence analysis; (b) Comparison between numerical simulation and experimental data [33].

2.5. Simulation Settings

Deep-sea sediments have an initial stress state under self-weight. If the vehicle load is directly applied without considering the initial stress field, the resulting unbalanced stress may affect the sinkage displacement and Mises stress results. Therefore, geostatic stress equilibrium was performed before the full-vehicle simulations. Because the Drucker–Prager model is difficult to automatically equilibrate in Abaqus, the initial geostatic stress field was imported repeatedly. When the maximum vertical displacement of the soil was less than 10^{-6} m, the soil was considered to have reached an approximately static equilibrium state under gravity.

To investigate the effects of mineral loading and initial pitch angle on the compression response of deep-sea sediments, eight simulation cases were designed, as listed in Table 1. The size of the Eulerian soil domain was $8\text{ m} \times 6\text{ m} \times 8\text{ m}$. The selected soil-domain size was determined by considering the localized deformation characteristics of the vehicle–sediment interaction. In the simulations, the main plastic deformation and high-stress regions were concentrated beneath and near the tracks, whereas the deformation near the lateral boundaries was limited. Therefore, the lateral clearance was considered sufficient for comparing the relative effects of mineral loading and initial pitch angle under consistent boundary conditions. In addition, the soil depth was selected to reduce the influence of the bottom boundary on the vertical stress field and sinkage response. A refined mesh was used in the central contact region with a mesh size 0.3 m, while coarser meshes were used away from the contact zone. The total number of elements was 32,400, and the element type was C3D8R. General contact was used with “all exterior” surfaces included in the contact domain, and a Coulomb friction coefficient of 0.3 was assigned. Boundary conditions were applied by constraining soil velocity in the X , Y , and Z directions at the corresponding boundaries to prevent excessive far-field material movement. To simplify the simulation, the initial configuration was set such that the vehicle just contacted the sediment surface. An initial downward velocity of 0.50 m/s was assigned to the vehicle, which was used to accelerate the settlement process and obtain the equilibrium sinkage response within a reasonable computational time. The total simulation time was set to exceed 5 s to ensure that the sinkage response reached a stabilized state. The initial pitch angle refers to the angle between the longitudinal axis of the vehicle and the horizontal plane. A positive pitch angle $\theta > 0^\circ$ indicates a forward-tilting attitude, in which the front end of the vehicle is lower than the rear end. The main numerical parameters are shown in Table 2.

Table 1. Simulation cases.

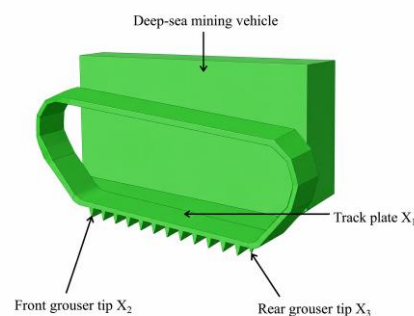
Case	Mineral Loading (t)	Initial Pitch Angle ($^\circ$)
Q1	0	0
Q2	4	0
Q3	8	0
Q4	10	0
Q5	0	2
Q6	0	4
Q7	4	2
Q8	4	4

Table 2. Main numerical parameters.

Material	Category	Parameter	Value	Unit
Deep-sea sediment	Density	Density	1400	kg/m ³
	Drucker–Prager	Cohesion	5.0	kPa
		Internal friction angle	6.0	°
		Flow stress ratio	0.8	—
		Dilation angle	0.1	°
	Elasticity	Elastic modulus	0.9	MPa
		Poisson’s ratio	0.3	—
DSMV	Weight	Weight in air	20.0	t
	Density	DSMV density	737.46	kg/m ³
	Loading	Mineral density	1780 (variable)	kg/m ³
		Mineral block dimensions	1.5 × 1.5 × 1.5	m
		Downward velocity	0.50	m/s
		Overall dimensions (L × W × H)	5.0 × 2.5 × 2.1	m
	Geometry	Track contact length	4.0	m
		Track width	0.6	m

3. Results

For clarity, three reference points were selected: the body coupling point X_1 , the front grouser point X_2 , and the rear grouser point X_3 , as shown in Figure 5.

**Figure 5.** Locations of the three reference points.

3.1. Influence of Mineral Loading on Vehicle Body State

To investigate the effect of mineral loading on the vehicle body state, the unloaded case Q1 and the loading cases Q2, Q3, and Q4 were compared. In these cases, the mineral load was placed at the rear storage bin, the initial pitch angle was set to zero, and different loading levels were achieved by changing the mass of the storage material.

The unloaded case Q1 was first analyzed to reveal the sinkage mechanism caused by the self-weight of the vehicle and to provide a reference for comparison with loaded cases. Figure 6 shows the displacement and Mises stress histories of the three reference points during penetration. At the initial contact stage, the vehicle sank rapidly because the high ground pressure induced rapid sediment flow and lateral displacement. The soil beneath the track could not immediately form an effective support structure, which accelerated the initial sinkage. Subsequently, as the soil bearing capacity increased, the sinkage gradually stabilized. At 5 s, the vehicle had already reached an equilibrium state. The sinkage at X_1 stabilized at about 0.25 m, and the average stress at X_1 stabilized at approximately 0.004 MPa. In contrast, the sinkage at X_2 and X_3 was larger, eventually stabilizing at about 0.33 m. The average stress at these two grouser points was about 0.0072 MPa, ap-

proximately 80% higher than that at the body reference point. This indicates that sinkage mainly occurred in the track–sediment contact region, while the vehicle body did not extensively contact the sediment under the unloaded condition.

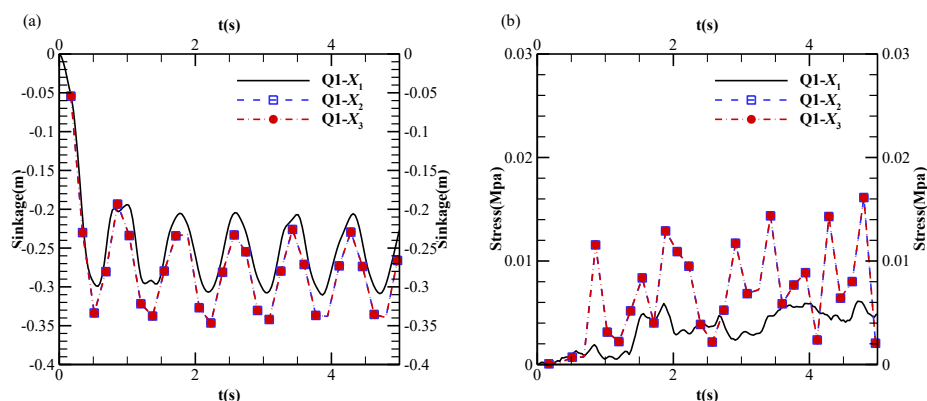


Figure 6. Sinkage displacement and Mises stress histories of the vehicle under the unloaded condition: (a) sinkage displacement, (b) Mises stress.

To further evaluate the effect of loading on body stability, a simplified critical loading estimation was conducted. According to Equation (2), when soil parameters and track contact area remain constant, increasing mineral loading directly increases the vertical load G , thereby increasing the track sinkage depth h . However, Equation (2) only describes the average sinkage relationship when the vertical load is distributed over the track contact area. In the present model, the storage bin is located at the rear of the vehicle, and increasing mineral loading produces an obvious eccentric load. Therefore, under high loading conditions, the vehicle does not simply undergo uniform overall sinkage; instead, the response is closer to a local rear-track sinkage problem.

Introducing λ_R as the rear-track load distribution coefficient, the local rear-track sinkage can be approximated as:

$$\lambda_R = \frac{R_R}{G_0 + mg} = \frac{G_0 x_0 + mg x_m}{L(G_0 + mg)} \quad (7)$$

$$h_R = \frac{\lambda_R G - 2a S_R}{S_R(2b + \gamma)} \quad (8)$$

where G_0 is the self-weight of the vehicle, m is the mineral loading mass, g is the gravitational acceleration, L is the distance between the front and rear support points, x_0 is the distance from the front support point to the unloaded center of gravity, x_m is the distance from the front support point to the mineral load center, and S_R is the rear-track contact area. Equations (7) and (8) indicate that increasing mineral loading not only increases the total vertical load but also increases the rear-track load distribution coefficient, making the rear-track sinkage and stress response more sensitive than the average body sinkage.

Based on simplified moment equilibrium and the critical condition $h_R = \Delta h$, the mineral loading at which the rear track reaches the local critical sinkage state can be calculated as:

$$m_c = \frac{L S_R [(2b + \gamma) \Delta h + 2a] - G_0 x_0}{x_m g} \quad (9)$$

In the baseline calculation, the equivalent shear-strength parameters were set as $a = 5.0$ kPa and $b = 55.0$ kPa/m, and the sediment unit weight was taken as $\gamma = 13.7$ kN/m³. Therefore m_c was estimated to be approximately 5.8 t. This result suggests that when the

load exceeds approximately 5.8 t, the rear track may preferentially enter a local deep-sinkage state, and the rear part of the vehicle may have a risk of contacting the sediment. This may further induce local stress concentration and nonlinear stress growth. It should be emphasized that the estimated critical loading of 5.8 t is based on simplified moment equilibrium, equivalent track contact area, and equivalent soil parameters. It is intended to indicate the relative variation in local rear-track sinkage risk under different loading conditions, rather than an absolute safety limit for field operations. Because the mechanical properties of deep-sea sediments are spatially variable, a basic parametric sensitivity analysis was further performed based on the analytical expression for the critical loading. In Equation (8), the equivalent bearing term can be written as:

$$B = S_R[(2b + \gamma)\Delta h + 2a] \quad (10)$$

where B represents the combined effect of the equivalent rear-track contact area, sediment shear-strength parameters, and sediment unit weight. By perturbing B by $\pm 10\%$ around the baseline value, the estimated critical loading varied from approximately 4.5 t to 7.1 t, as listed in Table 3. This shows that in the actual operation, the mechanical properties of deep-sea sediments are important factors to estimate the critical loading.

Table 3. Sensitivity of the estimated critical loading to the equivalent bearing term.

Condition	Variation in B	Estimated Critical Loading m_c
Weaker sediment/contact condition	−10%	4.5 t
Baseline condition	0	5.8 t
Stronger sediment/contact condition	+10%	7.1 t

Figure 7 shows the sinkage displacement histories of the three reference points under different loading conditions. The sinkage at X_1 increases with mineral loading, indicating a positive correlation between loading level and body sinkage. When the loading increases from 0 t to 4 t, the sinkage increment is limited, suggesting that the sediment still has remaining bearing capacity. When the loading increases to 8 t, the sinkage growth becomes more rapid, indicating that the soil gradually enters a more pronounced plastic deformation state. Under the 10 t loading condition, the vehicle reaches the maximum sinkage, with obvious local deep sinkage at the track region and significantly reduced vehicle stability. In addition, because the storage bin is located at the rear of the vehicle, increasing loading shifts the center of gravity backward, leading to higher vertical load on the rear track and nonuniform sinkage. The difference between X_2 and X_3 increases with loading, which is consistent with Equations (7) and (8) and helps explain the nonlinear increase in peak stress under high loading conditions.

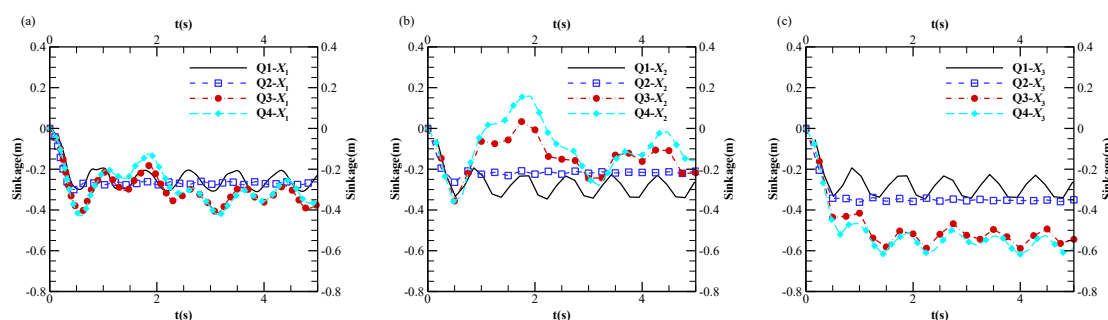


Figure 7. Sinkage displacement histories of the three reference points under different mineral loading conditions: (a) X_1 , (b) X_2 , (c) X_3 .

Figure 8 shows the Mises stress contours at equilibrium under different loading conditions. As the loading increases, the Mises stress in the rear-track region increases, and stress concentration becomes more pronounced. In Q1, the stress distribution beneath the track is relatively uniform, with only slight stress concentration near the track edges. In Q2, the load increases to 4 t, and a high-stress region begins to appear near the rear track, but the overall state remains stable. In Q3 and Q4, obvious rear-biased sinkage appears. Combined with the critical loading estimation, these results indicate that the rear track approaches or exceeds the estimated local critical sinkage range and that the rear part of the vehicle becomes more likely to contact the sediment. Meanwhile, plastic flow occurs in the sediment under high loading, and soil accumulation and shear failure are more likely to form near the rear track, further intensifying local stress concentration.

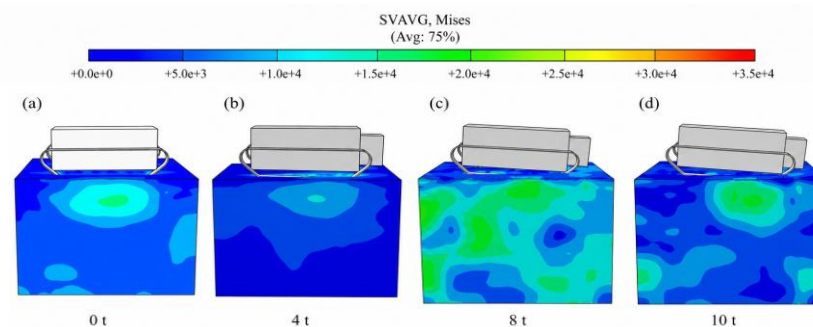


Figure 8. Mises stress contours at equilibrium under different mineral loading conditions: (a) Q1; (b) Q2; (c) Q3; (d) Q4.

Figure 9 shows the Mises stress histories of the three reference points under different loading conditions. The peak stress values are summarized in Table 4. When the loading increases to 4 t, the overall vertical load increases, but no severe instability occurs. The peak stress at X_1 increases slightly, indicating that the sediment still retains a certain bearing capacity. However, the stress at the rear grouser becomes higher than that at the front grouser, showing that the rear storage load shifts the center of gravity backward and increases the rear-track load. When the load increases to 8 t, rear-track-biased sinkage becomes more obvious, and the peak stress at X_1 in Q3 rises approximately 12.6 times that in Q2. The vehicle no longer exhibits simple overall sinkage, but gradually changes into a rear-biased sinkage mode characterized by rear-track preferential sinking, backward pitching, and local stress concentration. In Q4, the sinkage and stress response further deteriorate. The peak stress at the rear grouser X_3 increases from 0.0236 MPa under the unloaded condition to 1.3476 MPa, showing a strong nonlinear amplification. This indicates that the sediment beneath the rear track undergoes significant plastic flow and shear failure, greatly increasing the risk of vehicle immobilization.

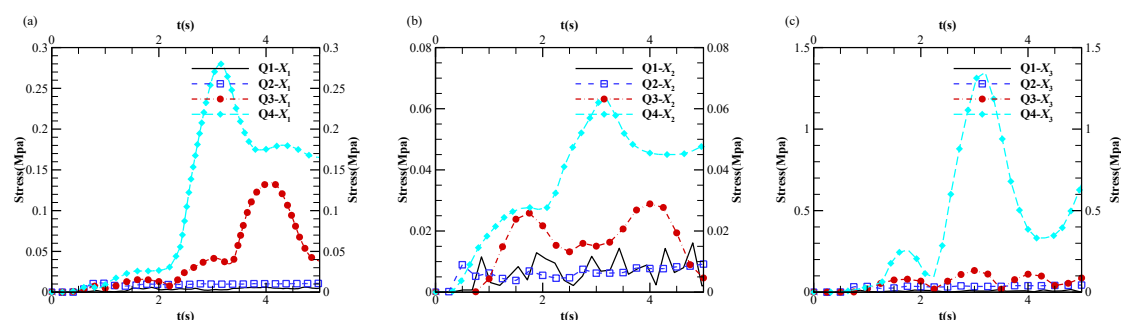


Figure 9. Mises stress histories of the three reference points under different mineral loading conditions: (a) X_1 ; (b) X_2 ; (c) X_3 .

Table 4. Peak stress at the three reference points under different loading conditions.

Case	Loading (t)	Peak Stress at X_1 (MPa)	Peak Stress at X_2 (MPa)	Peak Stress at X_3 (MPa)
Q1	0	0.0081	0.0236	0.0236
Q2	4	0.0114	0.0092	0.0437
Q3	8	0.1434	0.0288	0.1328
Q4	10	0.2799	0.0629	1.3476

In summary, mineral loading significantly affects vehicle sinkage and Mises stress response. Under the present model conditions, the loading level near 5.8 t can be regarded as a reference threshold for local rear-track sinkage risk, while loading conditions of 8 t and above lead to obvious rear-biased sinkage and increased stress concentration. The above results are based on the rear-loaded configuration considered in the present vehicle, in which the mineral storage bin is located behind the original center of gravity. If the mineral load were arranged closer to the vehicle center, the load increment would be more evenly distributed between the front and rear tracks. In that case, the rear-track load would increase more slowly with mineral loading, and the critical loading for local rear-track sinkage would be expected to increase. The corresponding sinkage mode would also tend to change from rear-biased sinkage to a more uniform overall sinkage mode. In contrast, if the mineral load was placed toward the front of the vehicle, the front-track load would increase, and the dominant risk would shift from rear-track local sinkage to front-track local sinkage.

3.2. Influence of Initial Pitch Angle on the Vehicle Body State

To study the influence of the initial pitch angle on the vehicle body state, the unloaded cases Q1, Q5, and Q6 and the 4 t loading cases Q2, Q7, and Q8 were compared.

Under the unloaded condition, the vehicle is only subjected to its self-weight. Figure 10 shows the sinkage displacement histories of the three reference points under Q1, Q5, and Q6. Under the 0° horizontal condition, the vehicle sinkage process is relatively stable, and the displacement histories of the three reference points are similar, indicating a relatively uniform load distribution and good attitude stability. When the initial pitch angle increases to 2° , the sinkage at all three reference points increases, and the sinkage difference between different positions begins to expand. The front part of the vehicle contacts the soil earlier and bears a larger vertical pressure, resulting in a faster sinkage rate at X_2 and a forward-tilting tendency. When the pitch angle further increases to 4° , the overall sinkage level continues to rise. This indicates that a larger pitch angle enhances asymmetric contact between the vehicle and sediment, causing the lower front track to penetrate more easily into the soft sediment.

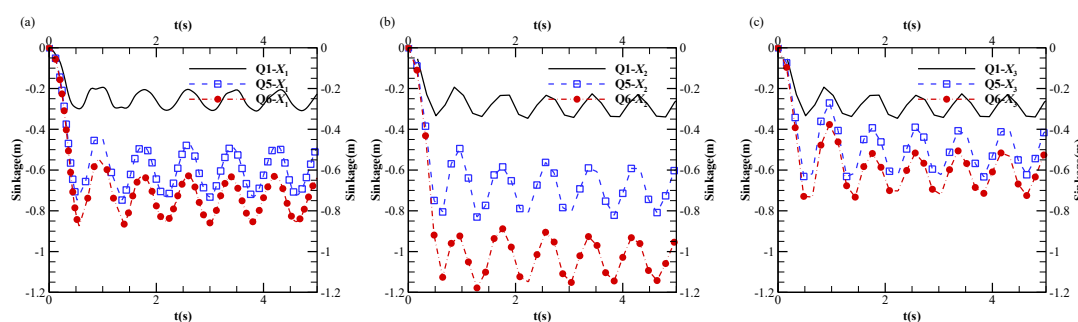


Figure 10. Sinkage displacement histories under different initial pitch angles without mineral loading: (a) X_1 ; (b) X_2 ; (c) X_3 .

Figure 11 shows the Mises stress contours at equilibrium for Q1, Q5, and Q6. Under the 0° condition, the Mises stress is mainly concentrated beneath the track, and the influence area is relatively small and uniformly distributed. Under the 2° condition, the Mises stress influence area inside the sediment expands, and the high-stress region extends toward the inclined direction of the vehicle. Under the 4° condition, the stress diffusion range further increases, and a clear stress response appears in the middle and lower sediment layers. This indicates that a larger pitch angle enlarges the soil disturbance region and enhances sediment plastic deformation.

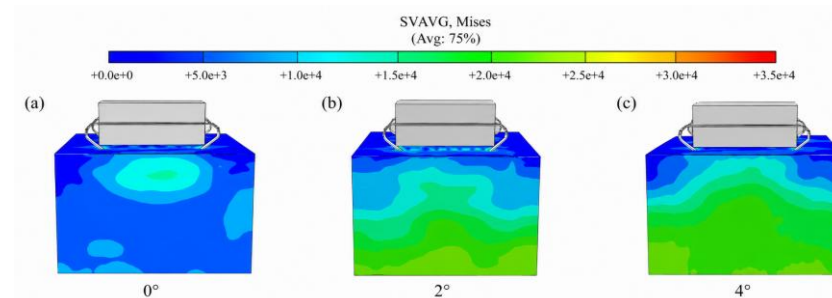


Figure 11. Mises stress contours at equilibrium under different initial pitch angles without mineral loading: (a) Q1; (b) Q5; (c) Q6.

Figure 12 shows the Mises stress histories of the three reference points under Q1, Q5, and Q6. Under the unloaded horizontal condition Q1, the stress at each reference point remains low, with only limited fluctuation, indicating stable contact between the vehicle and soil. When the initial pitch angle increases to 2° , the stresses at X_2 and X_3 increase significantly. The peak stress at the front grouser X_2 is slightly higher than that at the rear grouser X_3 , indicating that the front and rear tracks still have a certain degree of cooperative load-bearing capacity under a small pitch angle. However, the local Mises stress is already significantly higher than that under the horizontal condition.

When the pitch angle increases to 4° , local grouser stress is amplified considerably. The peak stresses at all three reference points in Q6 are significantly higher than those in Q5. In particular, the peak stress at X_2 is approximately 5.1 times that in Q5. This indicates that under a large pitch angle, the front track penetrates earlier and deeper into the sediment, causing local shear failure and lateral soil flow. The stress response is no longer a simple overall increase, but is characterized by strong local concentration at the front grouser. Therefore, under the unloaded condition, the influence of initial pitch angle mainly appears as a forward-tilting sinkage mode, in which the lower front track penetrates first and further worsens the vehicle attitude.

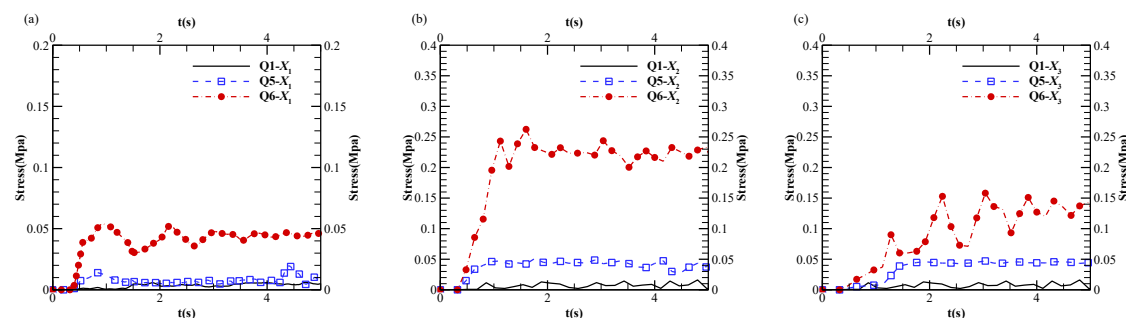


Figure 12. Mises stress histories under different initial pitch angles without mineral loading: (a) X_1 ; (b) X_2 ; (c) X_3 .

Compared with the unloaded condition, the effect of initial pitch angle becomes more significant under mineral loading. Figure 13 shows the sinkage displacement histories of Q2, Q7, and Q8 under the 4 t loading condition. In Q2, although the vehicle is initially horizontal, the mineral load is located at the rear storage bin, causing the center of gravity to shift backward. As a result, the rear-track sinkage is slightly larger than the front-track sinkage, and the vehicle shows a slight backward-tilting tendency. Nevertheless, the sinkage difference among the three reference points remains small, and the overall sinkage process is relatively stable.

When the initial pitch angle increases to 2° , the sinkage at all reference points in Q7 increases significantly, and the fluctuation amplitudes at X_2 and X_3 become larger. This indicates that the pitch angle increases local ground pressure and makes the track–sediment contact state more unstable. In this case, the vehicle is affected both by rear loading and by front penetration caused by forward pitch, leading to stronger soil disturbance at both the front and rear tracks. When the pitch angle further increases to 4° , all three reference points in Q8 show greater sinkage, indicating that the coupling between mineral loading and initial pitch angle causes more pronounced nonuniform sinkage. Under the 4 t loading condition, the initial pitch angle therefore aggravates body sinkage and expands the sinkage difference among different reference points, reducing attitude stability.

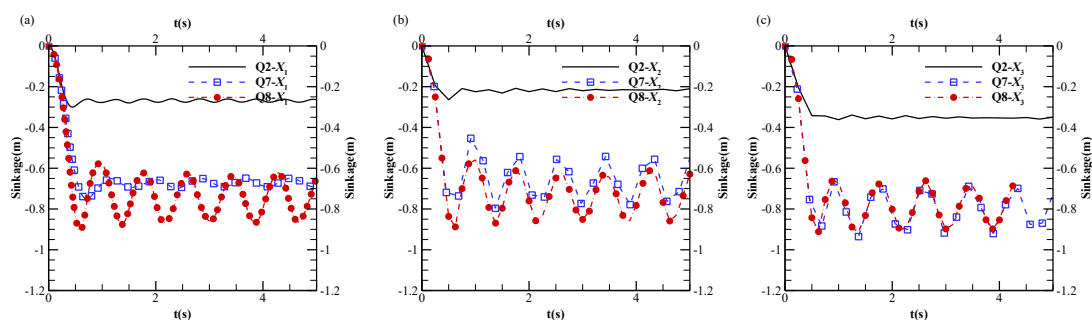


Figure 13. Sinkage displacement histories under different initial pitch angles with 4 t mineral loading: (a) X_1 ; (b) X_2 ; (c) X_3 .

Figure 14 shows the Mises stress contours at equilibrium for Q2, Q7, and Q8. When the pitch angle increases to 2° , the high-stress region inside the sediment expands significantly, and the stress distribution extends toward the inclined direction of the vehicle. This indicates that the pitch angle enhances track penetration and induces a larger region of plastic deformation. When the pitch angle increases to 4° , obvious stress concentration appears beneath the track and near the lower side. The disturbed soil region further expands. The front region forms local deep sinkage due to the pitch effect, while the rear region experiences high Mises stress due to mineral loading. Consequently, the vehicle undergoes substantial overall sinkage. This shows that the combined effects of loading and initial pitch angle significantly deteriorate the sediment-bearing state and make local shear failure and lateral flow more likely.

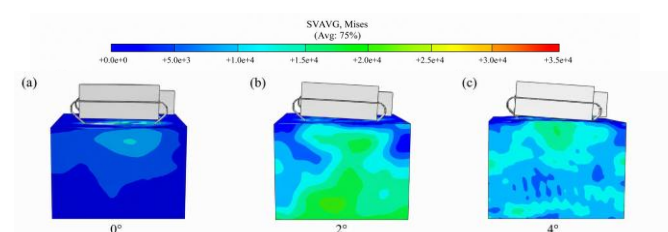


Figure 14. Mises stress contours at equilibrium under different initial pitch angles with 4 t mineral loading: (a) Q2; (b) Q7; (c) Q8.

Figure 15 shows the Mises stress histories of the three reference points under Q2, Q7, and Q8. Under Q2, the stress at each reference point remains relatively low, with only small local fluctuations, indicating stable contact under horizontal loading. In Q7, the peak stresses at X_1 and X_2 increase significantly, both reaching approximately ten times the corresponding values in Q2, while the stress at X_3 does not increase significantly. This indicates that a 2° initial pitch angle mainly strengthens the local contact between the front track and soil. In Q8, stress fluctuation becomes more intense, and large peak stresses appear at multiple reference points. The stresses at all three reference points are significantly higher than those in Q2 and Q7, indicating a clear coupled amplification effect between the 4 t mineral loading and the 4° initial pitch angle. In this case, the front grouser exhibits high stress concentration due to the pitch effect, while the rear grouser maintains a high stress level due to rear loading. Thus, both the front and rear tracks enter a high-risk contact state.

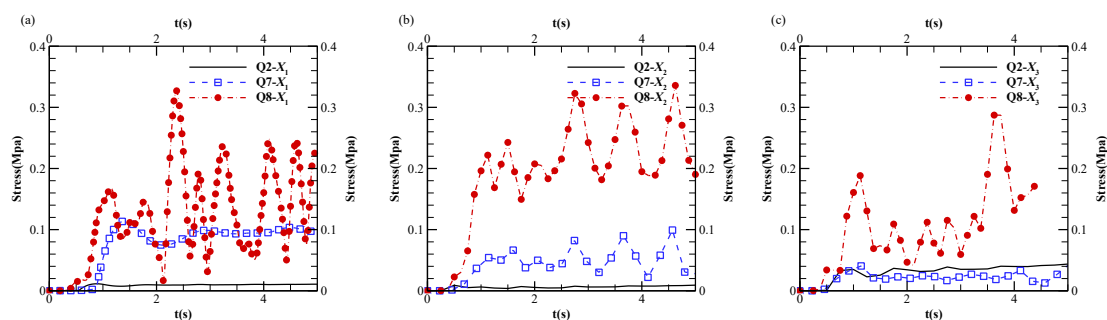


Figure 15. Mises stress histories under different initial pitch angles with 4 t mineral loading: (a) X_1 ; (b) X_2 ; (c) X_3 .

To compare the influence of pitch angle with and without mineral loading, the peak stresses of the three reference points under six cases were extracted, as listed in Table 5. The results show that the pitch angle increases the overall stress level of the vehicle and significantly enhances local stress concentration at the lower-side track. This effect is further amplified under mineral loading, indicating a clear coupling between loading and initial pitch angle.

Table 5. Peak Mises stress at the three reference points under different initial pitch angles with and without mineral loading.

Case	Loading (t)	Pitch Angle ($^\circ$)	Peak Stress at X_1 (MPa)	Peak Stress at X_2 (MPa)	Peak Stress at X_3 (MPa)
Q1	0	0	0.0081	0.0236	0.0236
Q5	0	2	0.0199	0.0510	0.0471
Q6	0	4	0.0543	0.2624	0.1580
Q2	4	0	0.0114	0.0092	0.0436
Q7	4	2	0.1142	0.0992	0.0437
Q8	4	4	0.3270	0.3358	0.2872

In summary, the initial pitch angle aggravates asymmetric sinkage and local Mises stress concentration, and its effect is further amplified under mineral loading. The vehicle therefore exhibits a coupled “front-tilting–rear-loading” sinkage mode with reduced attitude stability.

This study analyzed the sinkage and stress responses of a DSMV in soft seabed sediments from two aspects: mineral loading and initial pitch angle. However, several limitations remain. First, the vehicle body and tracks were treated as rigid bodies, and struc-

tural deformation was neglected. Second, the present work mainly focuses on stabilized sinkage and Mises stress responses rather than the initial transient impact process. The prescribed downward velocity was used as a numerical acceleration parameter to obtain a stabilized settlement state within a reasonable computational time. Therefore, the results should be interpreted under a quasi-static approximation. In addition, active track motion, slip ratio, traction force, and continuous driving were not considered. Third, the CEL model uses a homogeneous equivalent Drucker–Prager parameter set for the flow-plastic sediment layer and therefore does not explicitly consider sediment stratification, anisotropy, or spatial heterogeneity. It may not fully capture local variations in soil resistance during track penetration. Fourth, hydrodynamic effects and realistic mineral redistribution in the storage bin were not included. Future work should include a more rigorous dynamic treatment, such as kinetic-energy evaluation, dynamic amplification analysis, or velocity sensitivity analysis. In addition, track dynamics, terrain variation, sediment heterogeneity, and active leveling control should be coupled to improve the applicability of the model to real deep-sea mining operations.

4. Conclusions

In this study, the “Kunlong 500” tracked deep-sea mining vehicle was selected as the prototype vehicle. A vehicle–sediment interaction model was established in Abaqus, and the CEL method was used to simulate large-deformation contact between the track and flow-plastic deep-sea sediment. The Drucker–Prager model was adopted to describe sediment yielding and plastic deformation. The effects of mineral loading and initial pitch angles were investigated. The main conclusions are as follows:

1. Mineral loading is the main factor affecting the overall sinkage of the vehicle body and the stress response of the tracks. As the loading increases, both the vehicle sinkage depth and the local peak stress increase significantly. Because the storage bin is located at the rear of the vehicle, the sinkage mode gradually changes from overall sinkage to rear-biased sinkage.
2. Based on the sinkage theory and the moment equilibrium of the rear track, the loading level near 5.8 t was estimated as a model-based reference critical value for local rear-track sinkage risk. A basic parametric sensitivity analysis showed that when the equivalent bearing term varied by $\pm 10\%$, the estimated critical loading changed from approximately 4.5 t to 7.1 t.
3. The initial pitch angle aggravates vehicle instability. It changes the stress distribution between the front and rear tracks, leading to asymmetric sinkage and local stress concentration. Under both unloaded and 4 t loading conditions, the overall sinkage displacement and stress response of the vehicle increase with the initial pitch angle.
4. A clear coupled amplification effect exists between mineral loading and initial pitch angle. Particularly under the Q8 condition with relatively large loading and a large pitch angle, both the front and rear tracks enter high-stress states. The vehicle exhibits a coupled “front-tilting–rear-loading” sinkage mode, and its attitude stability decreases significantly.
5. The sediment sinkage and stress response show a nonlinear relationship with load variation. Based on these results, several engineering implications can be drawn. First, an excessively rearward storage-bin layout should be avoided because it increases rear-track loading and promotes rear-biased sinkage. Second, under the present equivalent-parameter assumptions, the estimated 5.8 t loading should be regarded as a reference warning value rather than a precise safety limit, while loading cases of 8 t and above should be treated as key risk-control conditions. Third, large initial pitch angles should be avoided during operation on soft sediments, and attitude control should be used to reduce front–rear load imbalance. Therefore, DSMV

operation should combine load monitoring, attitude regulation, and storage-bin layout optimization to reduce excessive sinkage and local stress concentration.

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Abbreviations

The following abbreviations are used in this manuscript:

CEL	Coupled Eulerian–Lagrangian
DSMV	Deep-sea mining vehicle

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