Indian Journal of Geo Marine Sciences
Vol. 53 (05), May 2024, pp. 398-408
DOI: 10.56042/ijms.v53i05.21673

Configurations of tracked vehicle for development of subsea mining machines with improved mobility on soft soil

C Janarthanan*[a,b], R Muruganandhan[a], K Gopkumar[b] & G A Ramadass[b]

[a]College of Engineering Guindy (CEG), Anna University, Guindy, Chennai, Tamil Nadu – 600 025, India

[b]National Institute of Ocean Technology, Chennai, Tamil Nadu – 600 100, India

*[E-mail: design.jana@gmail.com]

Received 01 April 2024; revised 17 May 2024

The National Institute of Ocean Technology (NIOT) has been actively involved in developing technology for a deep-sea mining machine designed to extract polymetallic nodules from depths ranging between 5000 and 6000 metres in the Indian Ocean. Designed specifically to collect nodules from soft seabeds, the project focuses on the development of a crawler-based mining machine. Manoeuvring and maintaining stability in low-cohesion soil with a bearing capacity below 10 kPa presents significant challenges. This paper conducts a study to determine the suitable track configuration, crucial for improving vehicle traction under deep-seabed soil conditions. The research compares explicitly the traction efficacy of long dual-track and short four-track configurations with the same contact area and bearing pressure on soft soil. Additionally, soil-grouser interaction studies were conducted using numerical simulation techniques to assess the mining vehicle's permissible sinkage and improve its traction performance. This involved developing a soil-machine interaction environment and simulating the dual and four-track configurations with seabed soil parameters. The research further compare the efficacy of two-tracks long-length and four-tracks short-length configurations with the same contact area and bearing pressure on soft soil. The drawbar pull simulations of the vehicle were conducted using dynamic and mathematical simulation tools in MATLAB to evaluate the mobility characteristics of tracked vehicle configurations under varying operational conditions. Based on the numerical results, the prototype model will be developed, and its performance under various traction conditions will be evaluated.

[**Keywords**: Four track, Grouser, Polymetallic nodules, Sinkage, Soft soil, Tracked vehicle, Undercarriage]

Introduction

The deep seabed holds potentially rich mineral resources, and mining these resources could prove invaluable for meeting mankind's future needs. However, developing technology for such endeavours poses significant challenges due to the high pressure, low temperature, and soft soil conditions of the seabed in the open ocean. India has been at the forefront of developing technologies for extracting polymetallic nodules from the seabed in the Central Indian Ocean (CIO) using a mining vehicle (Fig. 1). The mining system's configuration has evolved in phases to overcome the challenges of subsea environment.

The flexible riser concept was initially demonstrated in the Indian waters at depths of 410 and 512 metres[1,2]. Building on the insights gained from these sea trials, the mining system underwent further improvement to operate at deeper waters to assess its manoeuvrability and controllability at deep seabed. The deep-water mining vehicle underwent functional testing and qualification in Indian waters at a depth of 890 m(ref. 3), followed by testing in deep waters in the CIO at a depth of 5270 m(ref. 4). Based on the sea trial observations, it is essential to analyse the vehicle configuration in relation to the behaviour of soft seabed soils to ensure reliable movement during mining operations. The seabed soil consists of very soft, cohesive clay with shear strength typically below 2 kPa on the surface[5,6]. Seafloor sediments exhibit distinct physical and mechanical characteristics compared to terrestrial sediments, characterised by water saturated and lower shear strengths possessing poor bearing capacities[7].

Designing a mining vehicle suitable for these conditions, with controlled locomotion and enhanced traction, presents a considerable challenge. The key factors influencing the traction force exerted by the soil include the vehicle's contact area and the soil's internal friction angle. The following literature explored the traction force development for tracked vehicles.

Initially, the Mohr-Coulomb criterion was utilised to estimate the peak traction force without considering

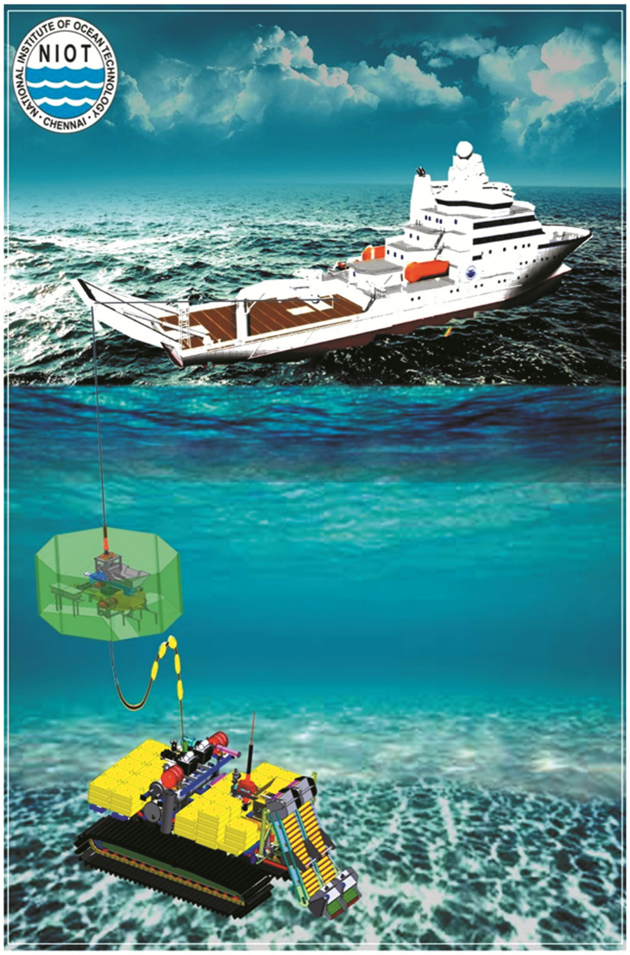

Fig. 1 — Integrated mining system using flexible riser concept

grouser height. Subsequently, Bekker's[8] empirical equation, modified to account for grouser parameters, was utilised to estimate the vehicle's off-road mobility. Experimental studies have assessed the traction forces of underwater trenchers on soft clay seafloors to determine soil bearing capacity under dynamic conditions[9]. Kim *et al.*[10] conducted set of experiments on track-sediment interactions to evaluate the influence of deep-sea mining vehicle dimensions on traction performance using recreated sediments. Later Schulte & Schwarz[11] conducted a study to analyse the mechanical properties of simulated sediments using various shear testing methods and established the shear stress-shear displacement relationship. To qualitatively assess the traction performance of a seabed mining vehicle on a soft seafloor, a dynamics model was developed in Recurdyn and a track-soil force user subroutine based on experimental results[12]. A simulation was conducted to analyse the straight-line travelling behaviour of a trencher on a custom-built seabed soil model, assessing the vehicle traction capabilities by Wang *et. al.*[13]. Additionally, track traction tests were performed on compacted and disturbed soils to evaluate their impact on the vehicle's drawbar pull[14]. A computational approach was introduced to assess the multi-pass effect on traction efficiency under specific soil and operational conditions[15]. Further analysis was conducted on the creep behaviour of soft seabed sediments beneath a mining vehicle's track, measuring the compression-shear creep curve and formulating an equation to estimate vehicle sinkage and traction force while accounting for soil creep effects[16]. The tracked deep-sea mining vehicle aims to achieve high traction force by maintaining low bearing ground pressure on the seafloor soil to ensure excellent manoeuvrability[17]. Most prior research on track-seabed interaction in subsea mining vehicles has primarily focused on two-track configurations. However, recent studies have shifted towards four-track vehicles to enhance traction and stability for higher mining efficiency. A traction model for a four-tracked deep-sea mining vehicle was developed, and its dynamic behaviour in obstacle negotiation was analysed through simulations, assessing it's gradient-climbing and turning capabilities under undulating terrain conditions[18]. Additionally, the superior mobility and stability of four-tracked mining vehicles compared to conventional dual-tracked systems were evaluated, including motion characteristics and dynamic responses during straight-line travel on a level seabed[19].

Since the CIO seabed sediment exhibits cohesive properties, the vehicle's traction capability is primarily influenced by the contact area between the tracks and the substrate. To enhance the traction force, the dimensions of the track, length and breadth, need to be appropriately sized to increase the contact area. In this paper, the primary focus is on examining the motion characteristics and dynamic behaviour of a tracked mining vehicle operating in soft soil conditions. The study extends as follows:

- Initially, a Finite Element (FE) model is employed to conduct sinkage analysis under a soil shear strength of 2 kPa. This analysis aims to determine the vehicle's bearing pressure required for safe static and dynamic operations underwater. The FE model, utilising the Coupled Eulerian Lagrangian (CEL) technique, is developed with varying bearing pressure conditions of the mining vehicle.

- Secondly, a Multi-Body Dynamic (MBD) model is meticulously recreated to accurately simulate the dynamic behaviour of both two-track and four-track configurations under soft soil conditions.
- Lastly, the configurations of the mining vehicles are analysed, comparing a two-track long-length configuration with a four-track shorter-length configuration, both subjected to the same contact area and bearing pressure on the soil. Mathematical model simulations are performed using Matlab, incorporating existing governing traction force equations for soft soil conditions. The traction force distribution of both mining vehicles is compared, providing insights for the advancement of deep-sea mining vehicle design.

Materials and Methods

Soil-machine interaction

Empirical models derived from Bekker's theory are widely utilised in terramechanics to assess the mobility of tracked vehicles. These models incorporate the shear stress-shear displacement characteristics of the terrain to estimate the traction performance of tracked vehicles across different soil conditions. Figure 2 depicts the characteristics curves for various soil types[20]. Soil type A - Loose sand and saturated clay; Soil type B - Organic terrain and saturated peat; and Soil type C - Deep sea soil, frozen snow and loam.

To assess a vehicle's mobility, it is important to determine the pressure-sinkage characteristics and the shear stress-shear displacement behaviour of deep-sea soil. The peak tractive effort attainable is influenced by the terrain's shear stress and the track's contact area. The soil's shear stress, governed by the Mohr-Coulomb criterion, is a function of its cohesion and internal friction angle.

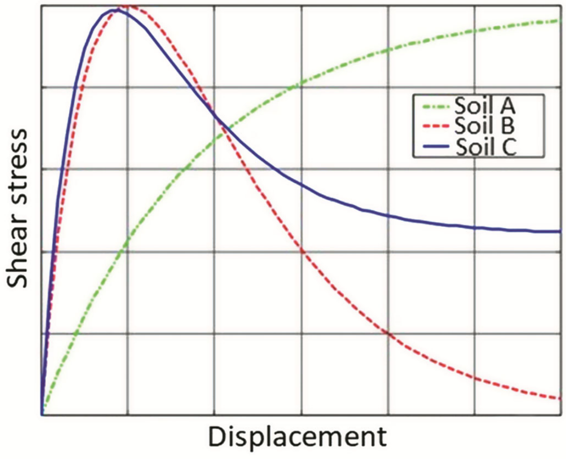

Fig. 2 — Shear stress-shear displacement curves for various soil types

$$\tau_{max} = (c + \sigma \tan \Phi) \qquad \ldots (1)$$

Where, τ_{max} - peak soil shear stress, c - cohesion of soil, Φ - angle of internal friction of soil, and σ - vertical stress.

For non-cohesive soil, shear stress is primarily dependent on the vehicle's weight

$$F_T = Ac + W \tan \Phi \qquad \ldots (2)$$

Where, F_T - traction force, W - vehicle weight, and A - track contact area.

In sandy soil, traction force depends on vehicle weight, as shear strength varies with normal load. In cohesive soils with near-zero friction angles, tractive effort relies on the track contact area. Track-soil interaction influences mobility, with static sinkage affecting ground pressure. Bekker’s pressure-sinkage model estimates the static sinkage of the vehicle as:

$$p = \left(\frac{k_c}{b} + k_\varphi\right) z^n \qquad \ldots (3)$$

Where, p - bearing pressure, k_c - cohesion modulus, k_φ - frictional modulus, b - grouser width, Z - sinkage, and n - exponential constant.

The primary determinant of the maximum tractive force achievable by a mining vehicle on soft terrain is the tangential shear strength of the soil. Therefore, the soil's shear characteristics play a crucial role in influencing the vehicle's manoeuvrability in such conditions. Researchers have performed field experiments on deep-sea beds, yielding shear stress-displacement curves similar to those in Figure 2. Initially, shear stress peaks with slight displacement, then decreases until stabilizing at the residual strength (τ_{res}). In soft soil, the contact shear stress beneath the track is determined using Wong’s shear stress-displacement model[21].

$$\tau = \tau_{\max} k_r \left\{1 + \left[\frac{1}{k_r\,(1-e^{-1})} - 1\right] e^{1-\frac{j}{k_w}}\right\} \left(1 - e^{-\frac{j}{k_w}}\right) \qquad \ldots (4)$$

Where, τ – shear stress, τ_{max} – maximum shear stress, k_r - ratio of the residual shear stress to the maximum shear stress, k_w - shear displacement where the maximum shear stress occurs, and j - shear displacement.

Slip is a common occurrence when navigating through deep-sea soil. Schulte introduced an equation for traction force, which takes into account slip conditions[20]. This equation incorporates shear stress-displacement relationships derived from experiments or semi-empirical models that characterise deep-sea soil behaviour. Assuming a uniform pressure distribution beneath a single track with a contact length denoted as L, the total tractive effort of a track can be calculated as:

$$F_T = (Ac + W\,tan\emptyset)K_R\left[1 + \frac{K_W}{sL}\left(e^{\frac{-sL}{K_W}} - 1\right)\right] - \left(\frac{e}{K_R(e-1)} - 1\right)\frac{K_W}{2sL}\left(2e^{1-\frac{sL}{K_W}} - e^{1-\frac{2sL}{K_W}} - e\right) \qquad \ldots (5)$$

Where, F_T - traction force, c - soil cohesion, W - vehicle underwater weight, $\emptyset$ - soil internal friction angle, s - slip rate, and L - vehicle contact length.

Sinkage experiments

The deep-sea mining vehicles are prone to sinking due to the high bearing load or slipping during dynamic operations. The degree of sinkage of the mining machine in very soft clays is critical, as the soil resistances acting on the mining machine depend on the amount of sinkage. The primary resistances due to sinkage include bulldozing and gradient resistances. When sinkage reaches a critical level, these external resistances may surpass the vehicle's maximum traction force. Bulldozing resistance arises from soil compaction at the leading surface of the undercarriage, particularly at the front drum, constituting a major portion of overall driving resistance. Gradient resistance occurs as increased slip at the track's rear leads to excessive soil deformation, causing the mining vehicle's rear to sink lower than the front. This altitude difference shifts the weight distribution, making gradient resistance a significant factor[22].

To mitigate sinkage, the normal load of the mining machine must be reduced, or the contact area of the mining machine must be increased. Experimental and extensive numerical studies have been conducted to determine the allowable sinkage of the vehicle under various normal loads and soil strengths[23]. The experiments of pressure-sinkage tests on soft soil are shown in Figure 3.

Grouser soil-interaction analysis

The seabed soil experiences substantial displacement under dynamic conditions, making conventional Lagrangian-based Finite Element Analysis (FEA) challenging because of severe mesh deformation[24]. In contrast, the Eulerian-based approach effectively handles large deformations by keeping nodes fixed while allowing material to flow through the mesh. Unlike the Lagrangian model, which tracks individual particles, the Eulerian method records material properties at fixed spatial points over time, capturing the evolution of flow. This approach prevents mesh distortion, enabling efficient modelling of significant deformations[25,26].

To simulate vehicle sinkage, a Finite Element Modelling (FEM) approach was implemented in ABAQUS/CAE 6.14, incorporating boundary conditions to account for the wall effect. A deep-sea soil domain was established; with soft soil properties defined using the Mohr-Coulomb failure criterion and plastic material behaviour. The following soil properties were utilised for the simulations.

In the numerical analysis, the grouser size of 300 mm × 300 mm was treated as the Lagrangian domain with discrete rigid conditions, while the soil was modelled in the Eulerian domain. The Abaqus/Explicit module was utilised to couple the Eulerian and Lagrangian domains, allowing the capture of large deformations of the soil. The FEM model was meticulously developed to closely resemble the experimental setup; ensuring accurate boundary conditions were applied to the grouser-soil model. Varying bearing pressure (underwater vehicle weight) was applied in each simulation, and the resulting sinkage values were plotted against the applied bearing pressure. The FEM models depicting the grouser-soil interaction domain are illustrated in Figure 4.

Multi-Body Dynamic (MBD) analysis of deep sea mining vehicle

Multi-Body Dynamic simulation is widely utilized to assess the traction behaviour of tracked vehicles operating on soft terrain. A comparative analysis of

Fig. 3 — Pressure sinkage test experiments

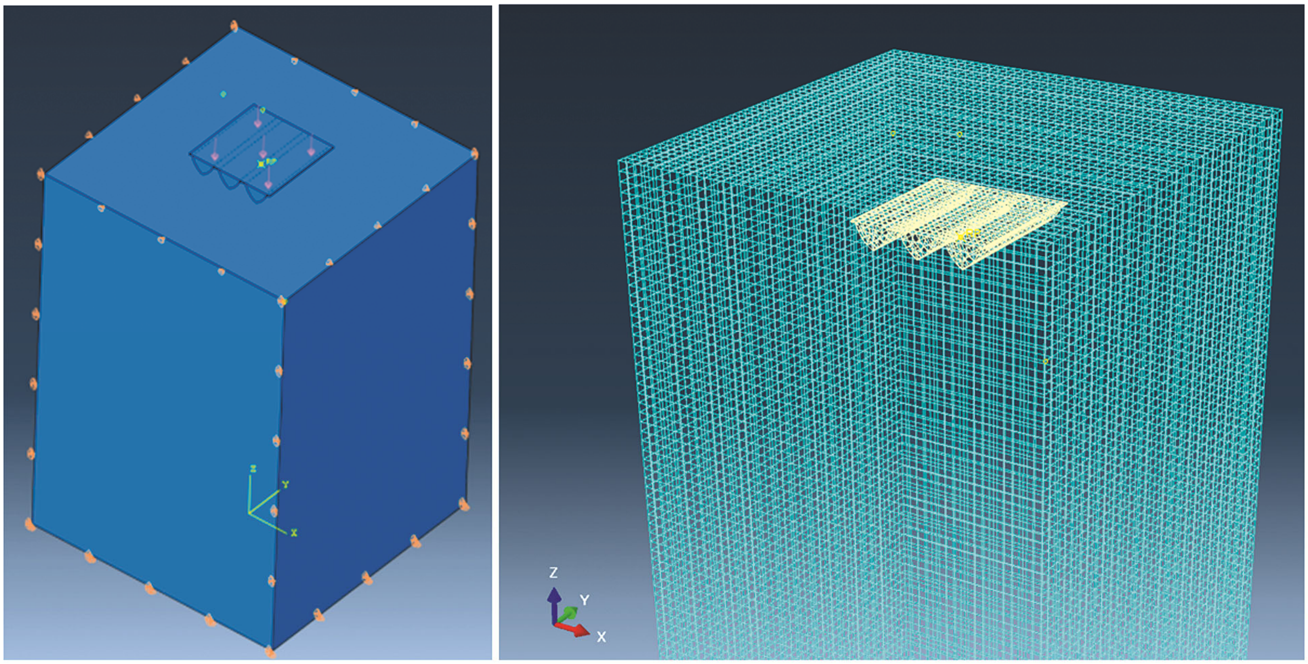

Fig. 4 — FEM model of grouser-soil interaction

rigid-body and multi-body tracked vehicle models was conducted to evaluate their dynamic responses and mobility characteristics under extremely low shear strength conditions[27]. A comparative study was conducted to assess track slip rates observed during nearshore tests of the MineRo-II subsea mining vehicle against dynamic simulation results. Using RecurDyn software, the analysis evaluated the vehicle's steering response and traction efficiency under varying seabed conditions[28]. A MBD model was formulated to simulate the locomotion of a deep-sea mining vehicle. This model enables the prediction of track slip rates and the evaluation of its mobility characteristics using RecurDyn software[29]. A MBD model of a tracked vehicle was constructed using ADAMS/ATV tool to assess its capabilities in the ditch and obstacle crossing as well as slope climbing. The simulation results were validated against experimental data obtained from a 150-meter lake test[30]. Recent research has concentrated on modelling four-track vehicles and dynamically simulating mining systems in soft soil conditions. In this study, a MBD model was developed with both two-track and four-track configurations to analyse the dynamic response of tracked vehicles on soft soil. The conventional ADAMS Tracked Vehicle (ATV) tool was employed to model the tracked vehicle, with the normal force between the terrain and grouser based on Bekker's model[8]. Forces acting in the travel direction and perpendicular to it between track segments were determined using methods proposed by Janosi & Hanamoto[31] (J-H model) and Wong[20] (Wong model). Soft soil experiences repetitive loading and the ATV model uses a rectangular mesh to capture the loading history. Each mesh segment records key parameters, including maximum sinkage and pressure for normal force calculations, along with shear deflection and shear forces for estimating these directional forces.

In the MBD model, all components were precisely replicated according to their reference configurations and geometric measurements, ensuring an accurate representation of their masses, inertias, and spatial coordinates. Detailed descriptions and precise models of each component of the track system are necessary for ATVs. The vehicle subsystem components, collection system, and other supporting structures were unified and fixed to the chassis as a single unit. The weight of the vehicle was considered equivalent to the underwater weight for all MBD simulations. Figure 5 depicts the MBD model of the tracked vehicle created in ATV.

In the MBD analysis, the flat terrain and soft soil conditions were modelled by incorporating soft soil parameters derived from in-house experimental data. Dynamic simulations were performed on the two-track long-length and four-track short-length configurations in ATVs. For the drawbar-pull simulation, a spring with various stiffness values

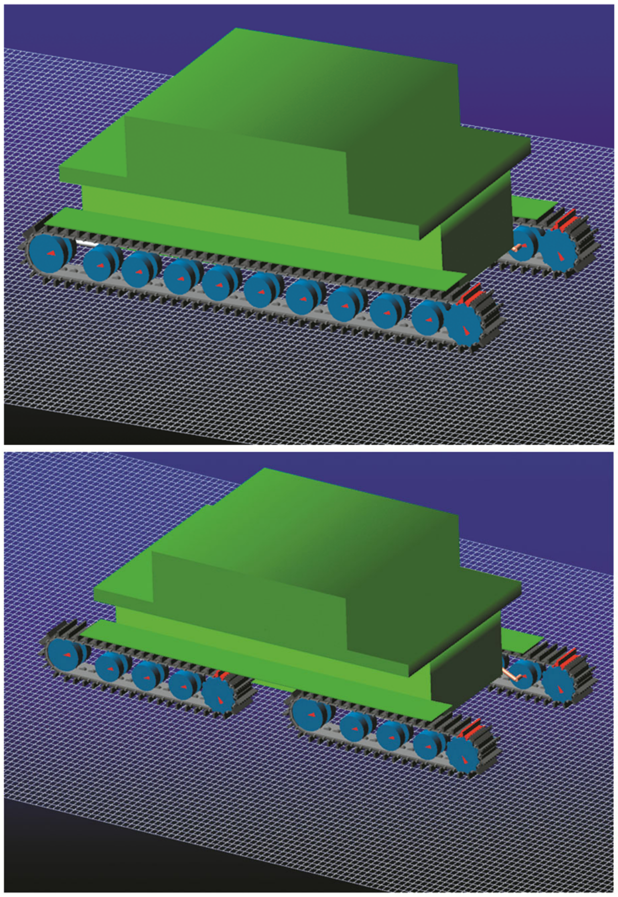

Fig. 5 — MBD model of two-track and four-track configurations

was attached to the rear side of the vehicle to simulate slip conditions and measure the peak traction force generated by the vehicle with different track configurations. Figure 6 depicts the drawbar-pull test model developed in the MBD domain.

Results and Discussion

Grouser soil finite element analysis

In the FEA model, the soft soil environment was recreated with an untrained shear strength of 2 kPa, employing soil material properties derived from deep-sea soil characteristics (Table 1). Numerical simulations were subsequently performed with varying bearing pressures applied to the grouser, and the resulting sinkage values were recorded for each simulation. Figure 7 illustrates the stress distribution and resulting soil sinkage due to grouser interaction.

Figure 8 shows the FEA results of grouser sinkage in a soft soil domain as a function of bearing pressure.

Understanding the sinkage behaviour of the vehicle's tracks in soft soil conditions is crucial for designing an efficient track configuration for the mining vehicle. The simulation results provide valuable insights into how the vehicle's sinkage varies with different bearing pressures and estimate the resistance forces acting on the machine during operation.

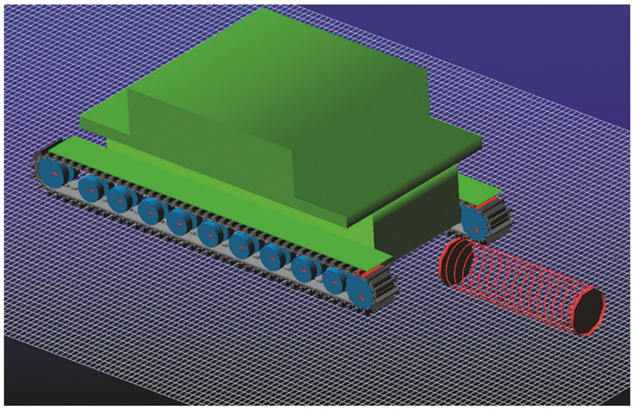

Fig. 6 — MBD model for drawbar-pull analysis

Table 1 — Properties of the soft soil

1	Density of soil	1100 Kg/m^3
2	Young's modulus	240 kPa
3	Poisson ratio	0.49
4	Internal friction angle	0°
5	Dilation angle	0°
6	Cohesion	2 kPa

As observed, when the tracks sink into the sediment, it leads to increased resistance, primarily due to bulldozing effects. To ensure reliable underwater mining operations, it's essential to keep the bearing pressure below 6 kPa for soft soil conditions.

Multi-Body Dynamic (MBD) simulations analysis

Based on the findings of the sinkage analysis, it is evident that the mining vehicle requires a larger contact area to achieve reduced bearing pressure on the soil. The current study has primarily focused on MBD modelling, comparing a two-track long-length configuration with a four-track short-length configuration. Both configurations were designed to maintain the same contact area and bearing pressure for the deep-sea mining vehicle. To evaluate the effects of dynamic parameters on vehicle performance, simulations were conducted using ATV software. In the MBD model, the seabed terrain was assumed to be flat without any undulations or gradients. The soft soil domain was simulated using properties typical of deep-sea soil, with a shear strength of 2 kPa. A contact-bearing pressure of 6 kPa was applied to the vehicles interacting with the soft soil. Dynamic simulations were conducted at a constant velocity of 0.15 m/s for all analyses.

Figures 9 and 10 illustrate the outcomes of the MBD analysis regarding the sinkage and pitch angle of the vehicles under identical loading conditions. The findings suggest that during vehicle motion, the two-track long configuration experiences greater sinking compared to the four-track short-length configuration. Furthermore, the comparative assessment reveals that the two-track configuration experiences a higher pitch angle than the four-track configuration.

The drawbar pull technique was implemented in the ATV tool by attaching a variable stiffness spring to the vehicle to simulate external resistance forces, thereby generating vehicle slip and measuring the maximum traction force developed by different vehicle configurations. The simulation results of the

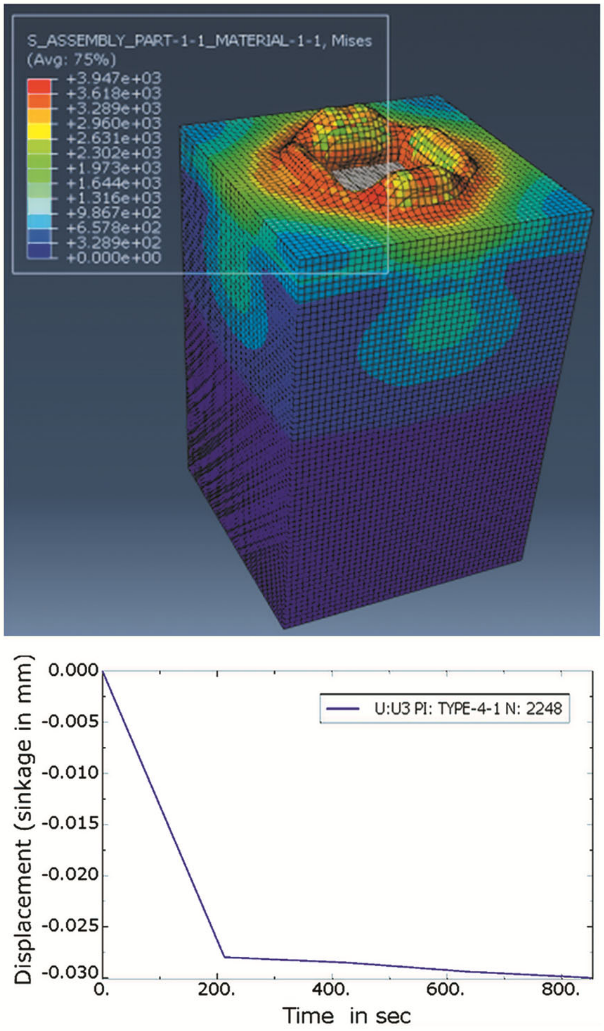

Fig. 7 — Stress distribution and sinkage of grouser

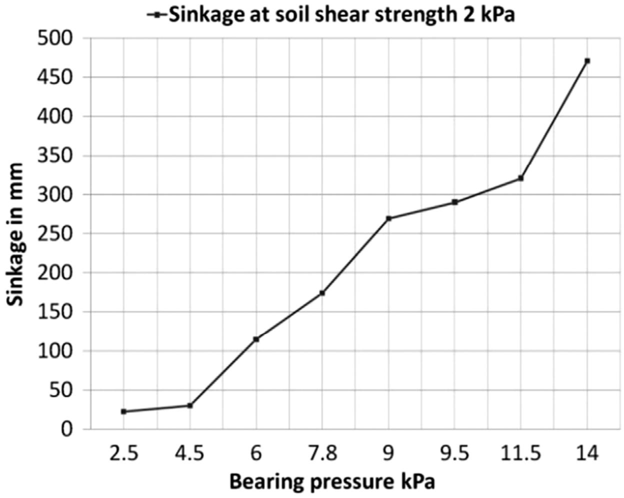

Fig. 8 — FEM results of grouser for sinkage analysis

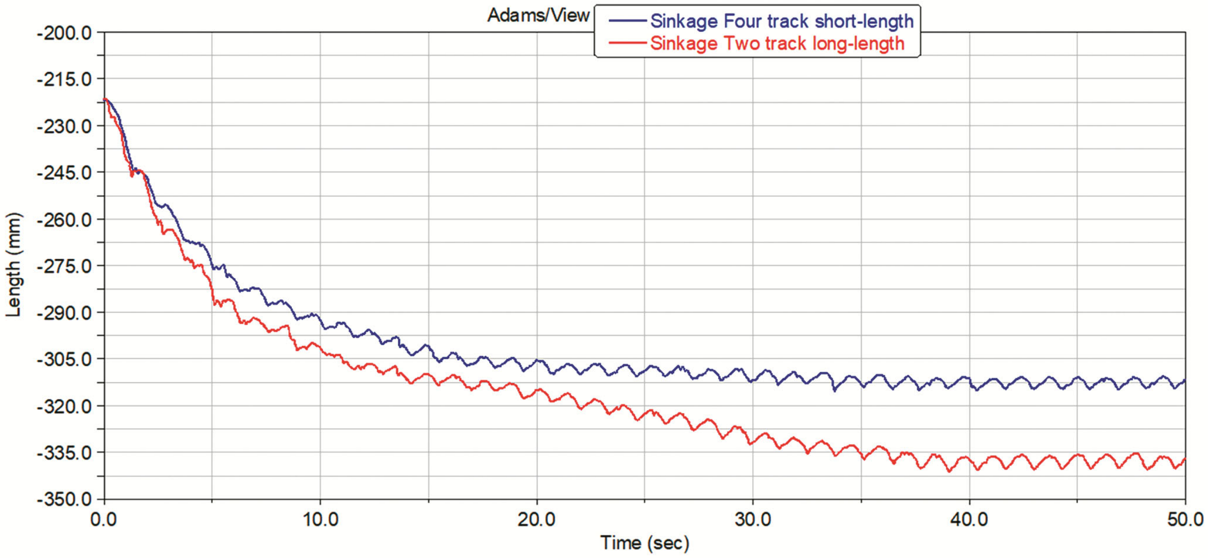

Fig. 9 — Sinkage of MBD vehicle model of two-track and four-track configurations

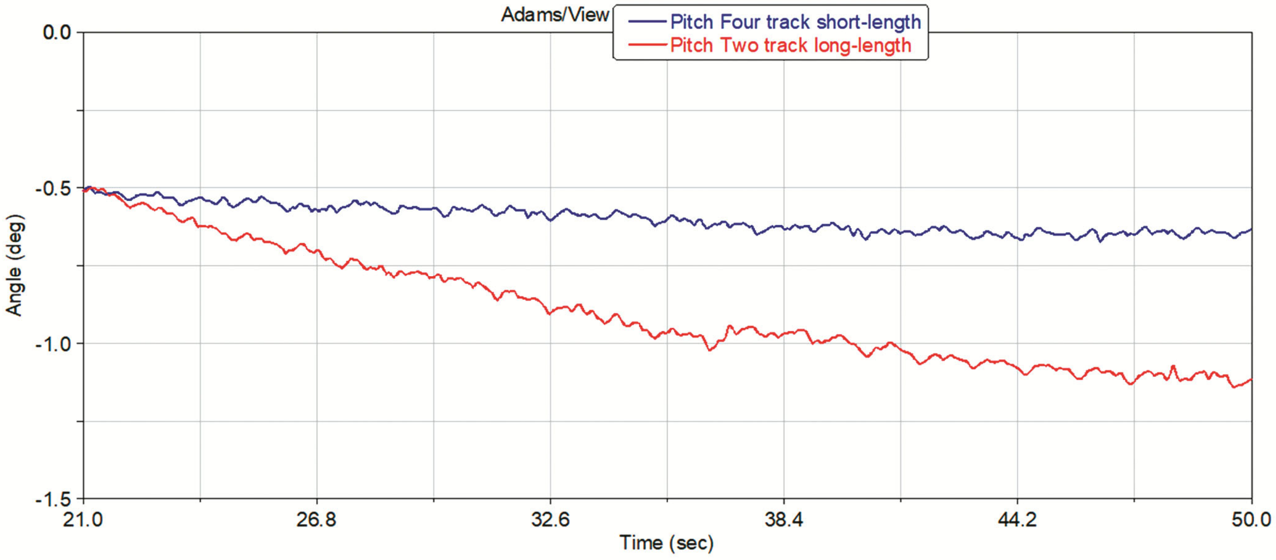

Fig. 10 — Pitch of MBD vehicle model of two-track and four-track configurations

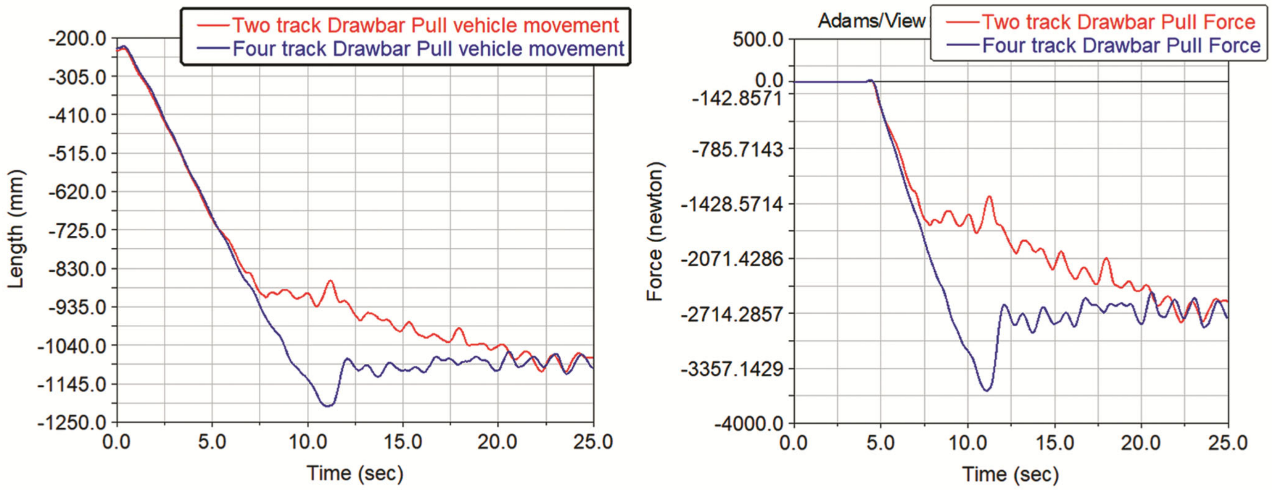

Fig. 11 — MBD results of vehicle movement and resistance force of two-track and four-track configurations

drawbar pull test (Fig. 11) clearly indicate that the movement of the four-track short-length vehicle exceeds that of the two-track long-length vehicle configuration under the same resistance force.

Mathematical model analysis

The traction force of both the two-track and four-track configurations was simulated in MATLAB, varying slip and track width based on a mathematical model. The traction force equation (5) developed by Enno Schulte, which is based on the shear stress-displacement relations characteristic of soft soil, was utilised in this mathematical tool. The geometric configurations, soil properties, and loading conditions were kept consistent with those used in the FEM and MBD analyses. It's important to note that in this mathematical simulation, the effects of the grouser were not accounted for in the governing equation. Figure 12 illustrates the traction force distribution concerning slip for both the four-track short-length and two-track long-length configurations, which possess the same contact area. It's evident that the traction force generated by the soil is consistently higher for the four-track short-length configuration compared to the two-track long-length configuration.

Figure 13 presents a surface plot derived from the mathematical simulation, demonstrating the traction force distribution with respect to variations in vehicle

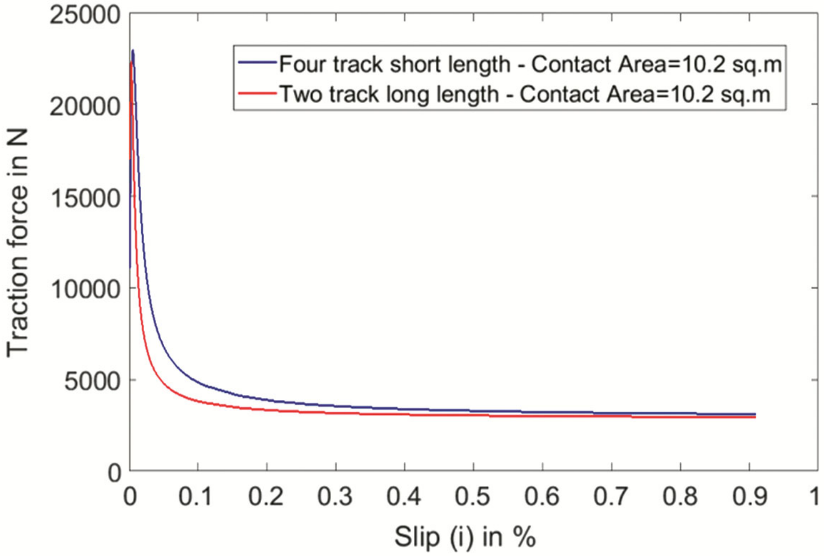

Fig. 12 — Traction force of two-track and four-track configurations

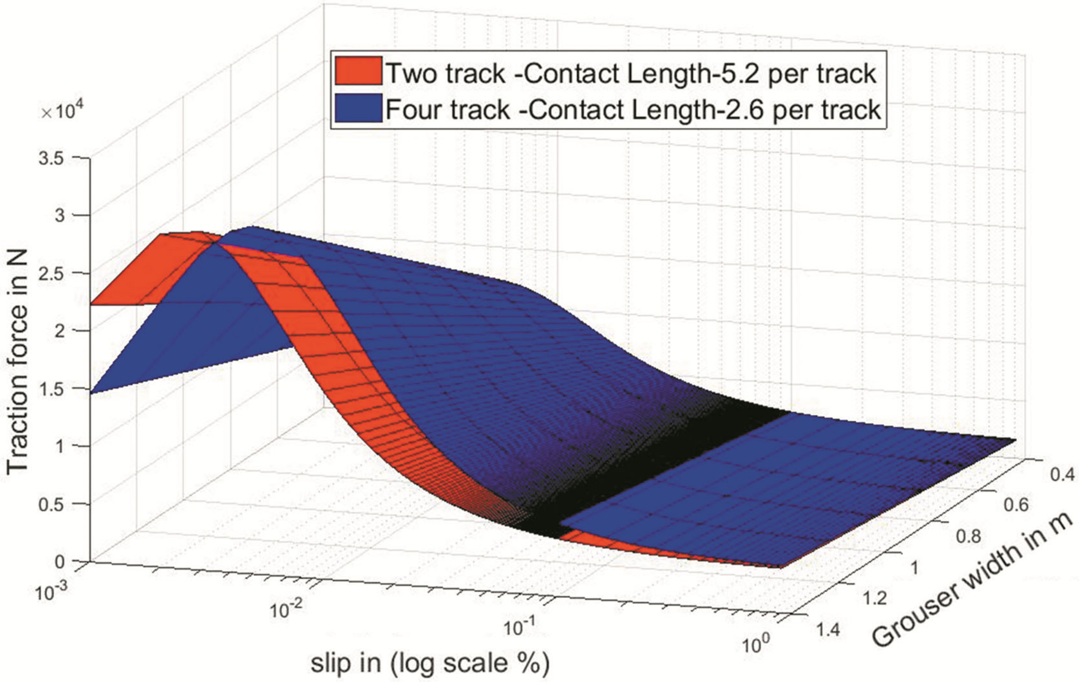

Fig. 13 — Traction force comparison w.r.t slip and grouser width

slip and grouser width. Both the four-track short-length and two-track long-length configurations, with the same effective contact length of 5.2 m of the vehicle, are compared. It's evident that the traction force developed by the soil for the four-track short-length configuration consistently exceeds that of the two-track long-length configuration across various grouser widths.

Conclusion

This study aimed to develop a tracked mining vehicle to improve traction in soft soil environments. Experimental and finite element analysis methods were employed to analyse soil-grouser interaction, focusing on sinkage of the mining vehicle. The results indicate that maintaining a vehicle contact bearing pressure below 6 kPa reduces bulldozing and gradient resistance forces. Comparative analyses were conducted between two-track long-length and four-track short-length configurations, keeping the contact area and bearing pressure constant on soft soil. Multi-Body Dynamic (MBD) analyses showed that the four-track short-length configuration achieved superior traction compared to the two-track configuration, consistent with the drawbar pull analysis in the MBD model. To validate the recommendations of MBD analysis, a mathematical model based on reliable governing equations suitable for deep-sea soft soil conditions was utilised. The mathematical simulation results further supported the superiority of the four-track short-length configuration in generating higher traction forces compared to the two-track long-length configuration across all track parameters of the deep-sea mining vehicle. Based on the outcomes of this study, it is proposed to adopt the four-track configuration for deep-sea mining vehicles to enhance traction capabilities and develop an efficient vehicle for collecting polymetallic nodules in challenging soft seabed environments.

Acknowledgements

The authors sincerely thank the Ministry of Earth Sciences, Government of India, for funding the technology development programs of the Deep Sea Mining group of the National Institute of Ocean Technology (NIOT) and for encouraging us to carry out the research work.

Conflict of Interest

The corresponding author, on behalf of all co-authors, confirms that there are no conflicts of interest associated with this work.

Ethical Statement

This research represents original work by the corresponding author, with no sensitive or proprietary data used. All experiments, simulations, and analyses were conducted in strict accordance with established scientific guidelines and institutional policies.

Author Contributions

CJ: Conceptualization, FEA and MBD analysis, and drafting the original manuscript; RM: Guided the analysis and contributed to writing, reviewing, and editing the manuscript; KG & GAR: Reviewed the work and provided the necessary research facilities.

References

1 Deepak C R, Shajahan M A, Atmanand M A, Annamalai K, Jeyamani R, *et al.*, Developmental Tests on the Underwater Mining System Using Flexible Riser Concept, *Proc 4th Ocean Mining Symposium of Int Soc of Offshore and Polar Engineers*, Szczecin, Poland, September 23-27, 2001, pp. 94-98.

2 Rajesh S, Gnanaraj A A, Velmurugan A, Ramesh R, Muthuvel P, *et al.*, Qualification tests on Underwater Mining System with Manganese Nodule Collection and Crushing Devices, *Proceedings of the 9th International Society of Ocean and Polar Engineering Conference (ISOPE), Ocean Mining Symposium*, Maui, Hawaii, USA, June 19-24, 2011, pp. 110-115.

3 Janarthanan C, Chandran V, Sundaramoorthi V, Viswanath B O, Dinesh Kumar D, *et al.*, Development and Testing of Locomotion Trials on Soft Sea Bed Soil and System Performance Checks of Experimental Undercarriage System, *Proceedings of the 28th International Society of Ocean and Polar Engineering Conference (ISOPE)*, Sapporo, Japan, June 10-15, 2018, pp. 152-159.

4 Janarthanan C, Chandran V, Sundaramoorthi V, Viswanath B O, Venketesan K, *et al.*, Deep water locomotion tests of polymetallic nodule mining machine, *OCEANS 2022*, Chennai, India, 21-24 February 2022, 2022, pp. 1–8.

5 Khadge N H, Geotechnical Properties of deep sea sediments from the Central Indian Ocean Basin, *Indian J Geo-Mar Sci*, 21 (1992) 80-82.

6 Khadge N H, Geotechnical Properties of surface sediments in the INDEX Area, *Mar Georesour Geotechnol*, 18 (2000) 251– 258.

7 Song L, The physical properties of surface sediments in oceanic polymetallic nodule, *Acta Oceanol Sin*, 6 (1999) 47–54.

8 Bekker M G, Introduction to terrain-vehicle systems, 1st edn, (University of Michigan Press), 1969, pp. 846. ISBN-13: 978-0472041442

9 Morgan N, Cathie D, Pyrah J & Steward J, Tracked Subsea Trencher Mobility and Operation in Soft Clays, *Proceedings of the Seventeenth International Offshore and Polar Engineering Conference*, July 1-6, Lisbon, Portugal, 2007, pp. 1366-1373.

10 Kim H-W, Hong S, Choi J-S & Lee T H, An experimental study on tractive performance of tracked vehicle on cohesive soft soil, *Proceedings of the Fifth ISOPE Ocean Mining Symposium*, Tsukuba, Japan, 15–19 September 2003, pp. 139-143.

11 Schulte E & Schwarz W, Simulation of tracked vehicle performance on deep sea soil based on soil mechanical laboratory measurements in bentonite soil, *Proceedings of the Eighth ISOPE Ocean Mining Symposium*, Chennai, India, 20–24 September 2009, 2009, p. 276.

12 Dai Y, Yin W & Ma F, Nonlinear multi-body dynamic modeling and coordinated motion control simulation of deep-sea mining system, *IEEE Access*, 7 (2019) 86242–86251. https://doi:10.1109/ACCESS.2019.2925714

13 Wang M, Wang X, Sun Y & Gu Z, Tractive performance evaluation of seafloor tracked trencher based on laboratory mechanical measurements, *Int J Nav Archit Ocean Eng*, 8 (2) (2016) 177–187. https://doi.org/10.1016/j.ijnaoe.2016.01.005

14 Benoit O, Gotteland P & Quibel A, Prediction of trafficability for tracked vehicle on broken soil: real size tests, *J Terramechanics*, 40 (2) (2003) 135–160. https://doi.org/10.1016/j.jterra.2003.10.003

15 Lyasko M, Multi-pass effect on off-road vehicle tractive performance, *J Terramechanics*, 47 (5) (2010) 275-294. https://doi.org/10.1016/j.jterra.2010.05.006

16 Ma W B, Rao Q H, Xu F & Feng K, Impact compressive creep characteristics of simulative soil for deep-sea sediment, *Mar Geotechnol*, 34 (4) (2016) 356–364. https://doi.org/10.1080/1064119X.2014.1003160

17 Sun P, Lu H, Yang J, Liu M & Li S, Numerical Simulation of Multi-Parameter Interaction Between Track Plate of Deep-Sea Mining Vehicle and Seabed Sediments, *Proceedings of the 32nd International Ocean and Polar Engineering Conference*, Shanghai, China, 5–10 June 2022, 2022, p. 49.

18 Xu Z, Liu Y, Yang G, Xia J, Dou Z, *et al*., Research on contact model of track-soft sediment and traction performance of four-tracked seabed mining vehicle, *Ocean Eng*, 259 (2022) p. 111902. https://doi.org/10.1016/j.oceaneng.2022.111902

19 Xia M, Lu H, Yang J & Sun P, Multi-body dynamics modeling and straight-line travel simulation of a four-tracked deep-sea mining vehicle on flat ground, *J Mar Sci Eng*, 11 (5) (2023) p. 1005. https://doi.org/10.3390/jmse11051005

20 Grebe H & Schulte E, Determination of Soil Parameters Based on the Operational Data of a Ground Operated Tracked Vehicle, *Proceedings of the sixth ISOPE Ocean Mining Symposium*, Changsha, Hunan, China, October 9-13, 2005, 2005, pp. 149–156.

21 Wong J Y, *Theory of Ground Vehicles*, 3rd edn, (John Wiley & Sons, New York), 2001, pp. 559.

22 Varshney N, Janarthanan C, Muthuvel P, Ramesh N R, Deepak C R, *et al*., Virtual modelling and navigation controls of underwater mining machine, *International Symposium on Ocean Electronics*, SYMPOL, Kochi, India, 23-25 October 2013, 2013, pp. 202–207. https://doi.org/10.1109/sympol.2013.6701931

23 Janarthanan C, Kuttikrishnan G, Sundaramoorthi V, Chandran V & Ramadass G A, Deep Sea Soil Sinkage Simulation and Experimental Studies for Development of Deep Water Mining Machine, *Mar Technol Soc J*, 56 (1) (2022) 72–82. https://doi.org/10.4031/MTSJ.56.1.1

24 B S Simulia, Installation and extraction of spudcans using Abaqus/Explicit, *Abaqus technology brief*, June 2010, pp. 4.

25 Tho K K, Leung C, Chow Y & Swaddiwudhipong S, Eulerian Finite-Element Technique for Analysis of Jack-Up Spudcan Penetration, *Int J Geomech*, 12 (2012) 64-73. https://doi.org/10.1061/(ASCE)GM.1943-5622.0000111

26 Müller F M, Pauly M, Gross M, Keiser R & Wicke M, Physics-Based Animation, In: *Point-Based Graphics*, A volume in The Morgan Kaufmann Series in Computer Graphics, edited by Gross M & Pfister H, (Elsevier, Amsterdam, Netherlands), 2007, pp. 340-387, https://doi.org/10.1016/B978-012370604-1/50008-0

27 Kim H, Soohyn H & Choi J S, Comparative study on tracked vehicle dynamics on soft soil: Single-body dynamics vs. multi-body dynamics, *Proceedings of the Fifth ISOPE Ocean Mining Symposium*, Tsukuba, Japan, 15–19 September 2003, 2003, p. 132.

28 Lee C, Kim H W, Hong S & Kim S M, A study on the driving performance of a tracked vehicle on an inclined plane according to the position of buoyancy, *Proceedings of the Ninth ISOPE Ocean Mining Symposium*, Maui, HI, USA, 19–24 June 2011, 2011, p. 104.

29 Dai Y, Yin W & Ma F, Nonlinear multi-body dynamic modeling and coordinated motion control simulation of deep-sea mining system, *IEEE Access*, 7 (2019) 86242–86251. https://doi.org/10.1109/ACCESS.2019.2925714

30 Li L & Jue Z, Research of China's Pilot-miner In the Mining System of Poly-metallic Nodule, *Proceedings of the Sixth ISOPE Ocean Mining Symposium*, Changsha, China, 9–13 October 2005, 2005, p. 124.

31 Janosi Z & Hanamoto B, Analytical determination of drawbar pull as a function of slip for tracked vehicles in deformable soils, *Proceedings of the 1st International Conference on Terrain-Vehicle Systems*, Turin, Italy, 1967, 1967.