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Modeling, calibration and validation of tractive performance for seafloor tracked trencher

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Abstract

Shear stress–displacement model is very important to evaluate the tractive performance of tracked vehicles. A test platform, where track segment shear test and plate load test can be performed in bentonite–water mixture, was built. Through analyzing existing literatures, two shear stress–displacement empirical models were selected to conduct verification tests for seafloor suitability. Test results indicate that the existing models may not be suitable for seafloor soil. To solve this problem, a new empirical model for saturated soft-plastic soil (SSP model) was proposed, and series shearing tests were carried out. Test results indicate that SSP model can describe mechanical behavior of track segment with good approximation in bentonite–water mixture. Through analyzing main external forces applied to test scaled model of seafloor tracked trencher, drawbar pull evaluation functions was deduced with SSP model; and drawbar pull tests were conducted to validate these functions. Test results indicate that drawbar pull evaluation functions was feasible and effective; from another side, this conclusion also proved that SSP model was effective.

Keywords: Shear stress–displacement; SSP model; Tractive performance; Drawbar pull; Seafloor tracked trencher

0. Introduction

Seafloor tracked trencher (STT) equipped with jetting or cutting systems is used to bury submarine pipelines or cables. The mobility of trencher requires both sufficient traction and sufficient bearing capacity. The working capacity and bearing capacity of trencher depend principally on vehicle dimensions and soil property of seafloor surface. Tracked walking mechanism has a larger contact area with ground than wheeled running gear, so, it can provide better floatation and larger traction forces. By shearing seafloor surface soil, trencher's tracks can produce traction force that propels trencher forward; and the available traction must be sufficient to enable trencher to overcome various resistances including vehicle weight due to slope/vehicle pitch and compaction resistance which arises as a consequence of creation of ruts.

For tracked vehicles, evaluation of trafficability of the unknown-terrain and optimization of traction potential are essential and lots of research works have been done. Janosi and Hanamoto deduced equations by means of the Land Locomotion Soil Value System and a soil shear stress–strain relationship to predict the drawbar pull of track laying vehicles as a function of slippage (Janosi and Hanamoto, 1961). Baladi and Rohani documented a mathematical model for predicting the steering performance of track-laying vehicles in environments ranging from soft soils to hard surfaces (Baladi and Rohani, 1978). Watanabe and Kitano presented a theoretical and experimental analysis of steering performance of articulated tracked vehicles on level ground, and developed a mathematical

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model for predicting the steerability of articulated units (Watanabe and Kitano, 1986). To evaluate the trafficability of seafloor soil, some research works have been done. Schulte developed a shear stress–displacement relationship function for seafloor tracked vehicle based on deep sea soil situ measurements and bentonite soil lab measurements (Schulte et al., 2003). Hyung-Woo Kim analyzed underwater tracked vehicle's dynamics on extremely soft soil by using Euler Parameters and investigated the hydrodynamic effects on performance of tracked vehicle (Hong et al., 2002). Most solutions were proposed mainly for terrestrial field, and it is unknown whether these models can be used to evaluate tractive performance of STT directly.

In this paper, a test platform was setup to analyze the existing shear stress–displacement models. Based on comprehensive analysis of deformation behavior of seafloor sediments and track segment shearing tests, a new empirical shear stress–displacement model was proposed. To validate the new empirical model, a series of track segment shearing tests were performed in seafloor soil substitute made of bentonite–water mixture. Through analyzing the main external forces acting on STT, a mathematical analysis model of tractive performance was deduced with the new shear stress–displacement empirical model. Experimental investigation was carried out to verify the validity of the tractive performance model by a scaled test model in soil bin.

1. Track–soil interaction

The attainable locomotion of a tracked trencher over seafloor surface is mainly based on shear forces which developed between track links and surface soil in longitudinal directions. Soil conditions have significantly effects on tractive performance. Mechanical behavior of seafloor surface soil varies considerably under a wide variety of environmental conditions; composition, porosity and water content can affect bulk soil mechanical behavior relative to vehicle/terrain dynamics. According to early surveys and tests, seafloor surface soil shows a similar characteristic as a type of "undisturbed firm soil" (Wu et al., 2009; Li and Li, 2010). This type of soil exhibits characteristics like that shear stress initially increased sharply and reached a "hump" of maximum shear stress ($\tau_{\max}$) at a particular shear displacement, and then decreased and approached a relative constant residual value (τ_{res}) with further increase in shear displacement, as shown in Fig. 1.

1.1. Existing empirical models

Shear stress–displacement relationship is the most important factor to evaluate trafficability and working capacity of a tracked vehicle. Many shear stress–displacement models have been developed for various types of soils. Based on numerous test measurements, Wong and his colleagues suggested to use the following equation to calculate effects of soil conditions on tractive performance,

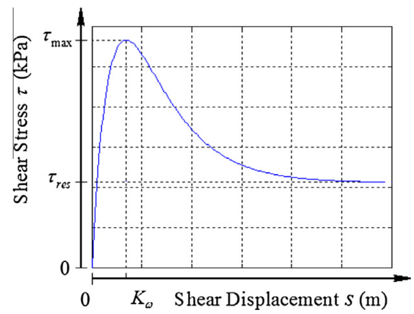

Fig. 1. Shear curve exhibiting a peak and constant residual shear stress.

and this equation has become the most widely used empirical shear stress–displacement model for tractive performance evaluation of land vehicles (Wong and Preston-Thomas, 1983; Wong, 2001).

$$\tau = \tau_{\max} K_r \{1 + [1/(K_r(1-1/e)) - 1]e^{(1-s/K_\omega)}\} \cdot (1 - e^{-s/K_\omega}) \tag{1}$$

where K_r is the ratio of residual shear stress τ_{res} to maximum shear stress $\tau_{\max}$; K_ω is the shear displacement where the maximum shear stress $\tau_{\max}$ occurs.

For evaluating the trafficability of seafloor surface soils, Schulte developed a relationship on the basis of lab measurements in bentonite–water mixture (Schulte et al., 2003),

$$\tau = \tau_{\max}\left[e^{-b(s-K_\omega)} + K_r\right]\frac{1}{(f \cdot e^{-d \cdot s} + 1)} \tag{2}$$

where b is the fading exponent; f is the soil fracture factor; and d is the soil fracture exponent.

1.2. Pressure–sinkage model

Due to elastic or plastic deformation, the sinkage of tracked vehicle is the main source of power and traction force loss. Seafloor soil, in fact, has a combined elastic–plastic character. If the seafloor soil is considered to be homogeneous within the depth of interest, pressure–sinkage relationship may take the forms shown in Fig. 2 (1), and it can be characterized by the following empirical equation proposed by Bekker (1969).

$$z = \left[\frac{p}{(k_c/b) + k_\phi}\right]^{\frac{1}{n}} = \left[\frac{W_{load}}{(k_c/b + k_\phi) \cdot b \cdot l}\right]^{\frac{1}{n}} \tag{3}$$

where z is the plate sinkage; p is the normal pressure; b is the plate width or smaller dimension of the contact area; k_c is the cohesive soil modulus; k_ϕ is the friction soil modulus; n is the soil deformation exponent; W_{load} is the normal load; l is the plate length.When $z = 1$,

$$p = \left(\frac{k_c}{b} + k_\phi\right)z^n\bigg|_{z=1} = \frac{k_c}{b} + k_\phi = K_b \tag{4}$$

where K_b can be described as the soil pressure deformation modulus.