Climbing Motion Analysis of the Mobile Automatic Lifting and Lowering Dual-Arm Tower Assembly Device on Dirt Roads

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Abstract. This paper systematically analyzes the motion characteristics of the mobile automatic lifting and landing double-arm clamping tower assembly device in soft terrain and slope environments through theoretical analysis and numerical research. First, a force model for the tracked chassis was established to analyze the nonlinear relationship between the depth of track front end sinking and ground pressure under soft soil conditions, and the influence of soil parameters on the sinking depth was explored. Next, the variation of pushback resistance under different slope angles was investigated. Finally, a model of the tower assembly device was established using RecurDyn, and slope climbing simulations were conducted to obtain the driving torque curve of the drive wheels. The results show that soil type and slope angle significantly affect track sinking depth and pushback resistance. Pushback resistance decreases with the increase of slope angle under sloped conditions. The research results provide a theoretical basis for the optimization design and enhancement of the device's adaptability to complex terrains.

Keywords: Mobile tower assembly device; tracked chassis; soft soil; bulldozing resistance; dynamic analysis

1 Introduction

The mobile automatic lifting and lowering dual-arm tower assembly device, as a new type of tower assembly equipment, offers flexibility and efficiency, making it suitable for constructing transmission towers in complex terrains. However, the motion stability and operational performance of the device in such environments still face numerous technical challenges [1]. Liu et al. [2] established a pressure distribution model for tracked vehicles on soft ground, Ding et al. [3] developed a prediction model for the sinking and sliding of tracked vehicles during turns, and Dong et al. [4] and Said Al-

Milli et al. [5] created a comprehensive framework to evaluate the stability of tracked vehicles on soft soil.

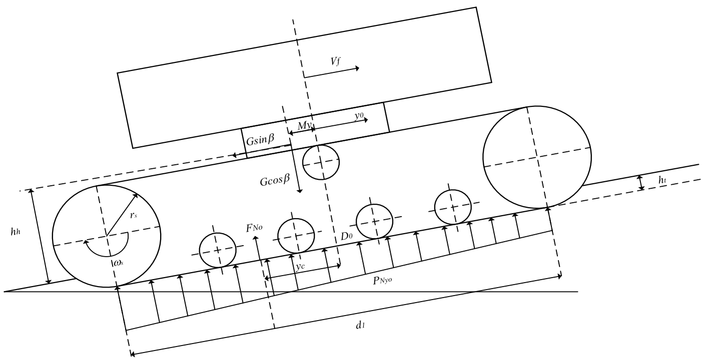
This paper focuses on the mobile tower assembly device, using theoretical analysis and numerical simulation to primarily analyze the motion characteristics of the tracked chassis on soft, sloping surfaces, revealing the influence of soil parameters and slope angles on the device's motion performance. The research findings not only provide a theoretical basis for the optimization of tower assembly devices but also offer valuable reference for the development of similar equipment in complex terrains.

2 The Climbing Dynamics Analysis of the Tower Assembly Device

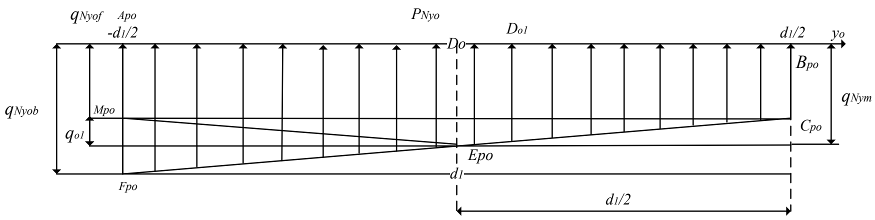
When the tracked chassis of the tower assembly device moves in a straight line on soft ground, the tracks will sink into the soil to some extent under the influence of gravity. The contact pressure per unit area of the tracked chassis has a nonlinear relationship with the sinking depth of the tracks [6], which is influenced by the soil's cohesive deformation modulus k_c and frictional deformation modulus k_ϕ,and expressed as:

$$p_e = \left(\frac{k_c}{b} + k_\phi \right) h_t^n \tag{1}$$

When the tower assembly device climbs uphill, the point of action of the pressure exerted by the tracked chassis on the slope surface changes, and the pressure varies with the slope angle [7]. The distribution of the ground pressure ratio on the outer track of the tracked chassis is shown in Fig.1. In the figure: y_o represents the positive direction of the y-axis in the horizontal reference frame yDx; y_c represents the lateral offset of the supporting force from the center of the tower assembly device; P_{yNo} represents the ground pressure on the bottom of the outer track of the tower assembly device; q_{Nyob}、q_{Nyom}、q_{Nyof} represent the normal loads borne by the respective parts of the outer track of the tower assembly device; F_{No} represents the total normal load borne by the outer track of the tower assembly device.



(a)



(b)

Fig. 1. Schematic Diagram of Ground Pressure Ratio of the Tracked Chassis of the Tower Assembly Device.

The average unit length of the outer track of the tower assembly device along the horizontal direction is denoted as the total normal load F_{No}, and the ratio of d_l to the contact length. The forward pressure q_{Nyof} and the rear pressure q_{yNob} at the ends have an offset compared to the average pressure q_{o1}, which causes the normal load to change in direction. The normal load is expressed as:

$$\begin{cases} F_{yo} = F_{No} - \dfrac{6\left(G\cos\beta M_y + G\sin\beta h_h\right)}{d_1^2} y_o \\ F_{No} y_c = \dfrac{1}{6} q_{o1} d_1^2 \end{cases} \tag{2}$$

Under the average load condition, the ground pressure ratio of the inner and outer tracks of the tracked chassis of the tower assembly device is:

$$P_{Nys} = \frac{F_{Ns}}{bd_1} - \frac{6}{bd_1^3}\left(G\cos\beta M_y + G\sin\beta h_h\right) y_s \tag{3}$$

When driving on a slope, the center of pressure of the tower assembly device shifts backward, causing the ground pressure ratio at the rear to be greater than at the front, resulting in an increased sinking depth. The ground pressure ratio at the front and rear ends of the tracked chassis is calculated through the integration of the front and rear contact areas as follows:

$$\begin{cases} P_{Nyqs} = \dfrac{2F_{Ns}}{3bD_t} - \dfrac{2}{d_1 bD_t}\left(G\cos\beta M_y + G\sin\beta h_h\right) \\ P_{Nyhs} = \dfrac{2F_{Ns}}{3bD_x} + \dfrac{2}{d_1 bD_x}\left(G\cos\beta M_y + G\sin\beta h_h\right) \end{cases} \tag{4}$$

The sinking depth at the front end of the tracked chassis of the tower assembly device is:

$$h_{tqs}^{'} = \left[P_{Nyqs} \middle/ \left(\frac{k_c}{b} + k_\phi \right) \right]^{\frac{1}{n}} \tag{5}$$

From equations (4), and (5), it can be concluded that the push-pull resistance generated by the soil on the tracked chassis of the tower assembly device when driving on a sloped soft surface is [8,9]:

$$F'_{ps} = b\left(0.67ch'_{tqs}k'_c + 0.5h'^2_{tqs}rk'_r\right) \tag{6}$$

When the tower assembly device experiences lateral mass offset, the load on the contact area between the tracked chassis and the ground is uniformly distributed. The traction force F_{js} of the inner and outer tracks of the tower assembly device is given by:

$$\begin{cases} F_p = b\left(0.67ch'_{tqs}k'_c + 0.5h'^2_{tqs}rk'_r\right) \\ k'_c = \left(N'_c - \tan\varphi'\right)\cos^2\varphi' \\ k'_r = \left(\dfrac{2N'_r}{\tan\varphi'} + 1\right)\cos^2\varphi' \\ \tan\varphi' = 2/3\tan\varphi \end{cases} \tag{7}$$

In the formula, N'_c and N'_r represents the bearing capacity coefficient for localized shear failure of the sandy foundation.

The driving resistance experienced by the tower assembly device F'_{ffs} is:

$$\begin{cases} F'_{ffs} = F'_{fm1s} + F'_{ps} + F'_{is} \\ F'_{js} = F'_{ffs} \\ F'_{is} = f_i F_{Ns} \end{cases} \tag{8}$$

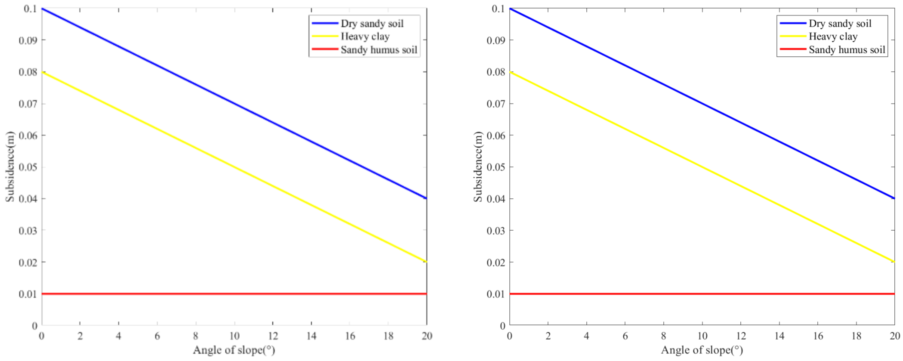
3 The Impact of Different Soils on Track Sinking Depth

Through the formula derivation, the sinking depth at the front end of the track is related to the soil parameters, as shown in Table 1. By substituting the parameters of the mobile automatic lifting and landing double-arm clamping tower assembly device and the soil parameters into the formula, the theoretical sinking depth at the front end of the track can be obtained [10]. The relationship between the sinking depth at the front end of the track and the slope angle is shown in Fig.2.

Table 1. Soil parameters.

Soil species	Humidness (%)	n	K_c (kN·m$^{-(n+1)}$)	K_φ (kN·m$^{-(n+2)}$)	c（kPa)	φ (°)	ρ (g/cm^3)
Dry sandy soil	0	1.1	0.95	1523.43	1.04	28	1.8

Sandy humus soil	11	0.9	52.53	1127.97	4.83	20	1.9
Heavy clay	25	0.13	2.7	1555.95	68.95	34	2.15

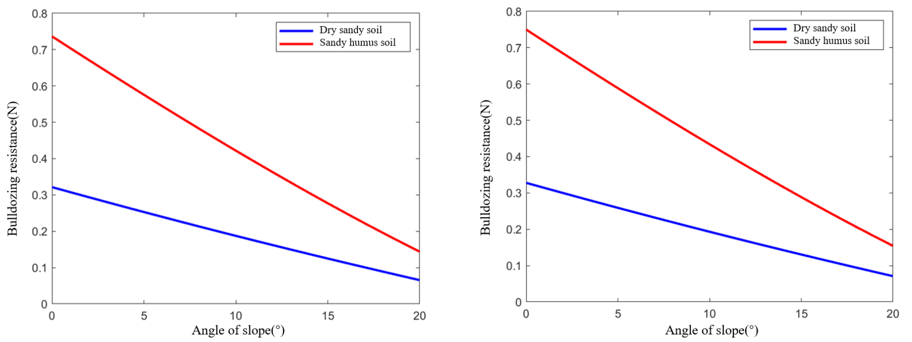


(a)The sinking depth at the front end of the left track.

(b)The sinking depth at the front end of the right track.

Fig. 2. Relationship between the sinkage of the front end of the track and the slope angle.

From Fig.2, it can be observed that as the slope angle increases, the sinking depth at the front end of the inner and outer tracks of the tower assembly device decreases. The sinking depth at the front end of the tracks in dry sandy soil is greater than that in sandy humus soil. On heavy clay surfaces, the sinking depth at the front end of the tracks is negligible, meaning the push-pull resistance experienced by the tower assembly device is zero. Additionally, the sinking depth of the right track is greater than that of the left track.



(a)The relationship between pushing resistance and slope Angle at the front end of left track

(b) The relationship between pushing resistance and slope Angle at the front end of right track

Fig. 3. Relationship between bulldozing resistance at the front end of track and slope angle.

The relationship between the push resistance at the front end of the tracks and the slope angle is shown in Figure 3. The trend of push resistance aligns with that of the sinking depth: as the slope angle increases, the sinking depth decreases, and the push resistance decreases. The push resistance of the left track is less than that of the right track.

4 Tower Assembly Device Slope Climbing Simulation

This chapter will conduct a simulation of the mobile automatic lifting and landing double-arm clamping tower assembly device in RecurDyn. In line with the design requirements of the mobile automatic lifting and landing double-arm clamping tower assembly device, the tracked chassis model is established in RecurDyn using the High-Speed Track Module (HM). The model established is shown in Fig.4.

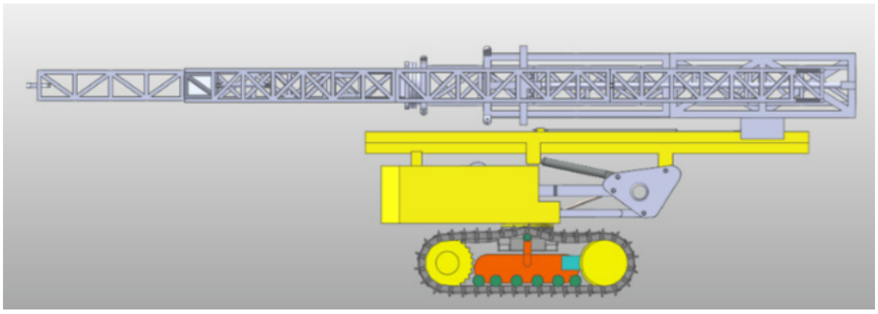


Fig. 4. The dynamic model of mobile automatic lifting and landing tower assembly device with floor-typed double horizontal arm holding pole.

According to the design requirements, the mobile automatic lifting and landing double-arm clamping tower assembly device should be able to climb a 20-degree slope. This section focuses on the obstacle-crossing simulation of the tower assembly device. First, a 4-meter-long 20-degree slope is created in the virtual environment, with the road surface condition set as hard terrain. The tower assembly device completes the slope climbing simulation at a speed of 0.5 m/s, with the driving wheel function defined as -STEP(TIME,1,0,6,84D). The simulation process of climbing the slope is depicted in Fig.5, the analysis results of the changes of torque and center of mass during the climbing process are shown in Fig.6.

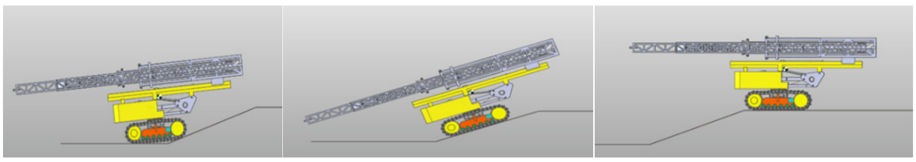


Fig. 5. Climbing process of mobile automatic lifting and landing tower assembly device with floor-typed double horizontal arm holding pole.

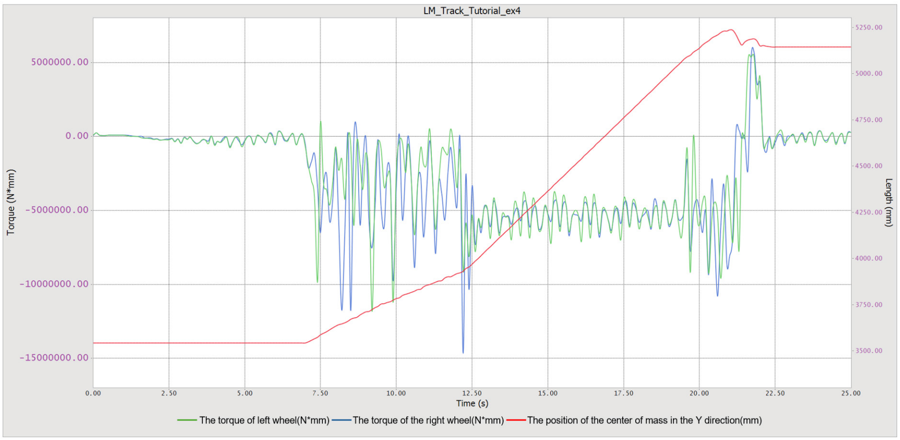


Fig. 6. The changes of slope road torque and centroid of mobile automatic lifting and landing tower assembly device with floor-typed double horizontal arm holding pole.

The analysis results indicate that the fluctuation trend of the driving torque is consistent with the motion process of the tracked chassis, and the mobile automatic lifting and landing double-arm clamping tower assembly device can meet the requirement of climbing a 20-degree slope.

5 Conclusions

This paper focuses on the motion characteristics of the mobile automatic lifting and landing dual-arm tower assembly device. Under soft slope road conditions, a detailed study was conducted on the force analysis of its tracked chassis, including the sink depth and pushing resistance. Through theoretical derivation, numerical analysis, and simulation analysis, the impact of soil parameters and slope angle on the device's motion performance was revealed, as well as the driving torque provided by the tracked chassis during the climbing process. The results show that variations in soil density and slope angle significantly affect the sink depth and pushing resistance at the front end of the track, with clear differences in sink depth and pushing resistance when the device moves on different soils.

This study provides a theoretical basis for the performance optimization and design improvement of the mobile tower assembly device under complex terrain conditions and offers a reference for the development and application of similar equipment in the future. Further research can combine experimental validation and multi-field coupling analysis to expand the applicability and reliability of the findings.

Acknowledgements

This work was financially supported by the State Grid Liaoning Electric Power Supply Co. (2024YF-83).

References

1. Lee Won kyo, F., Mun Sung Duk, S., Shin Kooyong, T.: Development of Eco-friendly Electric Transmission Towers in KEPCO. KEPCO Journal on Electric Power and Energy (2019).
2. Weiwei Liu, F., Kai Cheng, S.: An Analytical Model for Predicting Ground Pressure under a Rigid-Flexible Tracked Vehicle on Soft Ground. Mathematical Problems in Engineering (2020).
3. Zhao Ding, F., Yaoming Li, S., Zhong Tang, S.: Theoretical model for prediction of turning resistance of tracked vehicle on soft terrain. Mathematical Problems in Engineering (2020).
4. Al-Milli, Said, F., Lakmal D. Seneviratne, S. and Kaspar Althoefer, T.: Track–terrain modelling and traversability prediction for tracked vehicles on soft terrain. Journal of Terramechanics 47.3, 151-160. (2010).
5. Youkou Dong, F., Dingtao Yan, S., Xiaowei Feng, T.: Stability of tracked vehicles on soft grounds under multidirectional loading conditions. Canadian Geotechnical Journal. 60(11), 1743-1755. (2023).
6. Murakami, H., F., K. Watanabe, S., and M. Kitano, T.: A mathematical model for spatial motion of tracked vehicles on soft ground. Journal of terramechanics 29.1, 71-81. (1992).
7. Edwin P., F., K. Shankar, S., and K. Kannan, T.: Soft soil track interaction modeling in single rigid body tracked vehicle models. Journal of terramechanics 77, 1-14. (2018).
8. Wong Jo Yung. Theory of ground vehicles, 3th edn. John Wiley & Sons, Hoboken (2001).
9. Wong Jo Yung. Theory of ground vehicles, 4th edn. John Wiley & Sons, Hoboken (2008).
10. Li, Qiang, F., and Xintian Liu, S.: A soil mechanical model for deformable grounds under the dynamic action of high-mobility tracked vehicles. Recent Patents on Engineering 17.2, 92-104. (2023).