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Simulation analysis of interaction mechanism between triangular track and ground based on Bekker theory

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Abstract. Based on the Bekker theory, the relationship between the triangular track mechanism and the ground is analyzed in this paper. Based on this analysis, the interaction between the track plate and the soil was simulated under two working conditions: uniform straight climbing and spot turn is simulated in the ABAQUS, and the relationship between the stress change and the deformation of the track shoe under various working conditions was clarified. The relationship between the soil settlement amount under the track shoe and the ground pressure was obtained, and the change regulation between the triangular track mechanism and the ground action was obtained. Therefore, interaction analysis model of triangle crawler mechanism and elastic-plastic ground under various working situations was established. Based on the perfected prophase research, the important basic data can be provided for the optimal design of the triangle tracked mechanism.

Key words. Bekker theory, triangular track, soil settlement, ground pressure.

1. Introduction

For engineering vehicles, the walking environment is more complex, and they need to face various situations in actual walking. The traditional four-wheel walking wheel is unable to meet practical demands, and the inflexible traditional track cannot cope with different complicated landforms. Therefore, a more flexible walking device is needed to assist in going forward [1]. The triangular track developed on this is not only adaptable to complex landforms, but also as flexible as general wheeled devices. At present, the triangular track, with broad space in development [2], is gradually

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applied to many fields, such as industry, agriculture, and military. Triangular track is inevitably the trend of the development of future engineering vehicle walking devices [3]. Bearing its own and the vehicle's weight, triangular track will cause deformation of the ground in actual walking. The part that subsides meets Bekker theory and, on this basis, should be analyzed by the theory [4]. Currently, triangular track has been put into use in more than 50 countries and regions around the world [5], and there are a number of relevant agencies, including the famous American companies such as MATRACKS and TRACK [6], being involved in the development of triangle track. At present, the research on triangular track mainly focuses on light devices, and its application in this area is quite mature. However, the research of heavy equipment remains insufficient and is still in the initial stage [7]. In the future, triangular track will definitely become an important component of walking devices. Based on previous studies carried out by experts and scholars, this thesis conducts a simulation analysis on the interaction process between triangular track and the ground with Bekker theory, expecting to contribute to the development of triangular track system.

2. Analysis of triangular track structure and ground effects

2.1. The structure and function of triangular track system

Triangular track shows the future development direction of walking devices. It is a kind of modernized walking device [8] which is established partly based on wheeled structure and partly on track structure, and has both advantages of the two structures. The structure of the triangular track is shown in Fig. 1. Analyzed with the stability of triangles in actual process of walking, this structure has advantages in moving obtained from wheeled structure and stability from track structure. It is able to perform on different landforms with greater walking advantages [9].

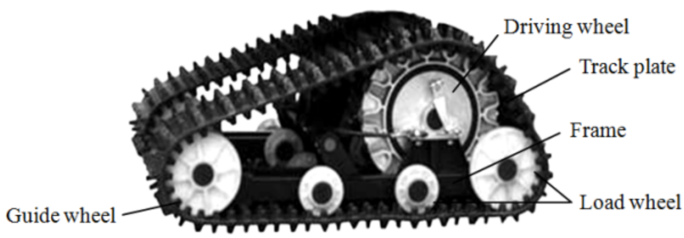

Fig. 1. Structure of a type of triangular track

2.2. Ground stress analysis based on Bekker theory

The direct contact between track and soil will produce ground pressure. Ground pressure is an important parameter of triangular track. It has an important impact on factors like traction and resistance in using triangular track devices. The ground pressure of triangular track is affected by many factors, such as track flexibility, thrust wheel data, and track rigidity. The influence of the number of thrust wheels is determined by factors such as the center distance of adjacent thrust wheels S and the pitch of tracks t. When walking on the ground, the track will cause ground pressure and settlement, which in turn, will react to the track. This kind of situation belongs to the category of Bekker theory. Therefore, it is necessary to study the mechanism of the interaction between triangular track and the ground with this theory. Triangular track is a kind of narrow-pitch track. When it is moving on the ground, its pressure can be regarded as in linear distribution. To study the mathematical model of track ground pressure on this basis, the model should be simplified first. During the operating process, the ground pressure of the track is related to its own gravity, mechanical resistance, center-of-gravity position, ground slope, velocity and other factors. The angle that the track forms with the ground and shift of the center of gravity can be negligible [10]. Under the conditions above, the stress analysis of triangular track was carried out.

The interaction between the track and the ground accords with Bekker theory, thus the soil is subjected to the pressure of the structure when it is acting on the ground. Here the term, soil pressure bearing capacity, can be introduced. It refers to the functional relationship between the depth that the track subsides and the compressive stress of the soil under the action of the triangular track. This thesis studies the walking process of triangular track in the sand. Because of the poor bearing capacity when walking in the sand, the track will be resisted by the ground subsidence. In the stress analysis of this process, it is not difficult to find that the effects of the stress are in a dynamic change. On this account, the stress can be treated in segments. In the movement of triangular track, it will lead to ground deformation under resistance and the resistance F_{c} can be calculated by the formula

$$F_{\mathrm{c}} = \frac{2b}{(n+l)\,K^{\frac{1}{n}}} \left(\frac{W}{A}\right)^{\frac{n+1}{n}} \tag{1}$$

.

Here, l is the track length, b is its width, the single track width is denoted as n, K is constant, W is the action force perpendicular to the plane and A is the area on which the force acts.

In actual moving process, the loading process can be quantified using the formulae (2) and (3). During the process, formula (4) can be obtained by combining Bekker theory and the and shear force deformation relationship by Jia Nokia. On this basis, supposing the track is under pressure both from movement and from interaction with the ground, put $j = ix$ (j being the shear displacement and i the track slip rate) and $\sigma = W/(2bL)$ into the formula, then formula (5) can be obtained:

$$\mathrm{d}F_r = \tau b \, \mathrm{d}x \,, \tag{2}$$

$$F_r = 2b \int_0^l \tau \, \mathrm{d}x \,, \tag{3}$$

$$\tau = (C + \sigma \tan \varphi) \left(1 - \mathrm{e}^{\frac{j}{k}}\right) , \tag{4}$$

$$F_r = (A_\mathrm{c} + W \tan \varphi) \left[1 - \frac{K}{iK} \left(1 - \mathrm{e}^{\frac{iL}{k}}\right)\right] . \tag{5}$$

Here, τ is the shear stress, C denotes the bond coefficient, σ is the soil compressive stress, and φ is the soil internal friction angle.

The formulae above show that the greater gravity the triangle track carries, the more pressure it exerts on the ground, and the deeper the ground subsides. When it is within the range of soil bearing capacity, the shear stress of triangular track will increase to further enhance the resistance over triangular track, which can be transformed into a kind of thrust from the perspective of structure in design. Based on this, simulation on the walking performance of triangular track can be further improved.

3. Transient analysis of interaction between track shoe and ground

Because the non-linear factors such as soil are contained in the model, the force relationship between the crawler and the soil is more complex [11]. The transient analysis step of the interaction between the track shoe and the soil is different from the ordinary transient analysis process. Since the stiffness setting of the contact pair has a direct effect on the convergence of the analysis results, so it is necessary to complete the model simulation through repeated selection and debugging of the experimental materials.

3.1. Establishment of finite element model

During the operation of the track, the deformation of the soil is caused by its squeezing on the ground, and the deformation of the soil also made the track suffered the change of the normal force and tangential force from the soil. The relationship between the force and the deformation of the two is mainly transmitted through the track shoe, the one-piece rubber track shoe would suffer the adjacent track shoe tension, the pressure and the shearing force of the thrust wheel, the soil would suffer the anisotropic force from track shoe, resulting in deformation, thus led to the reaction to the track shoe, so the track board would suffer tangential force and normal force from the soil.

The material of the track shoe in the track shoe-soil model is rubber, and the isotropic constitutive relationship in line elasticity is used in ABAQUS to simulate the track shoe. Its modulus of elasticity E is 5.5 MPa, Poisson's ratio ν is 0.43, tensile strength is 1.26 MPa, yield strength is 8.21 MPa, and density ϱ is 1.05 g/cm^3.

The soil material model is more complex because the deformation of the soil is not only related to the size of the load, but will be different because of the different stress path, which can engender elastic deformation and plastic deformation, the Drucker-

Prager material model in the ABAQUS can meet the requirements above. Drucker-Prager material model is generally used for granular materials; in the calculation, the total deformation is divided into elastic deformation and plastic deformation to be solved separately, Hooke's law is used in the calculation of elastic deformation part, while the plasticity theory is adopted in the calculation of plastic deformation part. The main characteristic parameters of the selected Drucker-Prager material model include modulus of elasticity–19.6 kPa, Poisson's ratio 0.23, internal friction angle 17.7 ° and the cohesive force 1.917 N.

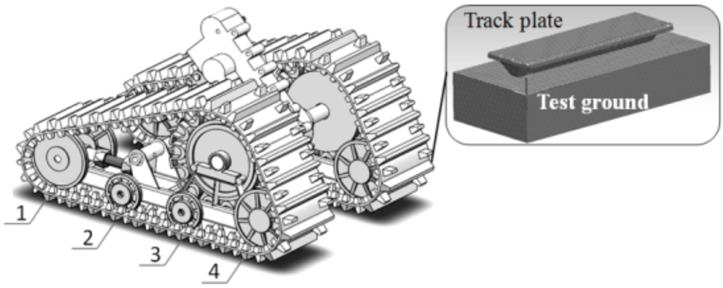

Fig. 2. Three-dimensional model of triangular track system

The rubber track shoe 1, the track shoe 2, the track shoe 3 and the track shoe 4 under the thrust wheel are taken as the research objects. The interaction model between the rubber track shoe and the soil are shown in Fig. 2. The interaction between the track shoe and the soil is simulated by ABAQUS, so the relationship between the track plate and the soil is analyzed for we have acquired results like the track shoe and soil deformation diagram and stress diagram. The relationship between the track plate and the soil was analyzed. The preliminary study has clarified the interaction relationship between the crawler plate and the soil under the stationary condition and the uniform linear motion condition. The continuous analysis and study on the two basic working conditions of climbing and turning are required in this paper, then the mechanism of the interaction between the triangle track and the ground is clarified further.

3.2. Simulation on climbing condition

Tracked vehicles conduct uniform straight climbing at 30 ° angle, and the stress condition of track shoe is relatively complex. The stress condition of the every track shoe under the thrust wheel remains the same as that in the uniform linear motion. The main forces are the pressure of the wheel on the track wheel, the friction force of the thrust wheel on the track shoe in an inclined direction, the tension between the track shoes in an inclined direction, as well as the vertical tension between the track shoes. For thrust wheel, its time of passing the track shoe is about 0.6 seconds under the conditions of constant speed, and the a transient analysis of 0.6 seconds on track shoe-ground model is implemented. The simulation results are shown in the following figure. Figure 3 shows the stress diagram of each track plate. The relationship between the stress change and the displacement change of each track shoe is shown in Fig. 4. It can be seen from the figure that the stress extremes of the track plates show a tendency to increase linearly from the front to the rear along the crawler's rolling direction, and the displacement extremes also show the same trend. Under the 30° angle uniform straight climbing condition, the track shoe's stress and deformation variable rate is slightly higher than that of uniform linear motion condition according to the different locations. Therefore, greater interaction force need be exerted between the track and the ground to enable the triangular track to maintain a uniform linear climbing state.

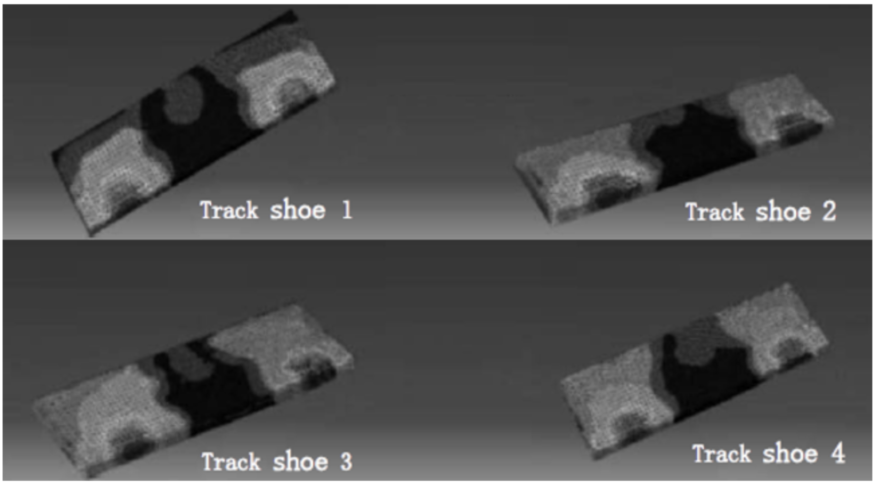

Fig. 3. Stress nephogram of track shoe under climbing condition

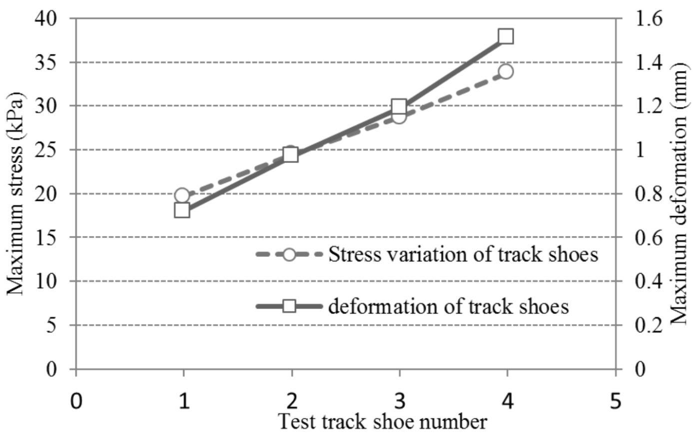

Fig. 4. Variation of stress and deformation of track shoe under climbing condition

At the same time, the change of soil settlement and the distribution of ground pressure under each track plate under this condition were analyzed. The soil settlement and ground pressure nephogram under different track plate were obtained, the relationship between the settlement and ground pressure of soil is shown in Fig. 5. As is shown in the picture, the maximum soil settlement and ground pressure under the track plate showed an increasing trend from front to back, especially soil settlement of track shoe 4 changed obviously. Under this condition, the maximum soil settlement is 1.05–1.08 times lager than the soil settlement under uniform linear motion condition. The maximum ground pressure is 1.01–1.02 times lager than ground pressure under uniform linear motion condition. The change rate of soil ground pressure and settlement is relatively fast under climbing condition.

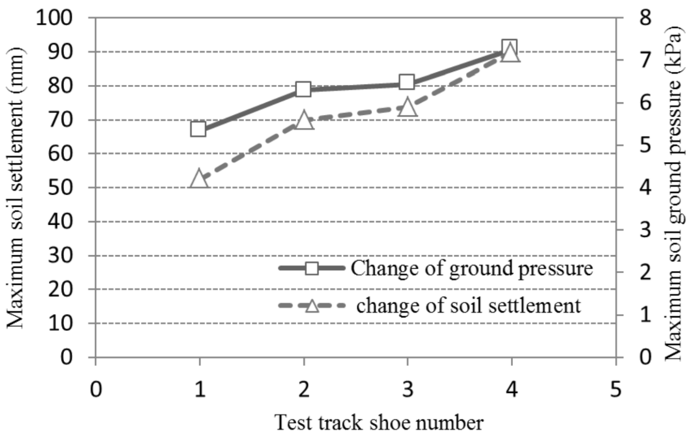

Fig. 5. Variation of soil ground pressure and settlement under climbing condition

3.3. Simulation on spot turn condition

In the simulation experiment under spot turn condition, the outside track shoe of steering process is taken as the object. The main forces are the pressure of the wheel on the track wheel in three directions, the tension between the track shoes in three directions. For support wheel, its time of passing the track shoe is about 1.0 seconds under the conditions of spot turn, and the a transient analysis of 1.0 seconds on track shoe-ground model is implemented. The simulation results are shown in the following figure. Figure 6 shows the stress diagram of each track plate. The relationship between the stress change and the deformation change of each track shoe is shown in Fig. 7. According to the picture, we can conclude that the stress extremum and displacement extremum of each track plate did not show obvious increased tendency, the maximum stress and maximum deformation of each track plate were basically the same.

Pointing to this condition, soil settlement and ground pressure of each track plate are simulated and analyzed. The soil settlement and ground pressure nephogram under different track plate were obtained, the relationship between the settlement and ground pressure of soil is shown in Fig. 8. As is shown in the picture, the maximum soil settlement and ground pressure under the track plate showed the trend of decreasing first and then increasing without showing a trapezoidal distribution. The

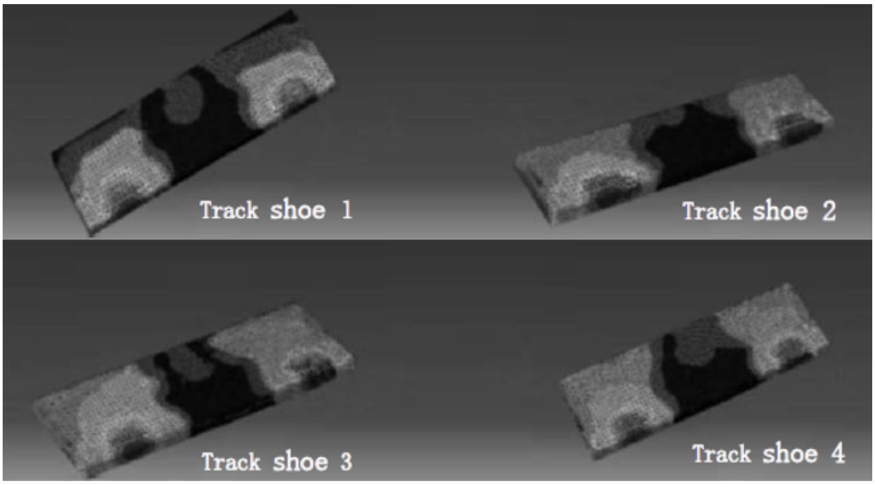

Fig. 6. Stress nephogram of track shoe under spot turn condition

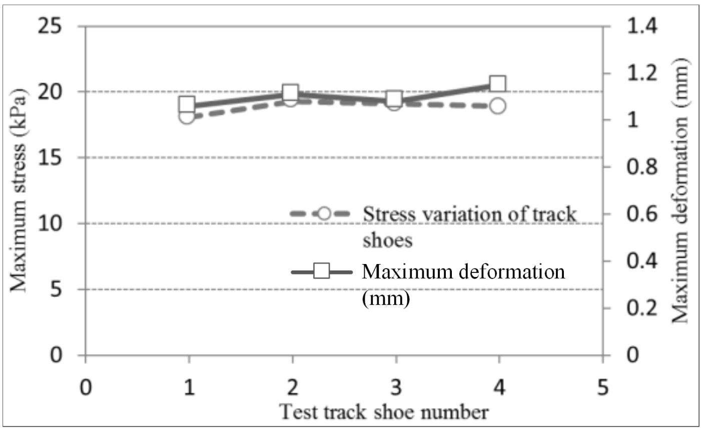

Fig. 7. Variation of stress and deformation of track shoe under spot turn condition

variation trend of soil ground pressure and settlement under the track is consistent, average value is 1.06–1.72 times lager than the value under uniform linear motion condition. According to the above analysis, it can be concluded that the triangle track mechanism still meets the relationship between the soil ground pressure and the settlement based on Bekker theory in the case of turning process.

4. Conclusion

Aiming at the analysis of the design process of triangular track, this research worked out the basic parameters by analyzing its stress condition through Bekker theory and from the perspectives of statics and dynamics. Combining with Bekker theory, relevant parameters can be worked out on the basis of force analysis. Af-

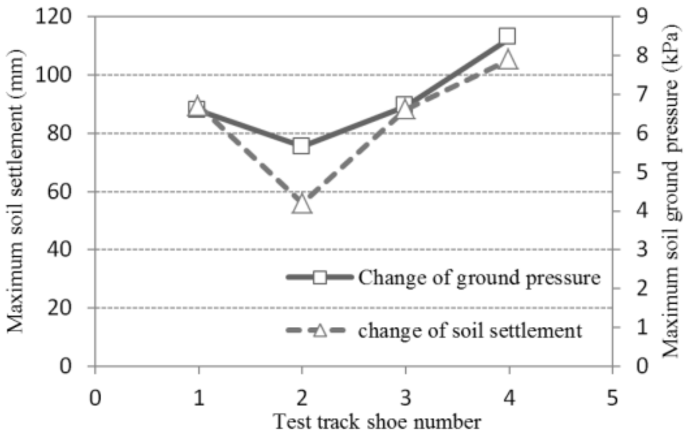

Fig. 8. Variation of soil ground pressure and settlement under spot turn condition

terwards, corresponding structural analyses and simulation analysis of interaction mechanism between triangular track and ground can be carried out. Analyzing based on the research above, according to the basic theory of ground mechanics and the contact theory, the finite element analysis method was used to establish the mechanical model of the interaction between the track shoe and the soil under the two basic conditions: uniform linear climbing at 30° angle and the spot turn in the ABAQUS model, and the numerical simulation analysis was carried out, so as to provide further supplement and improvement on the previous relevant research. Through the analysis of the numerical simulation results, the relationship between the stress change and the displacement change of the track shoe under the two conditions was defined. The relationship between the soil settlement amount under the track shoe and the ground pressure was obtained, and the change regulation between the triangular track mechanism and the ground action was obtained. Therefore, the triangle track mechanism-elastic-plastic ground interaction analysis model under various working situations was established, and based on the perfected prophase research, the important basic data can be provided for the optimal design of the triangle tracked mechanism.

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