Effect of grouser height on tractive performance of single grouser shoe under different moisture contents soil

Jun Ge[#1], Xiulun Wang[#*2], Koji Kito[#], Hiroshi Nakashima[+]

Graduate School of Bioresources, Mie University, Tsu 514-8507, Japan;

* College of Engineering, Anhui Agricultural University, Hefei 230036, China;

+ Graduate School of Agriculture, Kyoto University, Kyoto 606-8501, Japan

1 gejunahau@163.com, 2 wang@bio.mie-u.ac.jp

Abstract—The soil condition and grouser height of the track equipped on the crawler vehicle have a significant influence on tractive performance. The purpose of this study is to investigate the grouser height affect on tractive performance of a single grouser shoe under different soil moisture contents. Ten different moisture contents of clay soil were provided in this study. For each moisture contents, a penetration test, a direct shearing test, as well as density and moisture content measurements were performed for deriving the soil parameters. Based on the soil parameters under different moisture contents and the 3-dimensional shearing model proposed in this study, the tractive performance of a single grouser shoe was analyzed. The results showed that the track vehicles with a shorter grouser performed better under a dry soil, and performance with longer grouser tracks was better under higher moisture content soil.

Keywords: Single grouser shoe, 3-dimenstional shearing model, Tractive performance, Tracked vehicle.

I. INTRODUCTION

Tracked vehicles have been attracting attention from numerous researchers. Because tracked vehicles have a larger contact area with the ground, this results in providing better floatation and traction than wheeled ones, which makes them suitable for off-road terrains. Tracked vehicles have been applied in many fields, such as mining, forestry, agriculture, planetary exploration, military and construction [1]. For tracked vehicles, the tractive performance, including thrust, resistance and traction, is very important for their terrain trafficability, and it is influenced by both the factors of vehicles and terrains [2]. Significant research has already been concluded regarding the tractive performance of tracked vehicle. A. Bodin (1999) developed a tracked vehicle to study the influence of vehicle parameters on tractive performance in soft terrain. The experimental result showed that nominal ground pressure has a significant effect on the tractive performance of tracked vehicles in that soil [3]. Robert Grisso et al. (2006) reported an empirical model for tractive performance of rubber-tracks in agricultural soils [4]. W.Y. Park et al. (2008) developed a computer simulation program TPPMTV (Tractive Performance Prediction Model for Tracked Vehicles) for predicting the tractive performance of a flexible tracked vehicle [5]. Modest I. Lyasko (2010) investigated the effects of multi-pass on the tractive performance of the off-road vehicles. He concluded that the multi-pass has a significant effect on tractive performance and should be quantified using a new method proposed in that research [6].

Based on the former research by other researchers, soil and the track conditions are critical factors for predicting the tractive performance of tracked vehicles. Modest I. Lyasko (2010) presented an analysis and quantitative evaluation about the effect of soil conditions on tractive performance for off-road wheeled and tracked vehicles. He pointed out that to accurately calculate the tractive performance of a vehicle in a given soil condition, soil properties and parameters and their changes as functions of soil moisture content and density should be taken into account [7]. J. Liu et al. (2008) reported that the grouser height and slip are more critical factors for the motion performance than grouser spacing and thickness when the test soil was loose sand under 0.282% moisture content [8]. R. N. Yong et al. (1978) introduced the idea that the maximum drawbar pull for rigid track can be obtained through a large spacing of the grousers, and the rate of increase of thrust for the multiple grouser system in view of variation in grouser spacing is seen to be a useful indicator of track efficiency [9].

For this experiment, the authors wanted to investigate the effect of grouser height on tractive performance of a Single Grouser Shoe (SGS) under soils with different Moisture Content (MC). Some work has appeared previously on this aspect, such as Yang Yang et al. (2014), who used a novel wheel with an actively actuated lug to carry out an experiment, and the experimental result showed that the wheel with larger lug sinkage length can generate larger drawbar pull because the lug can penetrate deeper into the soil and provide larger contact area between the lug and soil [10]. There are also some similar research, like movable lug, has been carried out [11][12]. However, to date, a study on the effect of the grouser height on tractive performance of SGS under different MC soil has not been found.

Authors have already done the research which was about the effect of soil adhesion on tractive performance of SGS, and also have studied the aspect of comparing tractive performance of steel and rubber SGS under different soil MCs. For these prior two studies, grouser height was fixed as a constant value for predicting tractive performance of SGS in different soil conditions. Soil conditions significantly affect the tractive performance of tracked vehicles. In this study, 10 different MCs for the same test soil, which was adjusted by adding water into the soil, were applied for measuring soil parameters. For each MC soil, the soil parameters were measured. Then, the soil parameters were obtained and the data processing was carried out using fitted curves to quantify the soil parameters of the MC ranged from 8.5% to 53%. In order to predict the tractive performance of SGS with different grouser height, a SGS model and a 3-dimentional shearing model were proposed.

II. THEORY BACKGROUND

For tracked vehicles, there are four methods which could be used for predicting its tractive performance: experimental, empirical, semi-empirical and computer-aided method such as the Finite Element Method (FEM) and the Discrete Element Method (DEM) [1] [13]. In this study, the semi-empirical method which was initially developed by M.G. Bekker was adopted. This paper focuses on the tracked vehicles with the track of SGS, and one kind of single grouser shoe model was proposed as a research model, shown as figure 1.

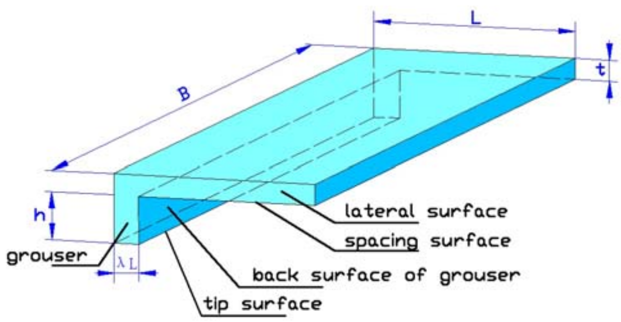

Fig.1. Single grouser shoe model.

When the track is driven by the sprocket on which is applied by torque, a shearing motion happens on the interaction surface between soil and track. In this process, the soil shearing failure type, such as a logarithmic spiral, determines the shearing force and area to the same grouser shoe of track. For predicting the tractive performance of SGS, a 3-dimentional shearing model was proposed in this study and the details are shown as figure 2.

Base on the 3-dimentional shearing model, the force which acted on the SGS is shown as figure 3. The SGS bears the load of the tracked vehicle and then presses on the terrain or soil beneath the spacing surface and tip surface. This load was denoted by W and the equilibrium equation which can be expressed as equation (1).

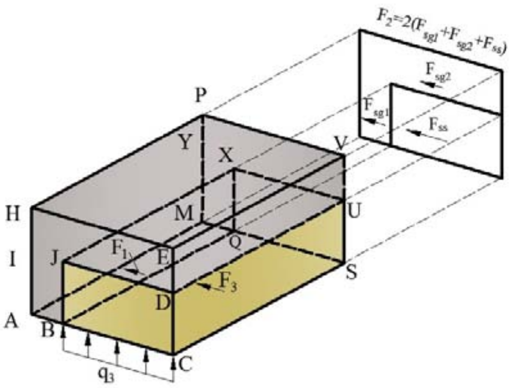

Fig.2. 3-dimentional shearing model.

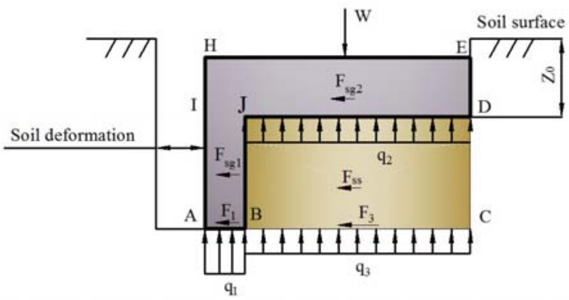

Fig. 3. The force acted on SGS.

$$W = L\left(k_c + Bk_\varphi\right)\left\{\lambda\left(h+Z_0\right)^n + (1-\lambda)\,Z_0{}^n\right\} \quad (1)$$

Where L is the shoe pitch; B is the width of SGS; h is the height of grouser; λ is the ratio of grouser thickness to shoe pitch; k_c is the cohesion modulus in Bekker`s equation; $k_\varphi$ is friction modulus in Bekker`s equation; n is the exponent of sinkage in Bekker`s equation; Z_0 is the sinkage of SGS.

The load results in sinkage which gives rise to running resistance. The running resistance is denoted by R and it is expressed as equation (2).

$$\mathrm{R} = \frac{\mathrm{k_c} + \mathrm{Bk}_\phi}{\mathrm{n}+1}\left\{(\mathrm{h}+\mathrm{Z}_0)^{(\mathrm{n}+1)}\lambda + \mathrm{Z}_0{}^{(\mathrm{n}+1)}(1-\lambda)\right\} \quad (2)$$

When the shearing action of the SGS is initiated between the SGS and the soil, thrust is generated by the shearing of the soil as shown in figure 2. In this figure, the thrust is the resultant of F_1, F_2 and F_3. F_1 is the shearing force on the tip surface of grouser (surface ABQM in figure 2) and it is expressed as equation (3). F_2 is the shearing force of the grouser shoe’s lateral sides, it consists of 3 parts: the shearing force of grouser lateral side (surfaces ABJI and MQHY in figure 2) F_{sg1} expressed as equation (4); the shearing force of spacing’s lateral side (surfaces IDEH and YUVP in figure 2) F_{sg2} expressed as equation (5); the shearing force of the lateral side of the soil beneath the spacing surface (surface BCDJ and QSUH in figure 2) F_{ss} expressed as equation (6). F_3 is the shearing force on the bottom surface of soil beneath the spacing surface (surface BCSQ in figure 2) and it is expressed as the equation (8).

$$\mathrm{F}_1 = \lambda\mathrm{LB}\left(\mathrm{C_a} + \mathrm{q_1}\tan\delta\right) \quad (3)$$

Where C_a is the soil adhesion; q_1 is the pressure on grouser tip surface; δ is the soil external friction angle.

$$F_{sg1} = \lambda hL\left[C_a + \tan\delta\tan\left(45-\frac{\varphi}{2}\right)\left\{\frac{\gamma_t(2Z_0+h)}{2}\tan\left(45-\frac{\varphi}{2}\right)-2C\right\}\right] \quad (4)$$

Where φ is the soil internal friction angle and γ_t is the soil density; C is soil cohesion.

$$F_{sg2}=\begin{cases} Z_0L\left[C_a+\tan\delta\tan\left(45-\varphi/2\right)\left\{\frac{\gamma_t Z_0}{2}\tan\left(45-\varphi/2\right)-2C\right\}\right] & Z_0\le t \\ tL\left[C_a+\tan\delta\tan(45-\varphi/2)\left\{\frac{\gamma_t(2Z_0-t)}{2}\tan(45-\varphi/2)-2C\right\}\right] & Z_0\ge t \end{cases} \tag{5}$$

Where t is the thickness of shoe spacing.

$$F_{ss}=(1-\lambda)hL\left[C+\left\{q_2+\frac{\gamma_t(h+2Z_0)}{2}\right\}\tan^2\left(45-\varphi/2\right)\tan\varphi-2C\tan\left(45-\varphi/2\right)\tan\varphi\right] \tag{6}$$

Where q_2 is the pressure on spacing surface of shoe (surface JDUH in figure 2).

Then, the F_2 can be denoted by equation (7) as follow.

$$F_2=2\left(F_{sg1}+F_{sg2}+F_{ss}\right) \tag{7}$$

$$F_3=(1-\lambda)LB(C+q_3\tan\varphi) \tag{8}$$

Where q_3 is the pressure on soil failure surface (surface BCSQ in figure 2).

Then, the thrust can be expressed as equation (9).

$$F=F_1+F_2+F_3 \tag{9}$$

The surplus of thrust from running resistance is the traction which was denoted by T and expressed as equation (10).

$$T=F-R \tag{10}$$

Ⅲ. EXPERIMENTAL METHOD

This study was a research on the effect of grouser height on tractive performance of SGS under different MC soils. For this purpose, the soil parameters of different MCs have to be first known, and then, based on the theory mentioned in section II, the tractive performance of SGS in those soils may be determined.

The method for measuring the properties of the soil in this study was almost the same as the bevameter technique. It has two parts: a penetration test and a direct shearing test.

3.1 Penetration test

The penetration test device was designed by the authors for this experiment and the diagrammatic illustration is shown as figure 4. The device consists of a soil bin, frame body, and penetration unit.

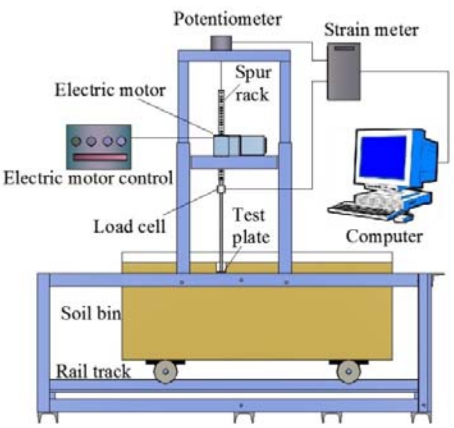

Fig.4. The diagrammatic illustration for penetration test device

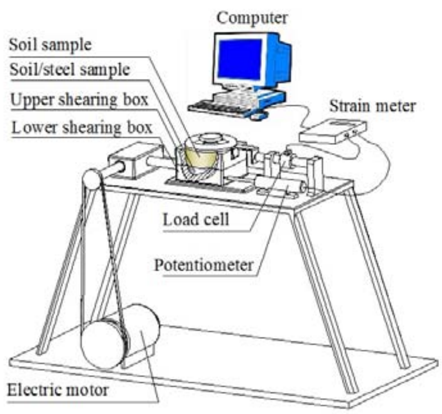

Fig.5. The direct shearing test device

As shown in this figure, the dimensions of the soil bin are 245 mm × 400 mm × 1000 mm. It can be slid on the rail with wheels by manual operation. There were two steel penetration test plates and the dimensions are 2.5 mm × 19 mm × 30 mm, 2.5 mm × 25 mm × 30 mm, respectively. When a test plate penetrated into the soil, the reaction force and displacement of the test plate were measured by load cell and potentiometer, respectively.

3.2 Direct shearing test

The shear test device used in this study was the direct shearing test device, shown as figure 5.

The main part of this device is the shearing box which is consists of an upper box and a lower box. The soil sample was always filled in the upper box; meanwhile, the lower box contained soil or steel circular plate to measure the adhesion/cohesion and friction angle. There is a screw rod driven by an electrical motor to push the lower shearing box moving forward. When the shearing was initiated, the shearing force was detected by a load cell and the shearing displacement was measured by a potentiometer.

3.3 Other conditions

The soil used in this experiment was clay soil and a sieve was used for eliminating particles which had a diameter greater than 2mm after being dried by the sun. For this clay soil, ten different MCs were applied for soil parameters investigation. The specific MCs were as follow: 8.6%, 12.5%, 17.2%, 22.3%, 27.7%, 28.9%, 34.2%, 39.4%, 47.0% and 54.4%.

According the previous research, the thinner the grouser thickness the higher the traction performance under the same grouser height. So in this study, the grouser thickness was set as 0.9 cm which means the ratio of thickness to shoe pitch was 0.1. In order to predict the tractive performance of SGS, the dimensions of SGS and the vertical load on SGS have to be known, and the details are shown in table 1.

Table 3 The dimension of single grouser shoe and vertical load

Item	Specific content
Pitch of shoe (L)	9 cm
Width of shoe (B)	15 cm
Thickness of spacing	3 cm
Grouser thickness	0.9 cm
Vertical load (W)	22.5 kg

Ⅳ. EXPERIMENTAL RESULTS AND DISCUSSION

For each moisture content soil, the penetration test, direct shearing test, density and MC measurement were performed. For every soil parameter obtained in penetration test and direct shearing test, a fitted curve was used for analyzing the soil parameters at the moisture contents ranging from 8.6% to 53%. Based on these soil parameters and 3-dimentional shearing model, the tractive performance such as thrust, running resistance and traction of SGS can be determined.

4.1 Soil parameters

The soil parameters are shown as table 4.

Table 4 The physical properties of experimental soil

No.	moisture content(%)	C (kPa)	φ (deg.)	Ca (kPa)	δ (deg.)	Kc (kgf/cm^{n+1})	KΦ (kgf/cm^{n+2})	n	Density (kg/m^3)
1	8.6	0.38	42.6	0.37	20.9	0.003	0.198	0.75	956.3
2	12.5	0.6	39.2	0.48	21.3	0.052	0.192	0.69	966.4
3	17.2	0.89	38.8	0.61	20.0	0.110	0.133	0.63	955.2
4	22.3	1.05	29.2	0.89	20.2	0.095	0.117	0.60	890.5
5	27.7	1.98	28.4	1.57	15.8	0.165	0.067	0.53	836.8
6	28. 9	2.01	26.7	1.70	15.2	0.176	0.090	0.47	854.3
7	34.2	1.78	28.4	1.35	17.8	0.180	0.035	0.60	869.0
8	39.4	1.27	27.1	0.88	18.9	0.164	0.073	0.53	975.2
9	47.0	0.83	25.1	0.71	18.7	0.128	0.156	0.51	1404.6
10	54.4	0.62	11.1	0.61	9.5	0.034	0.063	0.33	1609.1

4.2 The prediction results

Based on the obtained soil parameters and the approach introduced in section II, the tractive performance of SGS with different grouser height under different MCs could be determined. The thrust of SGS with different grouser heights is shown as figure 11.

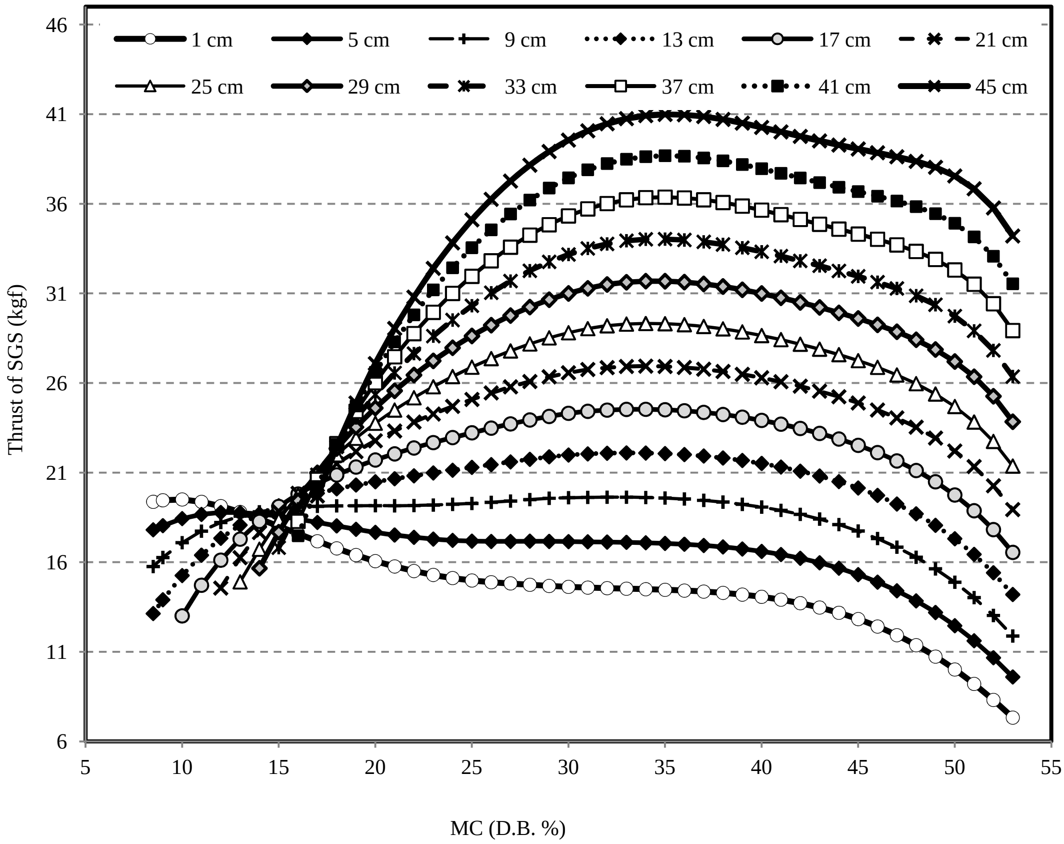

Fig.11. The thrust of SGS with different grouser height

The thrust is the resultant of the shearing force on the interaction between the SGS and the soil. In this figure, the thrust of SGS with 1 cm grouser height had large values when the MC was at the low level and it continuously decreased with the increase of MC until the end of the experiment. The thrusts of SGS with 5 cm and 9 cm grouser height increased with the increase of MC before 15%. After that, the 5 cm one decreased with the increase of MC, meanwhile, the 9 cm one lightly increased with the increase of MC until 35%, and then, it turned to decrease with the increase of MC until the highest MC level. Thrusts of SGS with other grouser heights had similar trends to each other. They all had a peak value at 35% MC. Before the peak value, they increased with the increase of MC, but after it, they started to decrease with the increase of MC until the highest MC level. This figure shows that around 15% MC was a conjunction of all these thrusts. Before 15% MC, the thrust of SGS with shorter grouser height performed better, but the inverse situation occurred after 15%. That is because the low MC soil had a relative greater friction angle, and as the increase of MC the higher grouser height could provide a relatively bigger area of interaction with SGS and soil.

Running resistances of SGSs with different grouser heights were also determined and are shown as figure 12.

From this figure, except the grouser height 1 cm and 5 cm, the thrusts of SGS had similar trends to each other. When the grouser height was less than 5 cm, the thrusts of SGS increased with the increase of MC before 35%, and then, it barely varied from 35% to 47% MC. After that, it started to rapidly increase with the increase of MC. When the grouser height was higher than 5 cm, the running resistance of SGS decreased with the increase of MC at first, and then, it barely changed with the increase of MC until a rapid increase at the highest MC level. In this figure, the thrust of the SGS with a shorter grouser height was always less than that of a higher grouser height at any given MC. The reason is that the SGS with shorter grouser height had a smaller sinkage under the same vertical load.

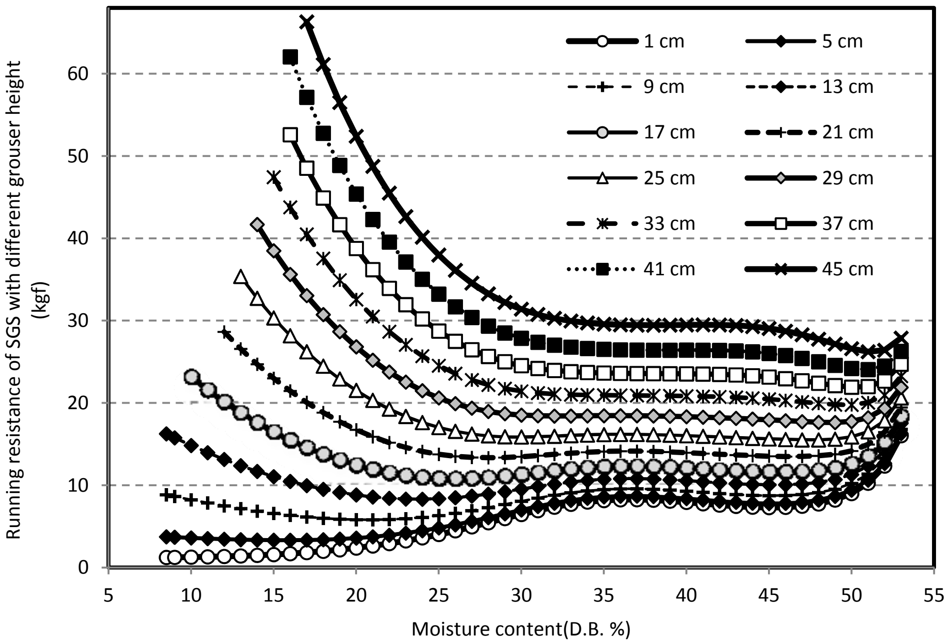

Fig.12. The running resistance of SGS with different grouser height

Traction is the difference of thrust to running resistance. Therefore, the traction of SGS with different grouser heights could be determined and is shown as figure 13.

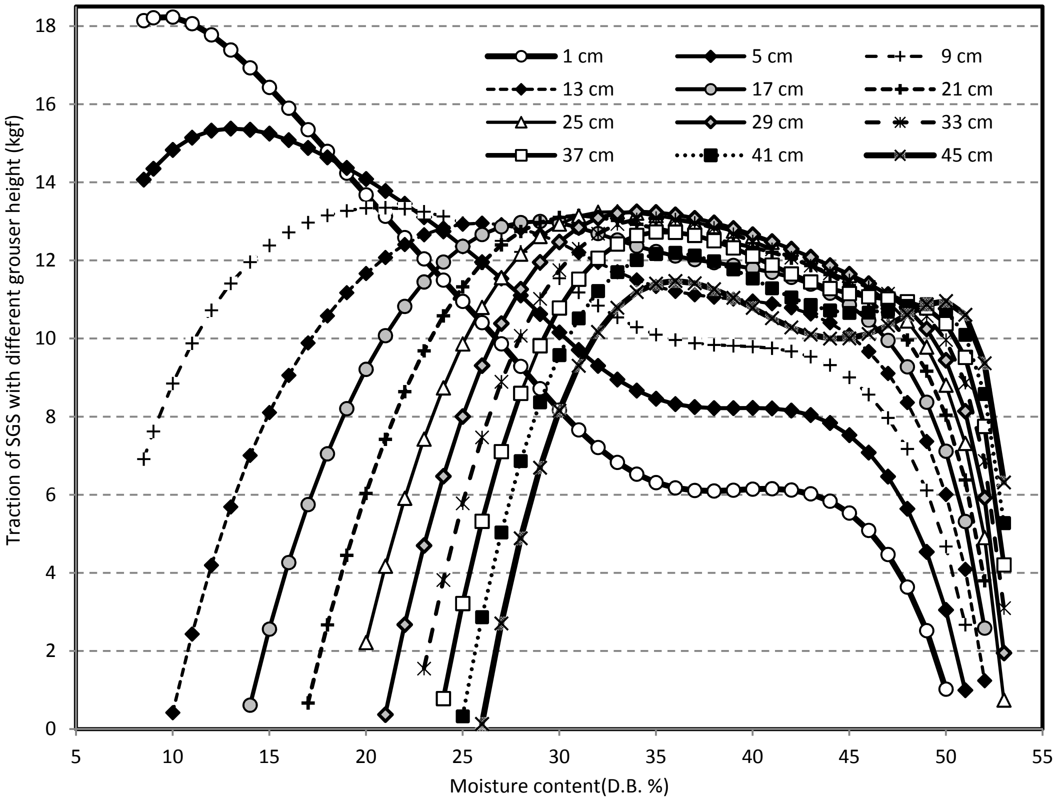

Fig.13. The traction of SGS with different grouser height

Obviously, the tractions of SGS with different grouser heights had more complex situations than that of thrusts and running resistances. When the grouser heights were 1 cm, 5 cm and 9 cm, the tractions of SGS had similar trends. They all increased with the increase of MC until the respective peak value when the MC was at a low level. Then, they decreased with the increase of MC except for the MC ranging from 36% to 42% where they barely changed with the increase of MC. When the grouser height ranged from 13 cm to 37 cm, the tractions of SGS increased with the increase of MC until their respective peak values during relatively low MC levels. After that, they decreased lightly with the increase of MC, and at the stages near the highest MC levels they decreased rapidly. When the grouser heights were 41 cm and 45 cm, the traction of SGS also increased with the increase of MC until the first peak value, and then, it decreased with the increase of MC until the trough value. After this trough value, it began to increase with the increase of MC until the second peak value. Like the other grouser heights' tractions, it rapidly decreased with the increase of MC at the stages near the highest MC levels.

Among these results, an optimum grouser height which can generate maximum traction exists for any given MC. Figure 14 shows the result of optimum grouser height under every MC ranging from 8.5% to 49%, and also graphs the results of correspondent tractive performances.

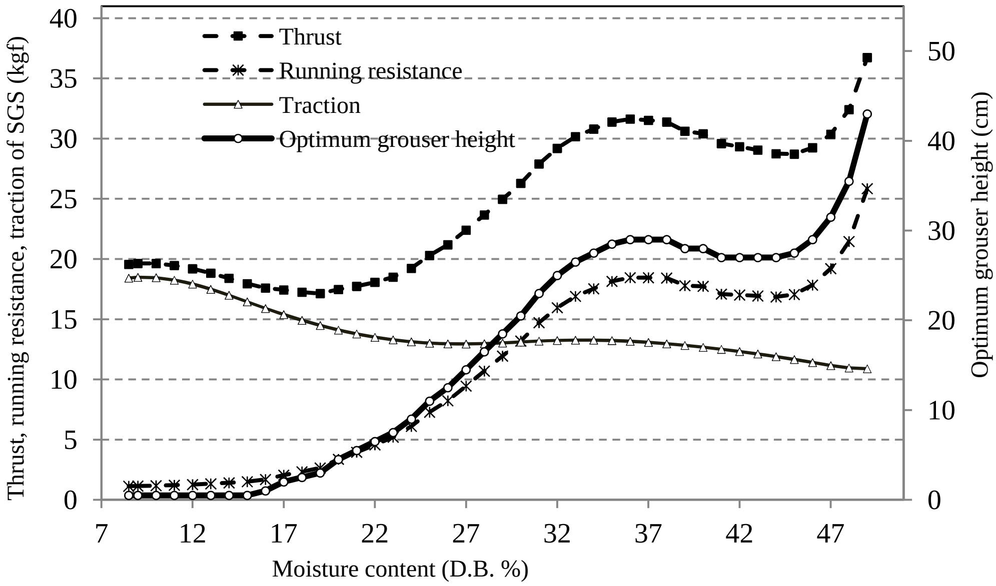

Fig.14. The optimum grouser height for given MC and correspondent values of tractive performance

Figure 14 shows that the SGS with the 1 cm grouser height was better when the MC was lower than 15%. Following that, the optimum grouser height increased with the increase of MC until the peak value of 26 cm at 36% MC. After the peak value, the optimum grouser height slightly decreased until the 43% MC. From then on, it began to rapidly increase with the increase of MC until the highest MC level. Among the corresponding tractive performance, they all had different trends with the change of MC. The thrust had almost no changes with the initial increase of MC, and then, it began to decrease with the increase of MC until the trough value at 19% MC. After the trough value, it increased with the increase of MC before the peak value of 32 kgf at 36% MC. Then, it decreased to the second trough value with the increase of MC. At the stage near the highest MC level, it rapidly increased with the increase of MC. Compared to the trends of optimum grouser heights, one can see that the thrust performance was largely influenced by the grouser height when the other dimensions of SGS were the same. Meanwhile, the running resistance almost continually increased all the way with the increase of MC from lowest to highest MC level except for the stage from 36% to 44% MC in which the resistance mildly decreased with the increase of MC. Different from the trends of thrust and resistance, the traction continuously decreased with the increase of MC under nearly the same rate of decrease. It may be concluded that the shorter grouser performed better under the relative low MC in the test soil used in this study.

V. CONCLUSIONS

In this study, clay soil was used as the test soil. Ten levels of MC were applied on this soil by varying the amount of water added. For each MC soil, tests such as penetration test, direct shearing test, density and MC measurement were performed for obtaining soil parameters. Based on these parameters and the 3-dimenstional shearing model, the tractive performance like thrust, running resistance and traction of SGS was calculated.

1) Depending on the MC of soil in which the machine or tracked vehicle is working in, different grouser heights should be adopted: If the MC is less than 15%, a track with shorter grouser height will be better; but if the MC is higher than 15%, the relative longer grouser height is better for generating the maximum traction.
2) For different MCs soil, the optimum grouser height which could generate the maximum traction was different. Furthermore, the traction generated by the optimum grouser height continuously decreased with the increase of MC in this experiment.

3) Base on this study, a relative dry soil condition is better for machines or tracked vehicle to work on.

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