MEASUREMENT OF SOIL REACTION FORCES BY A SINGLE FLAT WHEEL ON THE SLOPE SOIL BIN
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PENGUKURAN GAYA REAKSI TANAH DENGAN SATU BUAH SIRIP RODA SANGKAR TRAKTOR TANGAN DI BAK PENGUJIAN TANAH

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ABSTRACT
The ability of a cage wheel to climb slopes depends on the grip of the lug on the sloped soil. A lug wheel that sinks deeper will generate more force when climbing. This study aimed to measure the soil reaction force on a single flat lug wheel in the slope soil bin so that the optimal lug angle is obtained to enhance the ability of cage wheels to climb sloped soil. The experiment was carried out using a model of a single flat lug wheel (length of 10 cm, width of 3.5 cm, radius of 30.4 cm, and slope of 30º). Measurements of soil reaction forces on the lug were carried out on five lug angles (-15º, 0º, 15º, 30º, 45º) at three various sinkage depths (2.5 cm, 5 cm, 7.5 cm) at a rotational speed of 11 rpm. The moisture content, density, porosity used in this study were 45.61% (d.b.), 1.02 (g/cm), 44.02%. In addition, the particle size distribution of sand, clay, and silt are 8.038%, 13.396%, and 78.564%, respectively. The limits of soil consistency used in this study, including the plastic limit, water limit, and index limit, were 64.57%, 80.86%, and 16.29%, respectively. A set of measurement and data logger equipment is used to measure the reaction forces of the soil. The results showed that at the angles of -15° and 0° the lugs were able to penetrate the soil faster and deeper to produce a greater pulling force. This implies that a smaller angle of inclination will be more beneficial to the tractors wheel applied for climbing than a greater angle of inclination.

ABSTRAK
Kemampuan roda sangkar traktor tangan untuk mendaki lereng tergantung pada cengkeraman lug dalam memanjat tanah yang miring. Roda lug yang tenggelam lebih dalam akan menghasilkan tenaga yang lebih besar saat mendaki. Oleh karena itu, penelitian ini bertujuan untuk mengukur gaya reaksi tanah terhadap satu sirip roda lug datar pada bak pengujian tanah berlereng sehingga diperoleh sudut lug yang optimum untuk meningkatkan kemampuan roda sangkar dalam memanjat tanah berlereng. Percobaan dilakukan dengan menggunakan model satu sirip plat (panjang 10 cm, lebar 3.5 cm, jari-jari 30.4 cm, dan kemiringan 30°). Pengukuran gaya reaksi tanah pada lug dilakukan pada lima sudut lug (-15°, 0°, 15°, 30°, 45°) pada tiga kedalaman sinkage yang berbeda (2.5 cm, 5.0 cm, 7.5 cm) pada kecepatan putaran 11 rpm. Kadar air, densitas, porositas yang digunakan dalam penelitian ini adalah 45,61% (d.b.), 1,02 (g/cm), 44,02%. Selain itu, distribusi ukuran partikel pasir, lempung, dan lanau masing-masing sebesar 8,038%, 13,396%, dan 78,564%. Batas kekentalan tanah yang digunakan dalam penelitian ini meliputi batas plastis, batas cair, dan batas indeks berturut-turut adalah 64,57%, 80,86%, dan 16,29%. Satu set peralatan pengukuran dan pencatat data digunakan untuk mengukur gaya reaksi tanah. Hasil penelitian menunjukkan bahwa pada sudut -15° dan 0° lug mampu menembus tanah lebih cepat dan dalam sehingga menghasilkan gaya tarik yang lebih besar. Ini menyiratkan bahwa sudut lug yang lebih kecil akan lebih bermanfaat untuk roda traktor yang digunakan untuk memanjat daripada sudut lug yang lebih besar.

INTRODUCTION
The cage wheel is one of the traction tools (from many traction devices on off-road vehicles) that have the best performance in both wetland and dryland environments (*Sitorus et al.*, 2018). The use of cage wheels has proven to be one way to increase the mobility of hand tractors in paddy fields. Cage wheels can produce the pulling and lifting forces needed by hand tractors for soil tillage. The price of cage wheels on the market is

also more affordable and more straightforward to construct when compared to rubber tire wheels. However, existing cage wheels have not been optimally used in terraced rice fields because the mobility of hand tractors is still very low, especially due to the limited ability to move from a lower to a higher terrace.

Understanding the principle of pulling force from traction equipment is fundamental to help engineers design agricultural machinery and equipment that are suitable for environmental conditions (*Elwaleed et al.*, 2006). The performance of cage wheels continues to develop dynamically so that the maximum cage wheel capability is produced according to the condition of the land to be tilled. Some previous studies on single cage wheels have been carried out by measuring and observing the reaction forces of the soil. The effect of the soil reaction force on modifications to the lug wheel is then analysed so that the optimum pull and lift forces, and the slip that occurs, can be minimized. The analysis can be used to produce cage wheels that have high mobility to climb sloping land in terraced rice fields (*Cebro and Sitorus*, 2019).

The soil reaction force to the lug occurs when the wheel of the lug cage touches and penetrates the soil. *Raheman and Snigdharani* (2020) argued that the measurement of soil reaction forces to a single lug wheel can be carried out by designing test equipment in a soil bin. A single-lug wheel is mounted on an L-shaped transducer and rotated by a drive shaft. The strain gauge sensor is attached to the L-shaped transducer and drives the shaft to measure the normal force, the tangential force, and the torque. Measurement results are calculated and converted to pulling and lifting forces produced by the pulley wheel.

The normal forces and tangential forces acting on a single lug increase continuously and then begin to decrease after reaching their peak as long as the lug is in the soil. The graph of these forces produces a trend similar to that observed in the pull-force graph generated by a single lug on the soil. Based on the results of previous research, the pulling force of hand tractors using cage wheels can be known to be maximized by observing the normal and tangential forces acting on the lug wheel.

Several studies have been carried out on the angle of the lug cage wheel. *Ding et al.* (2011) explained that the angle of the lug influences the pull force produced by a single lug wheel. The angle of insertion that matches the conditions of the land can create a greater pulling force. It is caused by an increase in the normal force and the tangential force acting on the flat single lug. However, the sinkage of the lug and the physical and mechanical properties of the soil also influence the pull force. Research conducted by *Du et al.* (2018) has shown that smaller lug angles (30° and 45°) produce greater traction compared to larger lug angles (60°). In previous studies, it has also been found that the maximum lug strength can be obtained at a small lug angle (*Idkham et al.*, 2021; *Md-Tahir et al.*, 2019).

Other research on lug cage wheels has also been carried out. *Idkham et al.* (2018) conducted research of the slim-lug cage wheel on the soil bin and showed that the performance of slim-lug wheels was strongly influenced by the angle of the lug, but was less affected by the high dimensions of the lug wheel. *Pradhan et al.* (2017) showed that the traction of the hand tractor by varying the angle of the lug wheel can be produced by increasing the lug angle because it reduces resistance force and increases traction efficiency. *Raheman and Snigdharani* (2020) showed that to improve traction, it is necessary to consider the variation of design parameters for lug wheels, lug angle, lug distance, lug size, lug shape, and lug mechanism. *Pradhan et al.* (2018) measured the soil strength acting on the surface of a flat lug. The experimental result compared to the theoretical result, predicted by the theory of passive pressure, shows a satisfactory logical conclusion.

The pull force produced by a cage wheel can be increased based on previous studies. Increasing the pull force generated by the lugs on cage wheels will lead to increased mobility of hand tractors to be able to climb terraced rice fields so that they can move from one terrace to another higher terrace. This study was conducted to measure and observe the soil reaction force on a single flat lug in a soil bin, to determine the optimal lug angle in producing the highest pulling force for terraced rice field conditions.

MATERIALS AND METHODS

Test apparatus

Measurements of soil reaction forces are carried out on a single flat lug model, which is operated on the slope soil bin. The test apparatus consists of a soil bin, a single flat lug model, and a drive system. The soil bin is 1350 mm long, 550 mm wide, and 250 mm high. This soil bin can be sloped at an angle of 30° where it is the median from angle slopes of the land at the preliminary tests in the field (15°, 30°, 45°). The lug drive system is mounted on a trolley frame that is equipped with rollers so that it can move on the rails on the edge of the soil bin. This trolley weighs 456.2 N on slope soil bin 30°, and it can move back and forth on the rail. The creep sinkage can be adjusted by setting the height of the land in the soil bin. This study also uses variations of sinkage, i.e. 2.5 cm, 5 cm, and 7.5 cm. This lug sinkage was done to observe the influence of sinkage on the normal force, lift force, and the pull force from a single flat lug.

Single flat lug model

The lug drive system consists of a drive shaft connected to an L-shaped transducer. The rotation of the drive shaft produces a rotational motion on the L-shaped force transducer, so that the rotation angle on the lug can be observed. The radius from the centre of the drive shaft to the end of the fin plate is 30.4 cm. The lug is 10 cm long, 3.5 cm wide and 0.5 cm high. The lug used in this study was proportionally reduced to 1/3 of the actual size (lug wheel standard size is 28 cm in length × 9 cm in width). The reason is to reduce the soil reaction force in the experiment to reduce the cost of construction of the test apparatus. Bolts and nuts are used to attach the lug to the L-shaped transducer (Fig. 1). The lug mounted on the L-shaped force transducer in this study varied in five lug angles, i.e., -15°, 0°, 15°, 30°, 45°.

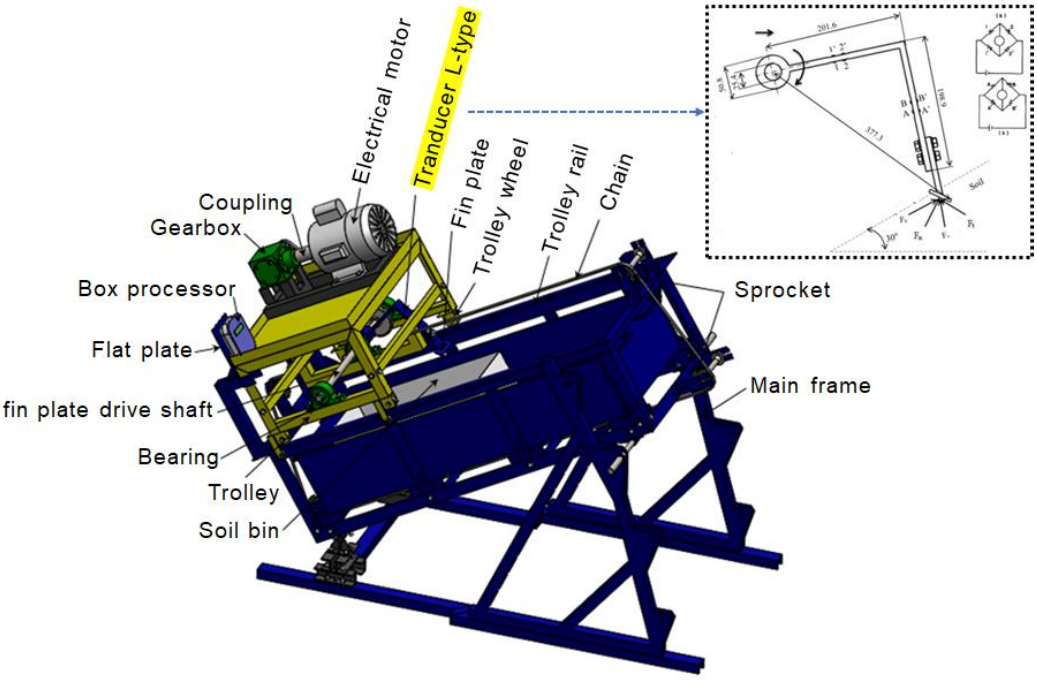


Fig. 1 - Test equipment schematic

The drive shaft of the lug is driven by an electric motor whose rotational speed is reduced by using the gearbox. The rotation of the gearbox shaft is forwarded to the lug drive shaft which is also reduced through a chain-sprocket to obtain a rotational speed of the fins of 11 rpm; it is according to the forward speed of the hand tractor for tillage. The lug drive system is mounted on a trolley frame that is equipped with rollers so that it can move on a pair of rails made on the edges of the soil bin frame. The trolleys have a weight of 456.2 N and can be sloped in a 30 ° soil bin and can move backward and forward on the tracks.

Data collection

Two strain gauges were mounted on the shaft to measure the torque of the shaft. Eight strain gauges were installed on L-shaped force transducer, four strain gauges to measure normal forces, and four strain gauges to measure tangential forces. A potentiometer was used as a sensor to measure the rotation angle. The potentiometer was installed with an axis in the centre of the lug shaft to obtain data on the rotation angle of the lug per unit of time. Ultrasonic sensors were mounted on trolleys to measure the actual distance of trolleys moving on the rail per unit of time.

The data recording system recorded data from each measurement by each sensor. The results of the ultrasonic sensor and the potentiometer sensor measurement data were displayed on the LCD screen and then stored in the memory card. All data measured from the strain gauge were sent through a set of instrumentation to the data logger, and then the data were displayed and stored on a PC. All the data that have been recorded are then calculated and processed using a computer. Before the experiment, all sensor units used were calibrated so that the data obtained were valid.

Test conditions

Soil conditioning is carried out by drying, sieving, measuring the initial moisture content, weighing the soil, mixing, and adding water so that the soil moisture content and penetration resistance of the soil achieved correspond to actual field conditions. The characteristics of the test soil are presented in Table 1.

Table 1
Properties of the soil used in the experiments

Soil moisture content (% dried basis)	Density (g/cm)	Porosity (%)	Particle size distribution (%)			Consistency limits (%)		
			sand	silt	clay	plastic limit	liquid limit	plasticity index
45.61	1.02	44.02	8.038	13.396	78.564	64.57	80.86	16.29

The measurements of the soil reaction forces (torque, normal force, and tangential forces) in this study were carried out on a soil slope of 30°. The experiment was carried out with five variations of lug angle, i.e., -15°, 0°, 15°, 30°, 45°. Each experiment for one angle of the lug was carried out at three different depths of sinkage of the lug, i.e. 2.5 cm, 5 cm, and 7.5 cm. Each variation of the experiment was carried out three times.

RESULT AND DISCUSSIONS

Measured forces

The pull and lift forces of the lug can be calculated from the normal and tangential forces measured by using the equation with some adjustments made to fit the conditions of this study. The pull force (vertical force) is calculated using Equation 1 and the lift force (horizontal force) using Equation 2.

$$F_v = F_n \cdot Cos(\theta - \lambda) + F_t \cdot Sin(\theta - \lambda) \tag{1}$$

$$F_h = F_n \cdot Sin(\theta - \lambda) + F_t \cdot Cos(\theta - \lambda) \tag{2}$$

Where, F_v = vertical force (N); F_h = horizontal force (N); F_n = normal force (N); F_t = tangential force (N); θ = lug rotational angle (°); λ = lug angle (°).

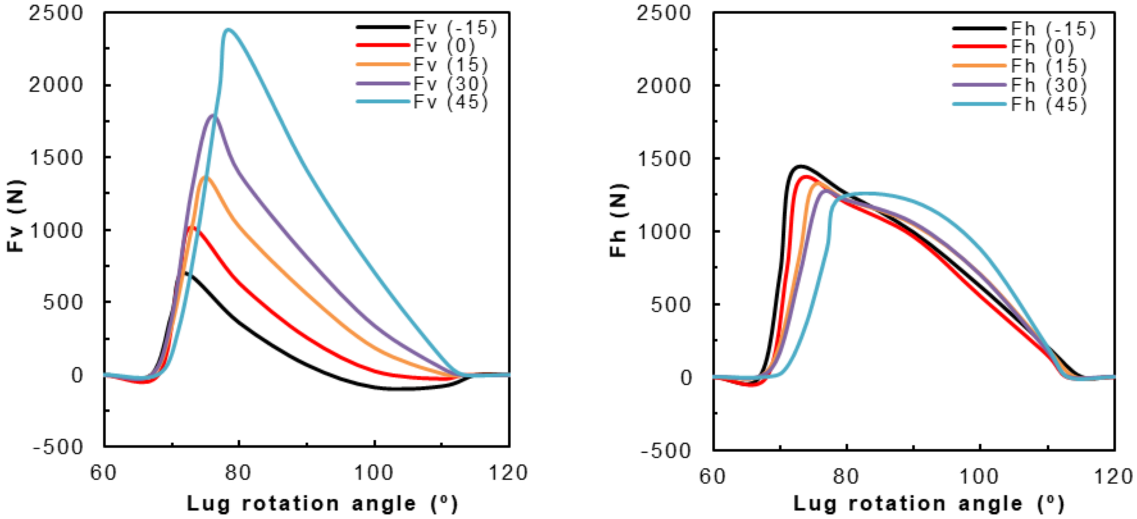
The soil that receives forces from the penetration of lug into the soil produces a soil reaction force. The reaction force is the lift force (vertical force) and the pull force (horizontal force) which causes the trolley to climb into the slope soil bin. It is obtained from the measurement of the normal and tangential forces on the L-shaped force transducer that is attached to the lug. When the lug enters, the soil collapses due to vertical failure due to the initial pressure caused by the downward movement of the lug. The soil beneath the lug is exposed to the heavy resistance to compression caused by the lug. Due to this effect, the normal lug force continuously increases until it reaches a peak value.

The effects of lug angle on lug forces

The results of the measurement of the soil reaction forces obtained from the test are low voltage values. Increasing the load received by the strain gauge increases the value of the measured voltage. The voltage value is substituted to the voltage-to-load calibration equation so that the torque value is obtained after multiplying by the gravitational acceleration and a spoke (lug arm) is applied and the normal and tangential forces are substituted after multiplying by the acceleration of gravity. Each of the soil reaction forces is connected to the rotation angle of the lug drive shaft, so that the change in the value of the soil reaction force is obtained versus the rotation angle of the lug drive shaft.

Experimental data from five fin angle variations and three sinkage variations are presented in Fig. 2 to Fig. 4. Fig. 2 shows a comparison of measurements of vertical forces and horizontal forces on 2.5 cm lug sinkage for various lug angles. The trend of the graph for each angle of the lug shows that starting at lug rotational angle of 68°, which is shortly after the lug touches the soil surface, the vertical force of 0 ° increases significantly to a peak value at 70° to 78° lug rotational angle.

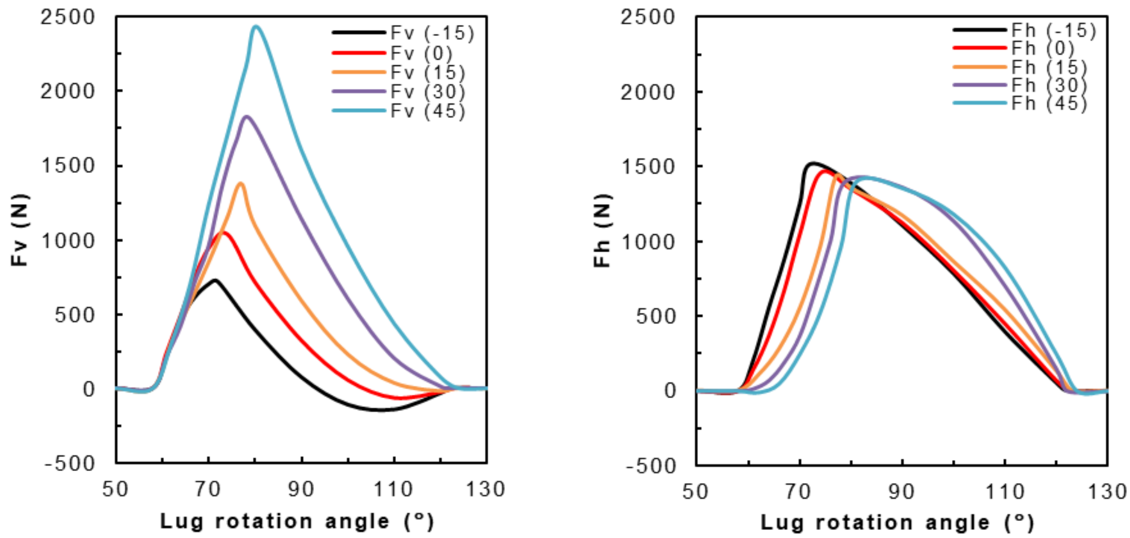
Next, it decreases more slowly until it returns to 0°, which is when the lug rotational angle is 113° or when the lug leaves the soil. The vertical force of 699 N with the -15° lug angle is seen to be the lowest, while the highest value (2370 N) occurs at the lug angle of 45°. Meanwhile, the horizontal force achieved by the -15° lug angle is 1417 N. On the other hand, the lowest one (1208 N) occurs at the 45° lug angle.



(a) vertical force (b) horizontal force

Fig. 2 - The soil reaction force on the rotational angle of the lug at 2.5 cm sinkage of the lug

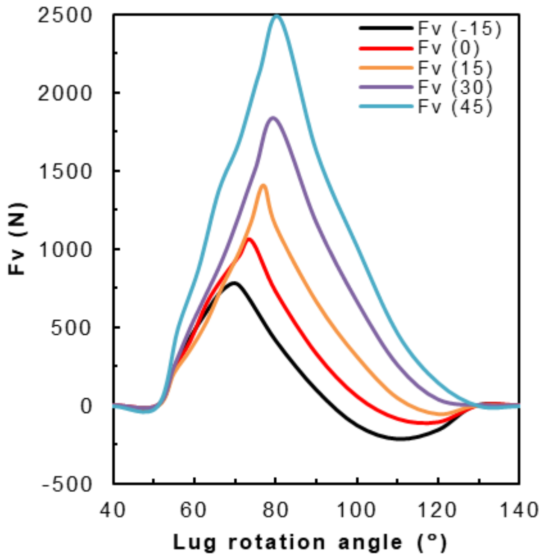
Fig. 3 presents the vertical force and the horizontal force on the sinkage of the lug of 5 cm for several lugs. The trend of the graph for each angle of the lug is almost the same as the sinkage of the lug at 2.5 cm, which starts from the lug rotational angle of 58°, which is shortly after the lug touches the soil surface, the vertical force from 0 increases significantly to peak value at the 70° to 85° lug rotational angle. Then, it gradually decreases until it returns to 0° which is when the lug rotational angle is 124°, or when the lug comes out of the soil. The vertical force with the lowest -15° fin angle is 705 N while the highest (2416 N) occurs at 45° fin angle. The highest horizontal force with a lug angle of -15° is 1515 N. On the contrary, the lowest horizontal force (1355 N) occurs at a 45° lug angle.



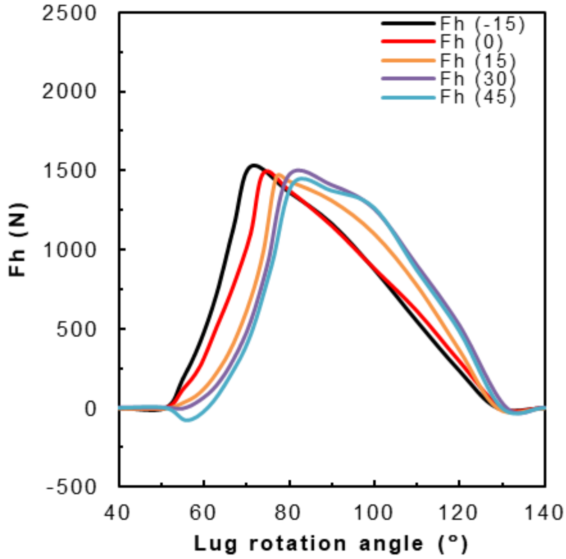
(a) vertical force (b) horizontal force

Fig. 3 - The soil reaction force on the lug rotational angle at 5 cm lug sinkage

Fig. 4 shows the vertical force and horizontal force in lug sinkage of 7.5 cm for several lugs. The trend of the graph for each angle of the lug is almost the same as the sinkage of the 2.5 cm and 5 cm lug sinkage that starts from the 45° lug rotational angle which is shortly after the lug touches the soil surface, the vertical force from 0 increases significantly to peak point at the 65° – 83° lug rotational angle. After that, it slowly decreases until it returns to 0°, which is when the lug rotational angle is 130°. The vertical force with the -15° lug angle is the lowest at 773 N, while the highest (2479 N) occurs at 45° lug angle. Meanwhile, the highest horizontal force with a lug angle of -15° is 1523 N; in contrast, the lowest force (1376 N) is at a 45° lug angle.



(a) vertical force



(b) horizontal force

Fig. 4 - The soil reaction force on the rotational angle of the lug at the sinkage of the 7.5 cm lug

The effects of lug angle and lug sinkage on lug slippage

Slippage is an unavoidable characteristic of traction devices that interact with the soil. This event also occurred in the lug when tested in a sloped soil bin in this study. The slip that happens can be calculated by measuring the actual movement compared to the theoretical movement. The amount of slip from this experiment for each variation of the lug angle on the three lug sinkage was calculated, and the results were compared. The theoretical distance of displacement is calculated by Equation (3). The actual distance is obtained from the measurement of the ultrasonic sensor. The slip that occurs in the experiment is calculated by Equation (4). The amount of slip is then compared to the sinkage of the lug, the horizontal force, and the angle of the lug tested.

$$D_t = \frac{22 \cdot \pi \cdot R_l \cdot t}{60} \quad (3)$$

$$S = \frac{D_t - D_a}{D_t} \quad (4)$$

Where, D_t = theoretical distance (mm); R_l = radius of the lug (mm), t = time the lug rotates (s); D_a = actual distance (mm); S = lug slippage (%).

The effect of lug slip on lug sinkage of the five lug angles tested is shown in Fig. 5. The result of slip-on horizontal force on the five lug angles tested is shown in Fig. 6 (horizontal force in function of lug slippage on the five lug angles tested). Increasing vertical force values indicate that the lug can be lifted to the surface of the soil so that it does not sink easily. Meanwhile, the increasing value of horizontal force means that lug produces an increasingly large pull force to climb slope soils bin. The lower angle of the lug is used to obtain a large pull force so that the lug can penetrate the soil more easily because the force of the vertical force produced is smaller. Increasing the penetration of the lug into the soil will cause the area of the soil to be cut by the lug, therefore the lug has a large grip on the slope walls and produces a large pull force.

The inclined vertical force is increased if the lug is sinking, and the lug angle rises as well. Meanwhile, the horizontal force increases as the lug sinks deeper and the lug angle is smaller. With the same normal load, the lug with a smaller lug angle (-15°) can penetrate deeper into the soil because the lug can penetrate the soil more easily. This phenomenon is caused by a smaller vertical force at a lug angle of -15°. A smaller lug angle (-15°) will produce a greater horizontal force. With the same lug sinkage, the greatest pull force is produced at -15° lug angle.

The lug must penetrate the soil deeper so that it can climb the sloping land, with a small tangential reaction of the soil. If the lug penetrates the soil more in depth, the horizontal force obtained increases. Therefore, the lug with the smallest angle (-15°) is optimal for climbing a sloping land (30°). Our results correspond to the research results of *Daca et al.* (2022) that lug sinkage influences the pull and lift forces of the lug, where pull and lift forces increase with rising sinkage. This research is also in line with the radial collapse zone theory presented by *Barbosa and Magalhães* (2015), stating that the more in-depth the lug penetrates the soil, the higher the radial zone of the soil is so that the soil reaction on the lug increases.

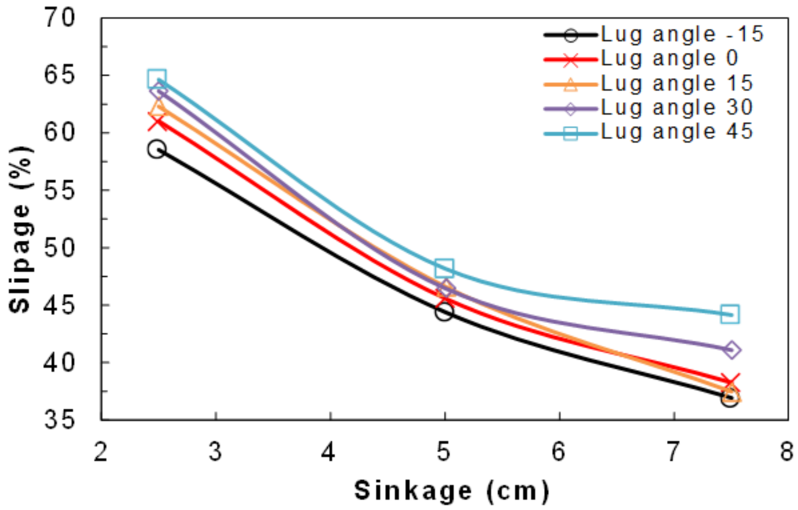


Fig. 5 - Lug sinkage versus lug slippage at the five lug angles tested

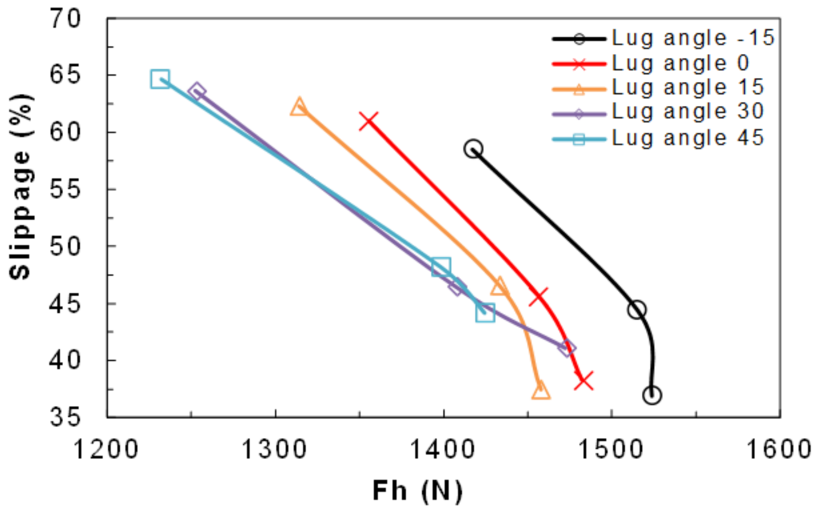


Fig. 6 - Horizontal force vs. lug slippage at the five lug angles tested

Slips cause the trolley with a normal load that is fixed for each variation of the experiment to not be able to reach its maximum displacement, so slips are a factor that should be minimized. The slip in this study increased when the sinkage test of the lug decreased and the angle of the lug increased. The increase in slippage also has an impact on the pull force produced, where the pull force decreases with increasing slippage. These results indicate that the lug with small lug angles (-15° lug angle) is more effective to climb the sloped soil because the frequency of slippage is rare and the pull forces are higher compared to the other lug angles.

CONCLUSIONS

A single-lug model with variations of the lug angle in soil bin with a slope of 30° which is equipped with an L-shaped force transducer) has been successfully developed. The experiments carried out verified that it is easier for the lug wheel with a smaller lug angle to penetrate the soil, so that it can achieve more in-depth sinkage for the same normal load. The test results at the lug angles of -15° and 0° in 7.5 cm lug sinkage indicate that the best lug angles that produce pull force are highest at 1523,807 N and 1482,262 N, respectively, the lift forces are smaller at 493.17 N and 1051,594 N, respectively, the torque is lower at 493.17 Nm and 500.47 Nm, respectively. This research indicates that the use of the lug angle of the cage wheel must be adjustable to a negative angle for the use of a hand tractor in the field step. In addition, future research from this finding is to design a cage wheel suitable for a hand tractor and do a field test before mass production.

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