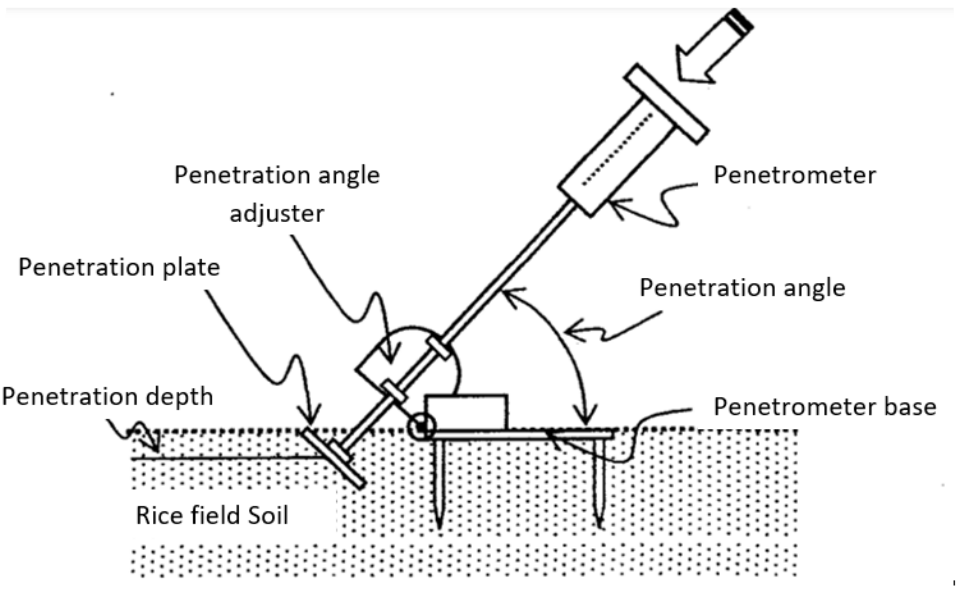
MEASUREMENT OF SOIL RESISTANCE TO PLATE PENETRATION AND ITS APPLICATION FOR DETERMINATION OF DESIGN PARAMETERS OF A LUG WHEEL



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Measurement of Soil Resistance to Plate Penetration and Its Application for Determination of Design Parameters of a Lug Wheel

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Abstract

The measurement of the soil resistance of paddy fields to plate penetration has been carried out at two locations with different soil characteristics using a penetrometer with the tip of the plate at several penetration angles to a depth of 20 cm. The soil resistance data is applied in the analysis for determination of lug tilt angle, lug size, number of lugs and wheel diameter of a lug wheel designed for plowing at both locations using local hand tractors. Measurement results show that with a plate tilt angle of 45°, produced the highest soil reaction forces, both in the horizontal and vertical directions, so that the lug inclination angle is necessary set to 45°, when lugs receive peak load. For fields with deep hard pans, soil resistance tends to increase sharply at a depth of 0-10 cm and at a depth of 15-20 cm. Soil resistance at a depth of 15-20 cm at a penetration angle of 90° was 60 kPa. For this location the optimum number of lugs is 14, the lug width is 8 cm, lug length is 35 cm and lug wheel diameter is 85 cm. For fields with shallow hard pans, the soil resistance increased sharply from 6 cm to 20 cm depth. Soil resistance at a depth of 15-20 cm at a penetration angle of 90° over 90 kPa. For this location the optimum number of lugs is 14, the lug width is 10 cm, lug length is 35 cm and wheel diameter is 85 cm.
Key words: design parameters, lug design, lug wheel, plat penetration, soil resistance.

Introduction

To improve the traction capability and solve the mobility problems of the two wheel tractor in the rice fields needed a new concept of the lug wheel used. From research that has been conducted in since several years ago, the movable lug mechanism of lug wheels has many advantages compared to conventional lug wheels with rigid lugs, i.e. generating lift force and higher pull force and efficiency (Hermawan et al., 1996, 1997, 1998, 2001). Wheel with movable lugs having movable lug plates on which the lug plates can be retained at a certain angle of inclination (with the ground line) during its rotation. Other tests also show the advantages of this type of movable lug wheel with lug-spring mechanism (Wiyono, 2005 and Listyati, 2005).

Basically, the design process for the lug wheel must include the soil condition of the paddy field and tractor construction condition, as a determining factor in the design results. The pulling force generated by the hand tractor in paddy fields is produced from the traction of the lug wheels used, which is an accumulation (resulting) of the reaction of the soil to the wheel lugs operating in the soil. To produce lift force (vertical) and thrust (horizontal) on lug wheels that meet the needs of the pull load (draft, and wheel rolling resistance) and the vertical load of the tractor weight, it must be an adequate ground reaction force (against the wheel lugs) is obtained. This interaction is necessary simulated in designing lug wheels for paddy fields. Rice field soil reaction force on the lugs need to be known in designing lug wheels.

The soil reaction force on the movable lug has been analyzed theoretically by Hermawan et al. (2000). The estimation of the soil reaction force can be divided into two stages, namely (a) the stage where the wheel lug moves to press the ground downwards and (b) the stage in which the wheel lug moves up to leave the ground. According to Hermawan et al. (2000), the conditions and forces that act when the lugs press the ground downwards are depicted in the schematic in Figure 1. The analysis of the reaction force of the soil on the lug (P) has been carried out by Hermawan et al. (2000). However, the analysis requires many parameters of soil characteristics to be measured or known. As an alternative, it is necessary to carry out measurements with instruments that are practical and easy to do, one of them by using a penetrometer (Hermawan, 2009).

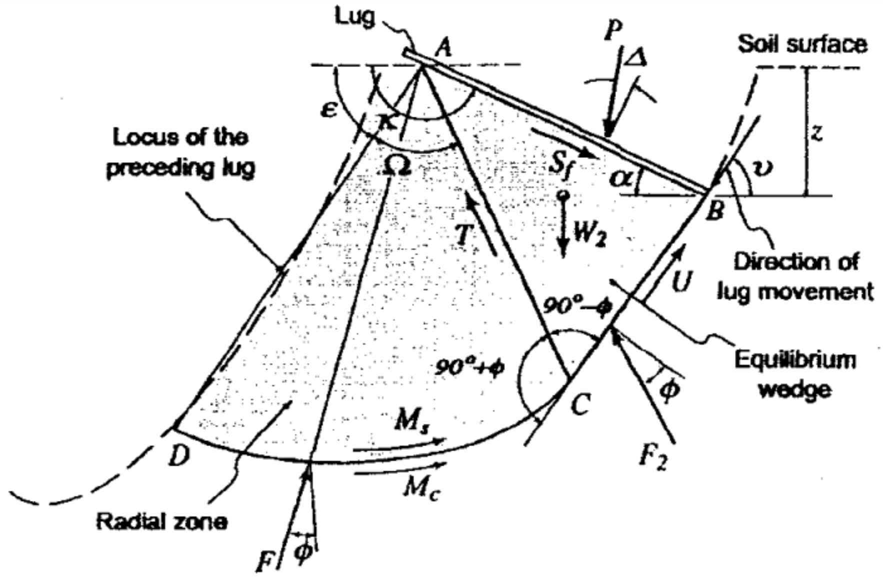

Figure 1. Schematic of zones, boundaries and equilibrium forces as the lugs move downward (Hermawan et al., 2000).

Based on this idea Cebro, et al (2006) and Hermawan (2009) have tried the process of the design of this lug wheel by the stages of measuring the soil resistance of paddy fields on plate penetration and the stages of measuring the construction of the tractor and the stages of its design analysis. This method can also be used for lug wheels with a spring-loaded lug mechanism. This paper will describe the method of measuring the soil resistance of paddy fields to plate penetration, and the application of the measurement results in determining the size and design of lug wheels for hand tractor.

Research Methods

Measurement of the characteristics of the soil resistance of paddy fields to plate penetration was carried out in the rice fields 1) Nagrak Village, Cianjur District, Cianjur Regency and 2) Munjul Village, Pabuaran District, Subang Regency. Survey of the two-wheel tractor dimension and weight data was carried out in both location, specifically for tractors commonly used in that locations. Determination and analysis of the design parameters were carried out at the Department of Mechanical and Biosystem Engineering, IPB University.

Measurement of the soil resistance on plate penetration using a penetrometer that equipped with plates and penetration slope retainers (Figure 2). The pressure plate used consists of three sizes, namely: a) 5 cm × 7 cm, b) 7.5 cm × 5 cm and e) 10 cm × 5 cm. Because of the wheel lug plate pressing the paddy field at an angle of inclination varies from 0° to 90°, then the soil resistance against plate penetration measured at pressure angles of 30°, 45°, 60°, 75° and 90°. Measurement was carried out at the stages of penetration depth: 2.5 cm, 5 cm, 7.5 cm, 10 cm, 12.5 cm, 15 cm, 17.5 cm and 20 cm. For each rice field area, measurements were carried out on three rice fields, and on each rice field plot the measurement was repeated three times (three locations). The condition of the paddy field was free of straw, and ready to be plowed (cultivated).

Compressive force data (in kg) measured using a penetrometer divided by size of cross section (area) of the plate was used to get the value of soil resistance to plate penetration (in Pa). The measurement results from several plots were analyzed so that a graph was obtained, the relationship between the plate penetration resistance and the depth of penetration at several angles of penetration. Then using the appropriate regression method, the value of the soil resistance to plate penetration at various levels of depth and several angles of lug inclination angle for these soils can be known. This value (data) is then used for simulation in determining the size of the lug plate, number of lugs and wheel diameter in the design process of a lug wheel.

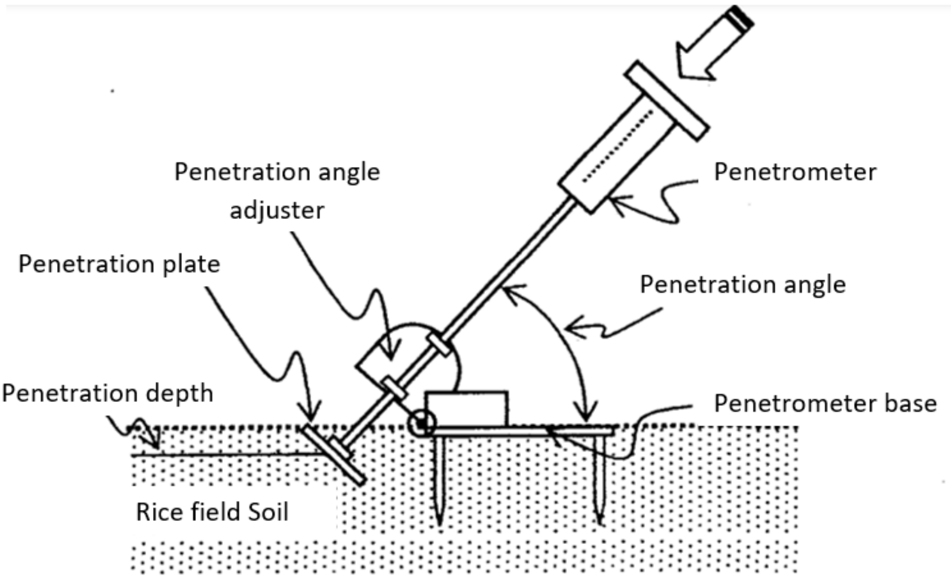

Figure 2. Instrument for measuring soil resistance of soil to plate penetration.

The specified lug wheel design parameters are: (a) wheel fin size, (b) strength of spring-loaded lug mechanism, (c) wheel diameter, and (d) the number of lugs. Data used in the purposes of the analysis are: a) data on soil resistance of paddy fields (at both locations) against plate penetration, b) construction data and weights of the two wheel tractor and c) data on the draft of the tillage implements as well as wheel rolling resistance. In addition, the basic formation of a deep two-wheel tractor plowing and plowing of paddy fields that are standard in Indonesia (Figure 3) and the position of the sections of the base of the tractor body against the ground and the wheels (Figure 4) must also be considered. The stages of analysis used are as has been done by Hermawan (2009).

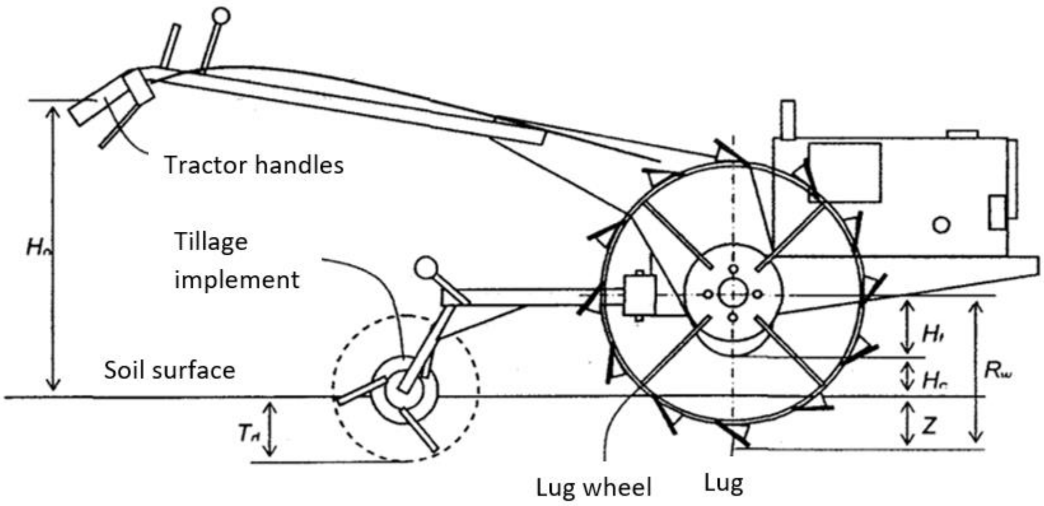

Figure 3. The basic formation of a two-wheel tractor for plowing and harrowing paddy fields in Indonesia.

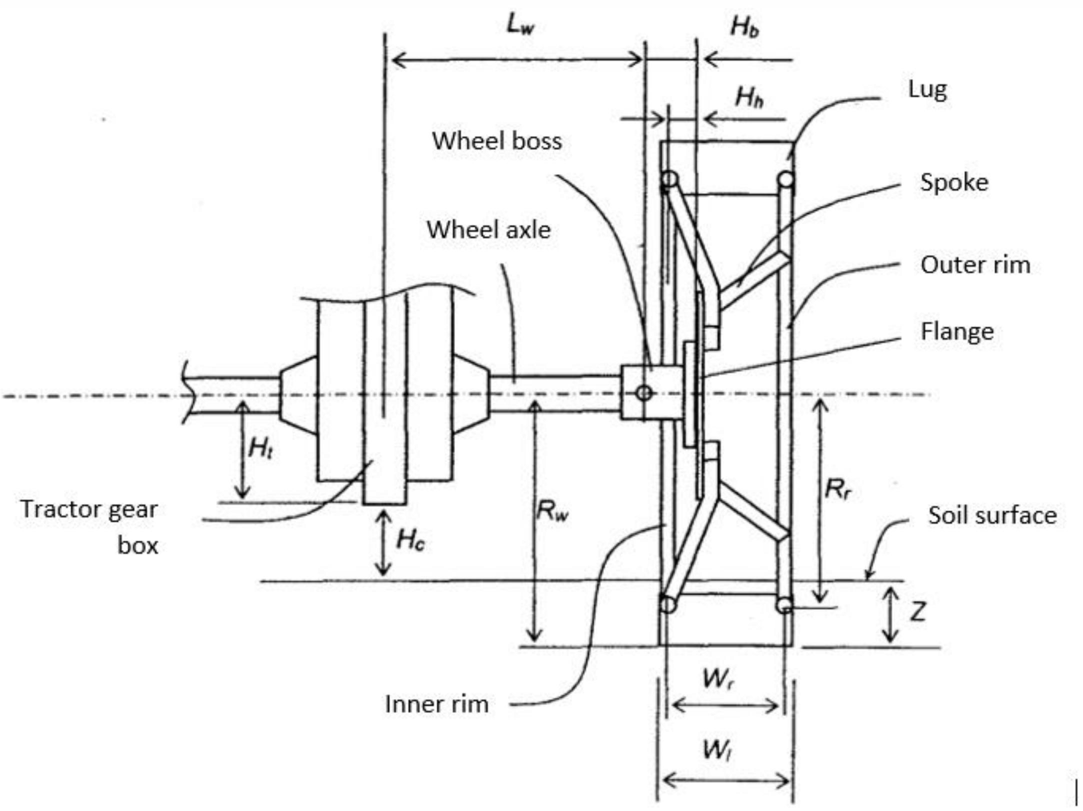

Figure 4. Wheel parts and scheme for determining wheel size.

From Figure 4, the outer radius of the fin wheel R_w can be determined by the equation:

$$R_w = H_t + H_e + Z \quad (1)$$

where: H_t is the base radius of the tractor reduction gear box, H_e is the ground clearance and Z is the sinkage of the wheel. Then the wheel diameter D_w is:

$$D_w = 2\,R_w \quad (2)$$

In addition, the maximum lug wheel diameter is limited by the free space available on the tractor, which limited by the engine crank arm (front) and tillage implement (rear). The two data must be observed on the tractor in use.

The size of the wheel lugs must be determined carefully through an assessment of the relationship between the horizontal pull load, the vertical load, the diameter of the wheel, the number of lugs, the size of the lugs and the sinkage of the wheel. The soil resistance data against plate penetration (measurements) is used to determine the size of this lug. In the analysis, the resultant soil reaction force on each active lug (acting on the ground) in the horizontal direction must be more than the pull load ($\frac{P_i}{2}$) and the rolling resistance of the wheel (F_{rr}). The resultant ground reaction force in the vertical direction must be greater than the weight of the tractor supported by the wheels ($\frac{W_t}{2}$).

$$\sum_{i=1}^{n} F_{sh} \geq \left(\frac{P_i}{2} + F_{rr} \right) \tag{3}$$

$$\sum_{i=1}^{n} F_{sv} \geq \frac{W_t}{2} \tag{4}$$

$$F_s = F_{sh} + F_{sv} \tag{5}$$

In this case: F_{sh} is the soil reaction force on the horizontal lug, and F_{sv} is the soil reaction force on the vertical lug, and F_s is the resultant soil reaction force on the lug.

The soil reaction forces on the active lugs are F_{s1}, F_{s2}, F_{s3} and so on (Figure 5) is calculated from the resistance of the soil to the plate penetration according to the depth (position of the lugs in the soil) and the angle of inclination of the lug plate in question.

$$F_{sn} = A_s \, T_{pn} \tag{6}$$

where: F_{sn} is the reaction force of the soil on the nth lug, A_s is the surface area of the lug and T_{pn} is the soil resistance of the nth lug (measured at the angle of penetration and the corresponding depth). From each of these reaction forces, the components of the horizontal and vertical directions can be determined.

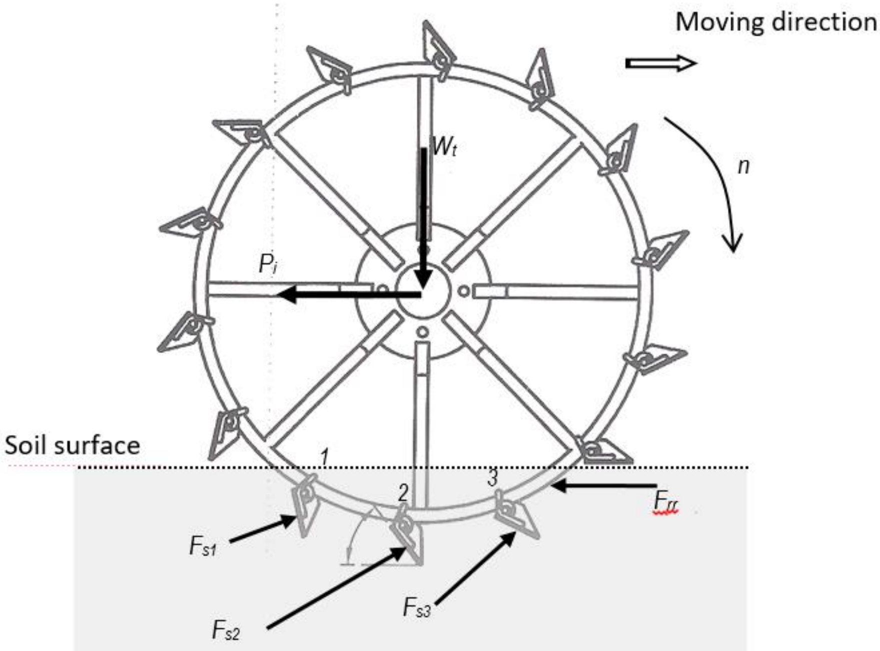

Figure 5. The forces acting on the lug wheel.

$$F_{shn} = F_{sn} \cos\alpha \tag{7}$$

$$F_{svn} = F_{sn} \sin\alpha \tag{8}$$

where: F_{shn} is the horizontal soil reaction force on the n^{th} lug, α is the tilt angle of the n^{th} lug, and F_{svn} is the vertical direction of the soil reaction force on the n^{th} lug.

The number of active lugs J_{sa}, lug size (cross-sectional area, A_s) and wheel sinkage Z will be related to each other in achieving force balance in the wheel system. The lug size is determined by optimization using the above equations.

Results and Discussion

The results of the measurement of the resistance of the paddy field to the penetration of the plate indicate that there is an increase in resistance for each increase in the depth of penetration. For rice fields in Cianjur Regency, the pattern of increasing resistance is not linear and tends to have a sharp increase at a depth of 0-10 cm, followed by a gentle increase at a depth of 10-15 cm and again a sharp increase at a depth of 15-20 cm. The results of the measurement of soil resistance to plate penetration for rice fields in Cianjur are presented in Figure 6-10 for penetration angles of 30^o, 45^o, 60^o, 75^o and 90^o, respectively. For rice fields in Subang the results are presented in Figure 11-15.

For rice fields in Cianjur, at a depth of 15-20 cm with a penetration angle of 90^o the resistance is about 60 kPa. The highest resistance is almost the same for each angle of penetration. Under these conditions, the two wheel tractor lug wheels are still difficult to hold at a depth of 15-20 cm. The sinking of the wheel (sinkage) will be higher in this Cianjur rice field location.

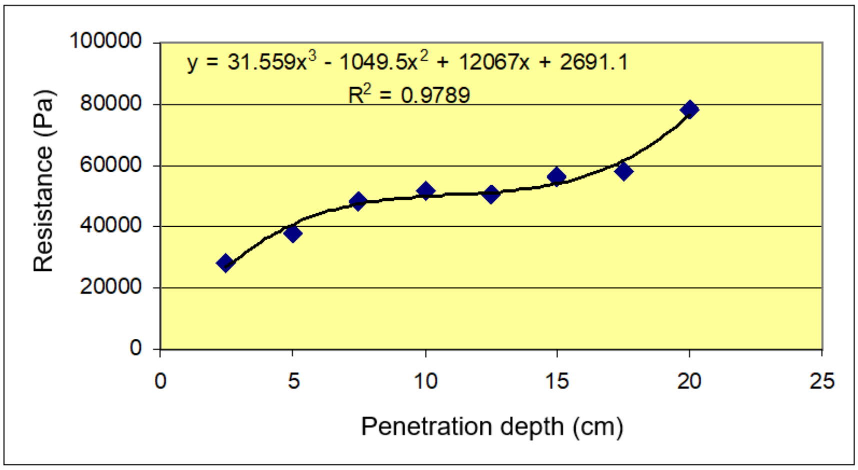

Figure 6. Plate penetration resistance at a penetration angle of 30° in the rice fields of Cianjur Regency.

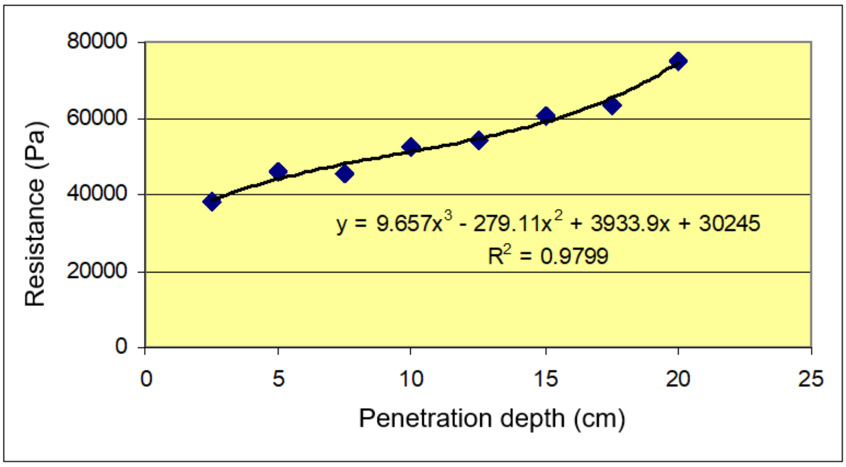

Figure 7. Plate penetration resistance at a penetration angle of 45° in the rice fields of Cianjur Regency.

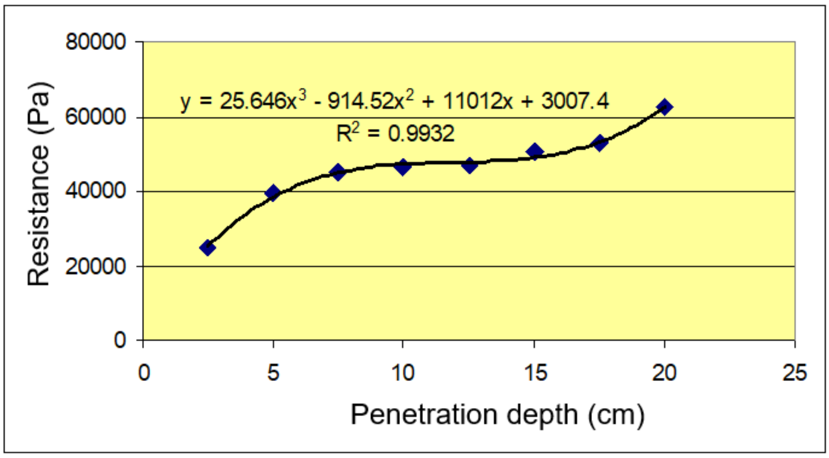

Figure 8. Plate penetration resistance at a penetration angle of 60° in the rice fields of Cianjur Regency.

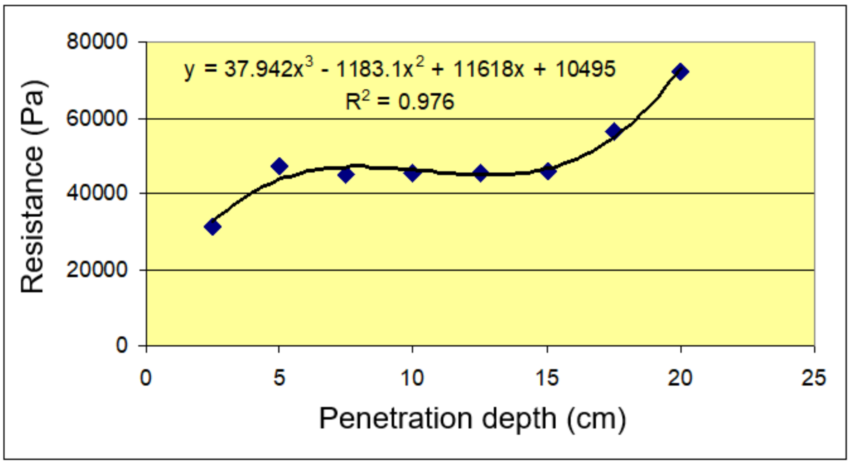

Figure 9. Plate penetration resistance at a penetration angle of 75° in the rice fields of Cianjur Regency.

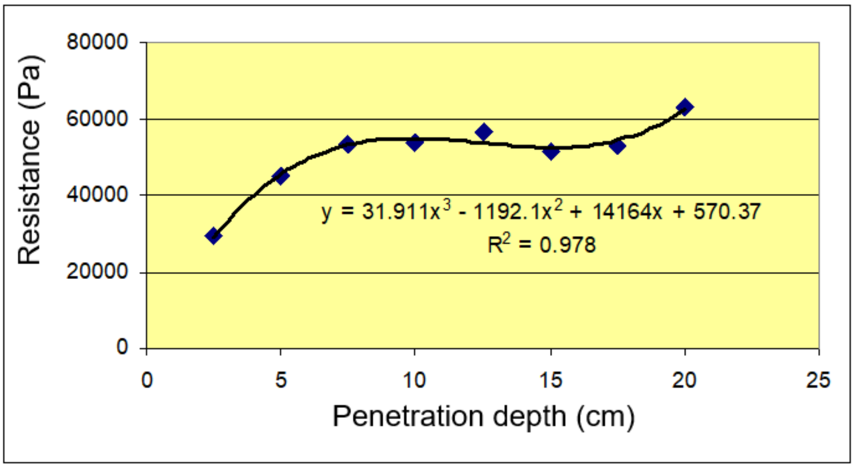

Figure 10. Plate penetration resistance at a penetration angle of 90° in the rice fields of Cianjur Regency.

In contrast to the Cianjur rice fields, the plate pressure resistance in the Subang rice fields has a characteristic that continues to increase quite sharply from 6 cm to 20 cm deep. Hard layers have been found at a depth of 15-20 cm. The measurement results show that at a depth of 15-20 cm, the compression resistance of the plate is more than 90 kPa (for a compression angle of 90°). With these conditions it can be predicted that the lug wheel can be held quite well at this 15-20 cm depth. Observations on the operation of the two-wheel tractor at the measurement site (Subang) showed that the wheels did not sink deep enough. The tractor can also operate without significant obstacles during tillage.

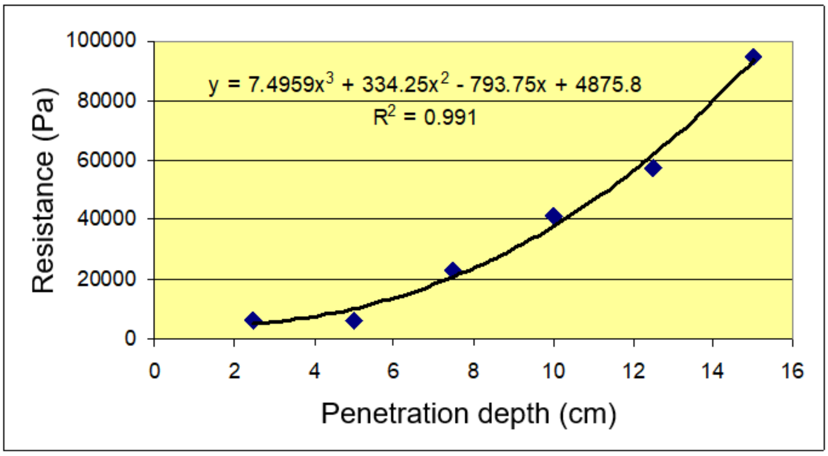

Figure 11. Plate penetration resistance at a penetration angle of 30º in the rice fields of Subang Regency.

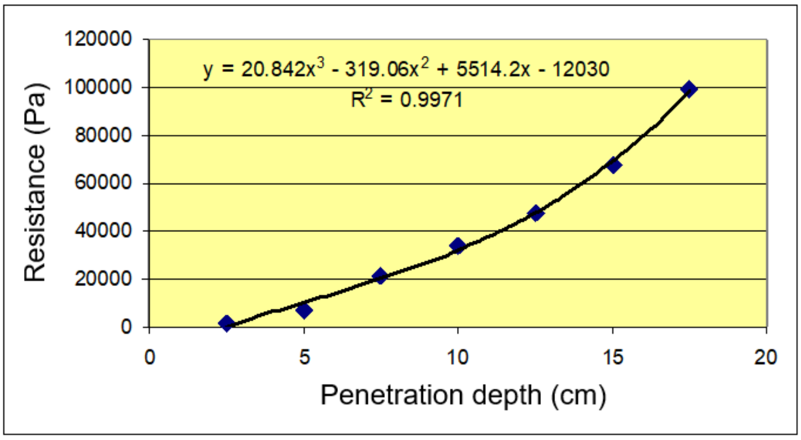

Figure 12. Plate penetration resistance at a penetration angle of 45º in the rice fields of Subang Regency.

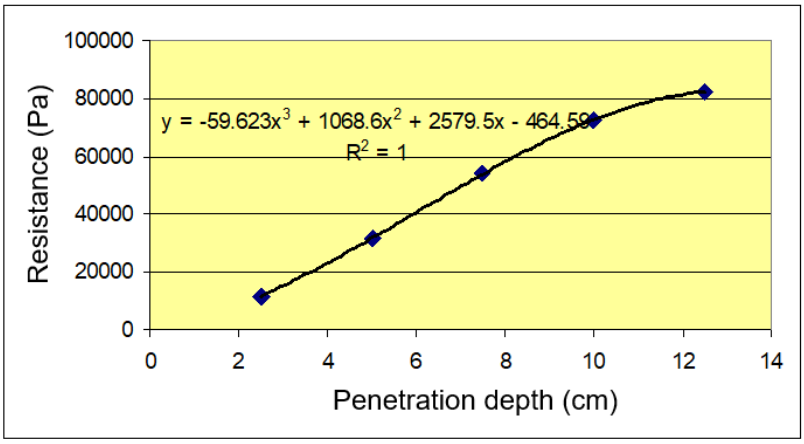

Figure 13. Plate penetration resistance at a penetration angle of 60º in the rice fields of Subang Regency.

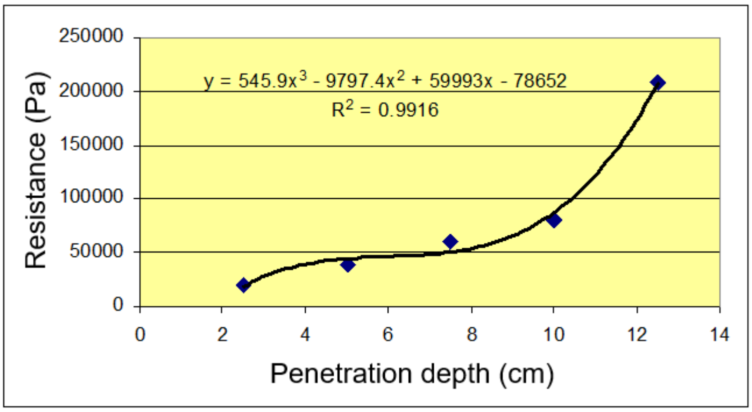

Figure 14. Plate penetration resistance at a penetration angle of 75° in the rice fields of Subang Regency.

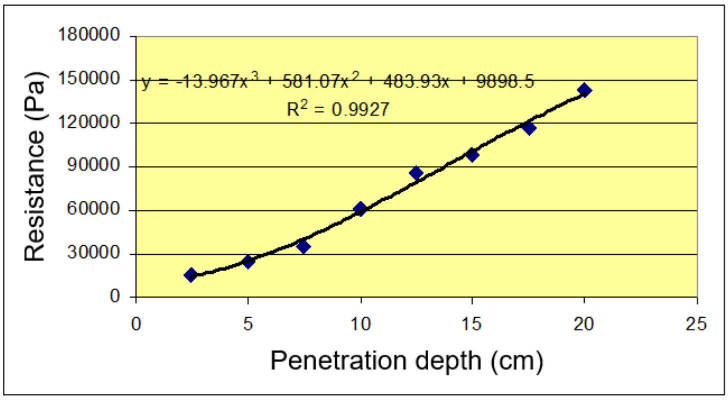

Figure 15. Plate penetration resistance at a penetration angle of 90° in the rice fields of Subang Regency.

The results of the measurement of soil resistance against plate penetration indicate that the deeper the penetration, the higher the soil resistance. Among the plate widths of 2.5, 3.75 and 5 cm (with the same length of 10 cm), plate with a narrower width tends to produce a greater soil resistance than wider plate. Among the compression angles of 30, 45, 60, 75 and 90 degrees, which results in better horizontal and vertical soil resistance is the 45° penetration angle. On this basis, the angle of inclination of the lug plate on the wheel in the design is determined 45° to the horizontal line. The depth of the hard paddy soil at the measurement site in Cianjur is quite deep (range 20-30 cm), while the rice field at the measurement site in Subang is quite shallow (in the range of 10-15 cm).

The results of the tractor construction measurements at both locations are presented in Table 1.

Table 1. Specifications of the local lug wheel and tractor used in Cianjur and Subang

Parameter	Dimensions dan Data	
	Cianjur	**Subang**
Tractor engine	Kubota RD8r	Kubota RD85
Tractor main frame	Quick G600	Quick
Total weight of traktor and lug wheel	325 kg	200 kg
Height of tractor handle (H_o)	113 cm	126 cm
Ground Clearence (H_c)	29.5 cm	28 cm
Radius of tractor gear box (H_t)	11.5 cm	14 cm
Outer radius of lug wheel (R_w)	41 cm	44.5 cm
Distance from gear box to wheel boss bolt hole (L_w)	20 cm	20 cm
Wheel boss bolt hole distance to flange (H_b)	1.5 cm	1.5 cm
Flange to inner rim distance (H_h)	3 cm	4.8 cm
Rim radius (R_r)	34.75 cm	74 cm
Distance between rim (W_r)	28.5 cm	40.8 cm
Rim number	2	3
Diameter of rim material	14.6 mm	1.59 (side) 1.05 (center)
Lug length (W_l)	27 cm	40 cm
Lug width	8 cm	11.75 cm
Lug plate thickness	4.5 cm	3 mm
Lug plate material	Steel plate	Steel plate
Lug number (L_n)	14	14
Lug linier space (L_s)	17.5 cm	20.7cm
Lug angle	42^o	30^o
Spokes number	8	5 inner, 5 outer
Distance of crank arm to lug wheel axle	48 cm	63 cm
Implement distance to lug wheel axle	89.66 cm	110 cm
Crank distance to the center of the body	30 cm	36 cm

The following describes the application of the measurement results in determining the design of the lug wheel for the Cianjur location. In analyzing the determination of the maximum diameter of the wheel, the data used are 1) the distance from the wheel axle to the crank arm is 48 cm, and 2) the distance from the wheel axle to the implement is 90 cm. From these data, and assuming that the maximum fist thickness when cranking the tractor is 5 cm, the wheel diameter of the tractor is obtained as follows. Maximum radius

R_{max} = 48 cm - 5 cm = 43 cm.

Maximum wheel diameter

$D_{max} = 2 \times R_{max} = 2 \times 43$ cm = 86 cm.

The minimum diameter of the lug wheel for Cianjur location is obtained from the data for the base radius of the reduction gear box (H_t) of 11.5 cm. By setting the ground clearance (H_c) not less than 5 cm and the wheel sinkage (Z) not more than 20 cm, the minimum radius of the wheel

$R_{min} = Z + H_c + H_t = 20 + 5 + 11.5 = 36.5$ cm.

Minimum wheel diameter

$D_{min} = 2 \times R_{min} = 2 \times 36.5 = 73$ cm.

Thus the minimum wheel diameter is 73 cm and the maximum is 86 cm. In determining the diameter of the wheel and the size of the lugs, it is planned to analyze the wheel diameters of 75, 77.5, 80, 82.5, and 85 cm.

The diameter of the wheel, the number of lugs and the size of the lug plate are determined from the calculation of the soil reaction force on the active wheel lugs. The size is chosen which provides a vertical directional reaction force exceeding the weight of the tractor and wheels (325 kg) where for one wheel it is 162.5 kg (1.6 kN). The soil reaction force in the horizontal direction is not less than the pull load and the rolling resistance of the wheels is 0.9 kN for one wheel. The compressive force is assumed to be 0.6 of the reaction force of the soil to the plate penetration (from the measurement data), taking into account that at the time of measurement the plate presses the soil which is still intact, while on the wheel the lug plate will press the soil which has been cut off one side by the lug that precedes it.

The results of the calculation of the soil reaction force on the lug wheel are presented in Appendix 1. Another thing to note is that if the turning angle is greater than 120 degrees, then the soil reaction force is considered zero, because the lugs are no longer pressing against the soil. It will leave the ground. This is for slips under 25%. (Hermawan, et al., 1996).

From observations in the field, with a wheel diameter of 82 cm, it turns out that the bottom of the tractor's gear box almost erodes the ground, the wheel sinks almost half. Therefore, the wheel diameter needs to be increased, even though there is limited free space (engine crank), and the maximum diameter can be 86 cm. The wheel lugs are 14 with a lug area of 217 cm^2 which needs to be expanded because with that size the sinking of the wheel is very deep. Accordingly, the lug area of the wheel must exceed 217 cm^2, when 14 lugs are used.

After simulating the force requirement on the active wheel lugs (F_v = 1.6 kN, F_h = 0.9 kN) and taking into account that the wheel diameter is 85 cm, the number of lugs selected is 14 pieces (based on field data obtained) with wheel sinkages 5, 10, 15, 20 cm, it is concluded that the number of lugs is 14, the lug spacing angle is 25.7^o, and the lug area is 280 cm^2.

In determining the length and width of the lugs, it is assumed that the wheel slip is 25% and the lug width is not more than 0.7 of the lug spacing. With a wheel diameter of 85 cm, the number of lugs is 14, the horizontal space between the lugs is 14.3 cm and the lug width is at least 10 cm (Table 2). By taking a lug width of 8 cm (qualified), and a lug area of 280 cm^2, the lug length is 35 cm.

Table 2. Horizontal spacing between fins and determination of fin width (Cianjur) with a wheel diameter of 85 cm

Lug number	Lug spacing (L_s)		Horizontal spacing	Maximum lug width
	(cm)	(^{o})	(cm)	(cm)
12	22.00	30.00	16.689711	11.6828
14	18.91	25.71	14.305467	10.01383
16	16.58	22.50	12.517283	8.762098
18	14.76	20.00	11.126474	7.788532
20	13.30	18.00	10.013827	7.009679

Thus, for the Cianjur location, the design parameters of the lug wheel are obtained as presented in Table 3.

Table 3. Design parameter of finned iron wheel for Cianjur location

No.	Design Parameters	Size, Number
1	Wheel diameter	85 cm
2	Lug number	14
3	Lug width	8 cm
4	Lug length	35 cm

Furthermore, using the same analysis method, the design size of the lug wheel for the Subang location is obtained as shown in Table 4.

Table 4. Design parameter of finned iron wheel for Subang location

No.	Design Parameters	Size, Number
1	Wheel diameter	85 cm
2	Lug number	14
3	Lug width	10 cm
4	Lug length	35 cm

Conclusion and Recommendations

Conclusions

1. The reaction force of the soil to the lug plate can be determined by practical measurements using a penetrometer with a tip equipped with a pressure plate, and measured at several levels of penetration angle.
2. The data from the measurement of the reaction of the paddy field to plate penetration can be used properly to determine the design of the lug wheels for a hand tractor.
3. The tilt angle of the lug that provides optimum lift and thrust is 45^o. Based on the results of the analysis of the design parameters of the movable lug wheel prototype for the Cianjur area: wheel diameter is 85 cm, number of lugs is 14, lug width is 8 cm, lug length is 35 cm. The design parameters of the movable lug wheel prototype for the Subang area: wheel diameter is 85 cm, number of lugs is 14, lug width is 8 cm, and lug length is 35 cm.

Recommendations

1. The process of designing a movable lug wheel with a spring-loaded lug mechanism needs to follow the design stages as described in this paper, among others, by using soil resistance data against plate penetration.
2. To provide optimum thrust and lift, the angle of inclination of the lugs when working in the ground needs to be set to 45^o.

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