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EVALUATION OF DESIGN PARAMETERS OF WHEELS OPERATING ON SOFT PADI SOIL

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RINGKASAN

Satu kajian ke atas kertas-kertas terbitan yang lepas mengenai dengan perhubungan antara sifat-sifat fisikal tanah dan "trafficability" atau kebolihan trektor dan jentera-jentera bergerak di atas tanahnya telah dijalankan. Untuk ini sifat-rupa tanah-tanah sawah di rantau Muda telah dikaji. Kekuatan tanah didapati bergantung kepada paras air dalam tanah itu. Dalam kajian mengenai "trafficability" di atas tanah-tanah sawah padi yang lembut, didapati bahawa kesanggupan "bearing" dan "traction" tanah itu adalah faktor-faktor yang mustahak ketika mereka bentuk roda. Satu bentuk tayar roda untuk digunakan di atas tanah-tanah sawah padi yang lembut telah dicipta mengikut teori dan tayar-tayar yang berbentuk tersebut telah didapati dan diuji dibendang. Dari keputusan yang diperolihi kuat menunjukkan bahawa ada korelasi di-antara kegunaan yang ditunjukkan oleh tayar dibendang dan teori yang dikemukakan.

INTRODUCTION

The need for mechanisation in rice production was evident even before the introduction of double-cropping. Seasonal labour shortages during peak labour period of land preparation, transplanting, harvesting and transportation, and the rising costs of labour could not be effectively solved without mechanisation. Timely performance of each of the above field operations through mechanisation is of necessity in order to meet the rigid schedule requirements of double-cropping.

A major constraint in rice mechanisation is soft soil trafficability. Bogging of agricultural machines (e.g. tractors) in soft soil padi land is a continual problem in Malaysia. It therefore becomes necessary to carry out mobility studies of agriculture machine on soft padi soil. This could take the form of fundamental investigation of the stresses induced by the machine on the soil, bearing capacity and traction capacity of the soil and their interrelations. The ultimate aim would be the study of the traction phenomenon for the purpose of establishing design specifications of the traction wheels.

BASIC TRAFFICABILITY CONSIDERATION

The basic requirements for trafficability are that the soil in contact with the wheels must have sufficient bearing capacity to prevent the wheels from sinking too deep and sufficient traction capacity to provide the necessary forward thrust of the wheels (1). Both bearing capacity and traction capacity of the soil are functions of the shear strength of the soil as well as the design specifications of the wheels. Traction failure can occur without appreciable sinkage for a smooth or treadless tyre on wet clay soil which has a hard pan just below the surface. On the other hand sinkage failure will always be accompanied by traction failure (3). Therefore in the design of wheel parameters for soft paddy soil, both traction and sinkage capacities are to be considered simultaneously.

REVIEW OF RELEVANT WORK

(i) Relationship between trafficability and soil properties

Much work had been carried out on the study of the relation between trafficability and physical properties of the soil (2, 3, 4, 5, 6). In most of these studies, the bearing traction capacity was measured empirically in terms of the cone index (kg/cm^2) at certain cone penetration depth (cm). The minimum soil bearing capacity for power tiller mobility and tractor mobility in Muda area was reported to be 1.6 kg/cm^2 and 2.9 kg/cm^2 respectively at cone penetration depth of 20 cm(2).

The maximum tolerable sinkage of a tractor wheel as measured from the lug base was reported as 10 cm. which was equivalent to a travel reduction of about 40% (3). In a separate study on soil bearing capacity in Muda area by MARDI, it was found that 100% slip occured when depth of wheel sinkage was more or less one-third the diameter of the wheel (4).

Empirical relations for prediction of trafficability and the traction ratio of tractor, the draft of plow and the torque of rotary tiller from the cone index, plate sinkage or shear resistance of the soil were derived and presented by KISU (5). WISNER and LUTH (6) developed and presented empirical relations for prediction of towed force (or motion resistance) of towed wheel, required wheel torque of driving wheel, wheel pull (parallel to soil surface) and tractive efficiency in terms of cone index. Reasonally good prediction was claimed by the latter for tyres ranging from 14 to 33 in. (35.6 cm. to 83.8 cm.) in width, 33 to 65 in. (83.8 cm. to 165 cm.) in diameter and wheel load from 800 to 6500 lbs. (363.0 kg. to 2950.0 kg.) on cohesive-frictional type of soil.

(ii) Relationship between trafficability and wheel parameters

The effects of lug angle and lug spacing on traction performance of a pneumatic tyre was experimented by TAYLOR (7, 8). In clay and silt loam, there was no clear indication that lug spacing affected the tyre tractive performance. Effect of lug angle on tractive performance was found to be negligible. In an earlier report, however, it was claimed that high angle lugs (80 degrees) were best for clay, the low angle lugs (40 degrees) in loam and an intermediate angle lugs (65–70 degrees) in sand.

Under field conditions reported at Netherlands, wider lug spacing on deep lug tyres (R-2 tread) provides better self-cleaning in very wet clay. Shallow lugs (R-1 tread) smears and losses self-cleaning ability in wet clay and occurs at lower drawbar pull with more closely spaced lugs. It should be noted here that lug spacing and lug height may interact with other lug variable like lug angle, lug shape, tread width and tread curvature to affect the tyre tractive performance.

DATT and OJHA (9) carried out a theoretical study on traction phenomenon in puddled soil condition. Their theory of traction wheels explains as to why the performance of cage wheels is better than the pneumatic wheels in the puddled soil.

PROCEDURE AND SCOPE OF STUDY

A systematic study was carried out on the physical characteristics of the soil in Muda and on its trafficability; and the reasons for the soil decreasing bearing capacity to support the weight of tractors. The effect of the water table level on soil properties was also noted. Soil bearing capacities at cone penetration depths of 10 cm., 20 cm., 30 cm., and 40 cm. were measured during the various stages of rice production in a 12 m. x 10 m. experimental plot in Muda. The soil composition was 58% clay, 30% silt and 12% sand in the top 10 cm. layer. A Fiat 540 tractor was used in the trafficability trials.

The other part of the study consists of the investigation of the traction phenomenon in the soft paddy soil in order to design wheels which will give the maximum traction efficiency. This theoretical work follows partly the analytical work of DATT and OJHA (9) and that of ONAFEKO (10) and is being developed subject to the soil conditions prevailing in Muda, a major coastal rice growing area in Malaysia.

The last part of the study was the derivation of wheel design specifications and the conducting of performance studies on the designed traction wheels.

SOIL CHARACTERISTICS

Soil conditions was found to be quite accurately specified in terms of cone index (kg/cm^2) only if measurements were taken at more than two cone penetration depths e.g. 10, 20, 30 and 40 cm. This might be clearer if we examine *Fig. 1*. It can be seen that the soil resistance to cone penetration was not uniform nor does it vary uniformly with depth. The cone index at 10 cm. depth was distinctly different from that at 20, 30 and 40 cm. whose values tended to be similar (4). This is characteristic of the soil in padi land which has a hard pan several inches below the surface. The thickness of the clay soil above the hard pan however varies from area to area. In certain areas it may be bottomless mud flats.

The padi land was wet most of the year as can be seen from *Fig. 1*. It was only during the main season harvesting period that the land was effectively drained. During off-season harvesting period, it was difficult to dry the field completely. The average rainfall for the month of July, for example was 198 mm. for the three year period from 1971–73 while the pan-evaporation rate was estimated to be about 170 mm. As a result of the soil condition the use of tractors normally resulted in bogging or formation of ruts and disturbing the subsoil. The use of strakes and similar devices to lever the tractor out of these bogs, invariably penetrated deeper into the pan resulting in more damage to the soil.

In a separate experiment it was found that the water table level should be at least 30 cm. below ground level in order to achieve soil bearing capacity of 3.0 kg/cm^2 at 20 cm. cone penetration depth. It was noted that the saturated wet clay below the water table level and the less wet upper layer of soil was a bogging-trap to tractors (and combines) once this upper layer of soil was being displaced or penetrated by the wheels.

TRACTION IN SOFT PADDY SOIL

The tractive efficiency of the traction wheels in soft paddy soil is quite low. The present study on traction wheels was therefore aimed at improvement in the design of the wheels. Relations governing the effect of wheel parameters on traction in soft padi soil conditions were developed and presented below.

(i) Buoyancy force on the wheel

The buoyancy force on the wheel depends on the volume of muddy water that is being displaced by the wheel as it sinks into the layer of soft clay soil. This bouyancy force reduces

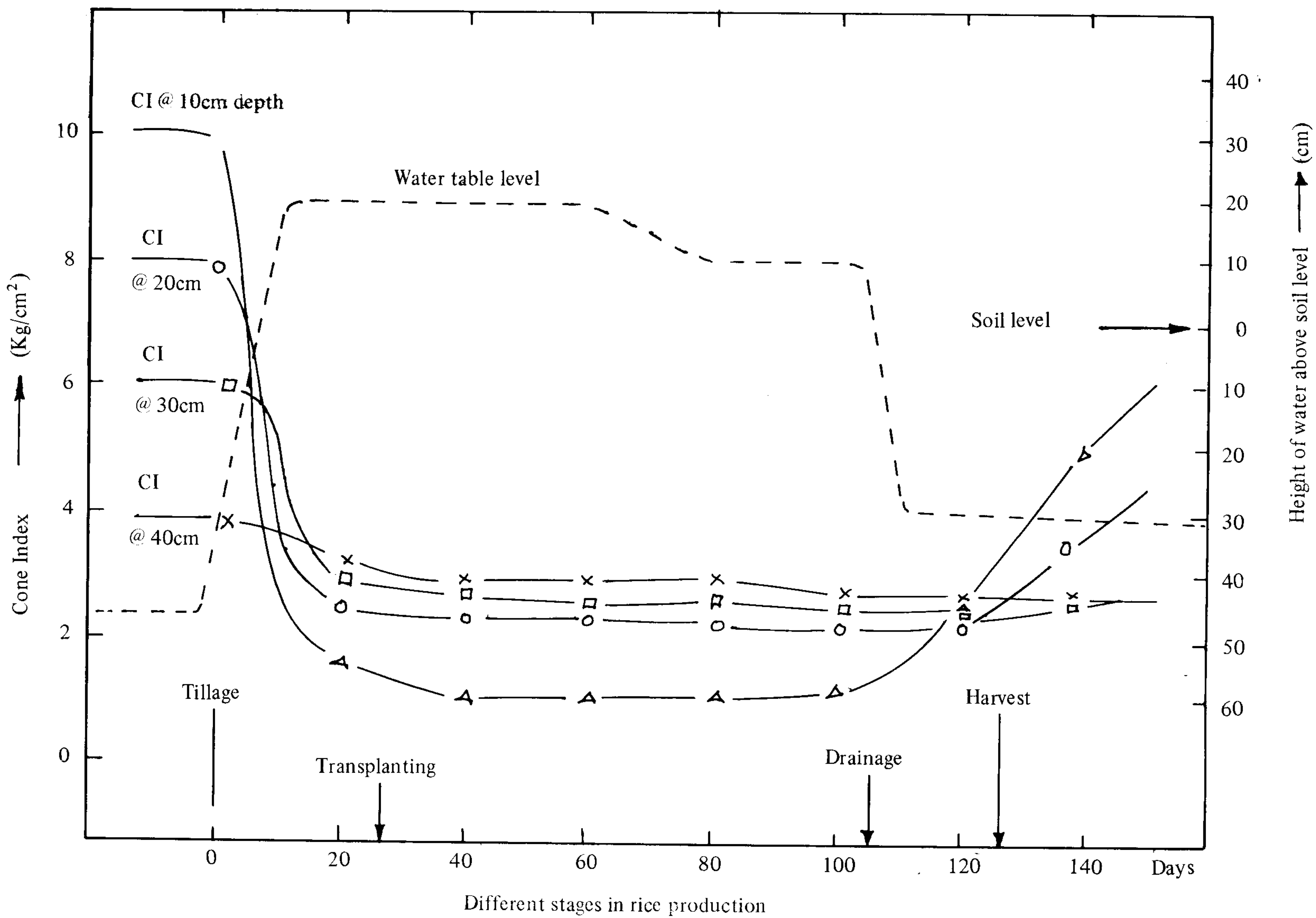

Figure 1. Soil cone index at different stages of rice production.

the force exerted by the wheel on the soil. The latter force (exerted by the wheel on the soil) is reduced to zero if the bouyancy force equals the normal load on the wheel.

Assuming the muddy water to be a liquid of specific weight φ, the buoyancy force, M acting on a solid wheel of radius r and width b is given by the weight of muddy water displaced, i.e.

$$M = b\varphi\,[r^2 \cos^{-1}(\frac{r-k}{r}) - (r-k)\sqrt{2rk-k}] \qquad (1)$$

where k = depth of wheel below liquid surface.

(ii) Rolling resistance of a solid wheel

The rolling resistance losses of a rigid wheel operating on deformable terrain of soft soil padi land can be obtained by considering all the forces acting on the wheel.

Assuming the soil shear stress and bearing stress at the wheel-soil interface to be uniform and equal to t and p respectively (as shown in *Fig. 2)*, the component forces acting on the rigid wheel (of radius r and width b) as shown in *Figures 3 and 4* can be expressed by the equations below.

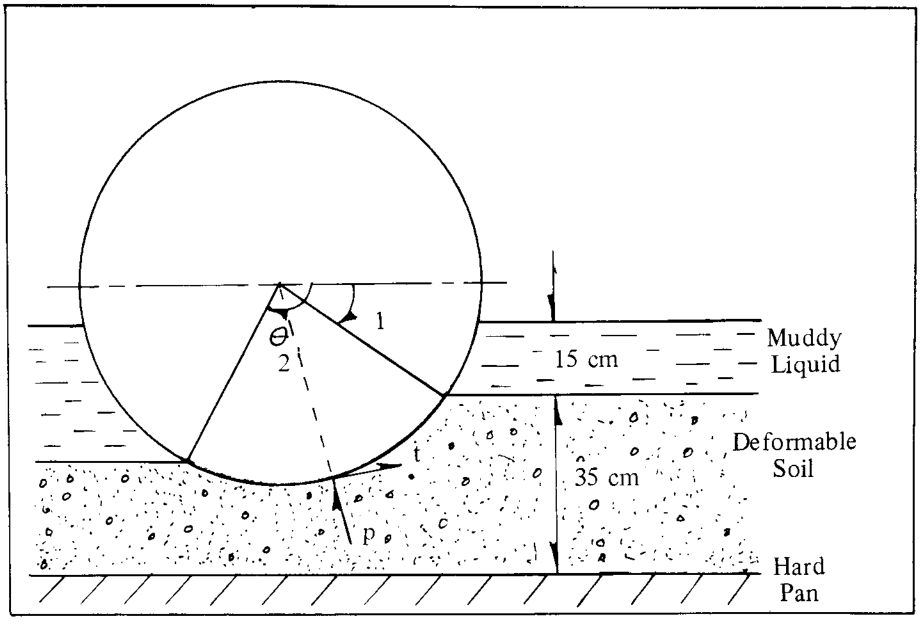

Figure 2. Soil stresses induced by wheel.

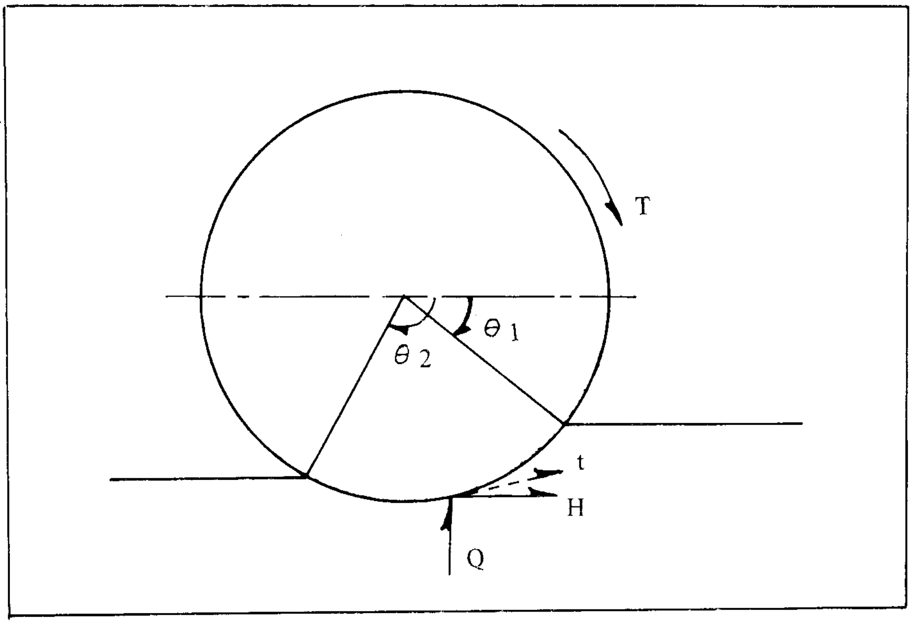

Figure 3. Component forces of soil shear stress 't'.

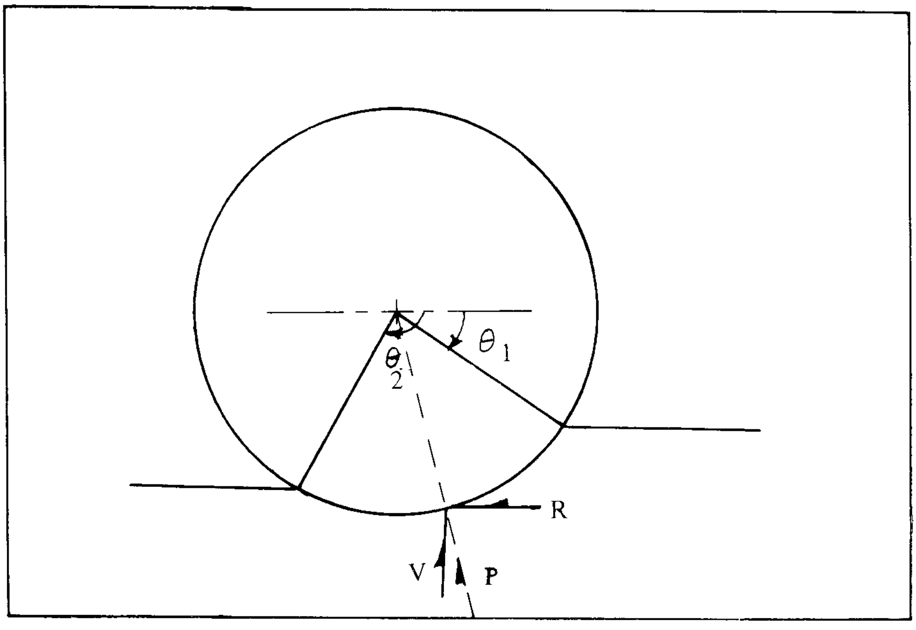

Figure 4. Component force of soil bearing stress 'p'.

The translational rolling resistance, R as shown in *Fig. 4* is given by the horizontal component force due to soil bearing stress p, i.e.

$$R = \int_{\Theta_1}^{\Theta_2} p.\text{Sin}\,\Theta\,.\,rb\,d\Theta$$

$$= rbp\,(\text{Sin}\,\Theta_2 - \text{Sin}\,\Theta_1) \qquad \text{---------- (2)}$$

The radial support force, V as given by the vertical component force due to soil bearing stress p is,

$$V = rbp\,(\text{Cos}\,\Theta_1 - \text{Cos}\,\Theta_2) \qquad \text{---------- (3)}$$

The tractive (or braking) force, H as shown in *Fig. 3* is given by the horizontal component force due to soil shear stress t, i.e.

$$H = rbt\,(\text{Cos}\,\Theta_1 - \text{Cos}\,\Theta_2) \qquad \text{---------- (4)}$$

The shear support force Q as given by the vertical component force due to soil shear stress t is,

$$Q = rbt\,(\text{Sin}\,\Theta_2 - \text{Sin}\,\Theta_1) \qquad \text{---------- (5)}$$

The driving (or braking) torque T is given by the moment of the tangential force due to soil shear stress t about the axis of rotation of the wheel, i.e.

$$T = \int_{\Theta_1}^{\Theta_2} r.t.\,rbd\Theta$$

$$= r^2 bt\,(\Theta_2 - \Theta_1) \qquad \text{---------- (6)}$$

The total losses in a wheel consist of internal or mechanical losses due to friction, rotational losses due to slip i, viscousity of muddy liquid and shear support force Q, and translational losses due to translational rolling resistance R and viscousity of muddy liquid (or drag). The total motion resistance of the wheel is due to these losses which vary with the slip i.

(iii) Effect of lugs

The effect of lugs on a tyre is to increase the wheel's grip onto the soil. Shearing of the soil may then possibly take place at the soil interface, tangential to the tip of the lugs. Slip occurs when the soil masses between the lugs are not able to withstand the tractive thrust applied by the lugs on them. This would be clearer if we consider the soil mass between two successive cuts made by lugs of a moving wheel as shown in *Fig. 5*. The path of the tip of a lug as it comes into contact with the soil at zero slip condition is shown by the dotted line. It is noted that the soil in front of the lug is compressed as the lug is being lifted out of the soil with the forward motion of the wheel for the case where the lug is straight and orientated normal to the wheel as in *Fig. 5*. The shape of the lug should therefore preferably follow the contour of the dotted line so that the whole back surface of the lug is in contact with the soil to spread out the tractive thrust at lug-soil interface, and so that the lug can lift itself out of

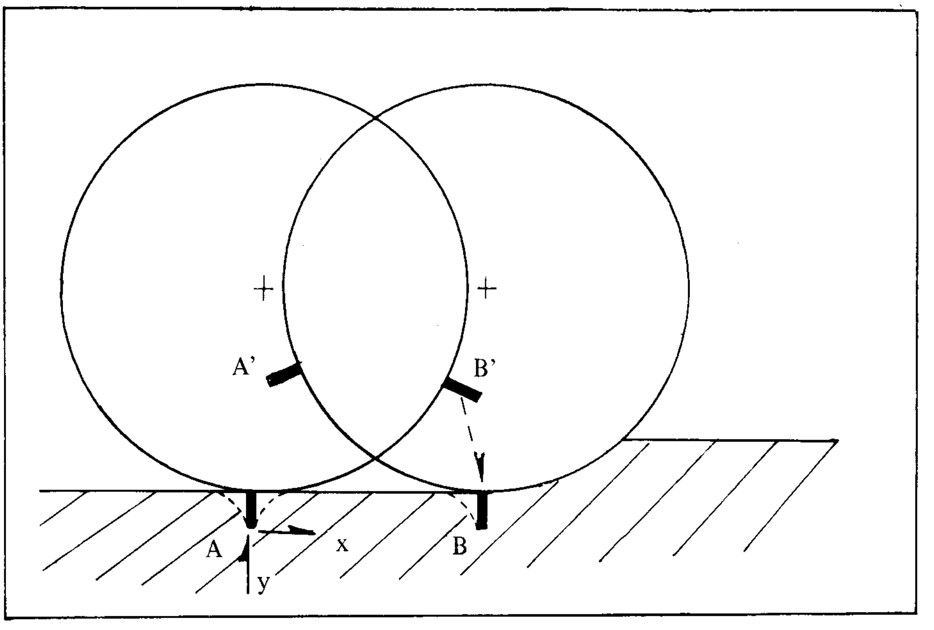

Figure 5. Successive soil cuts made by lugs.

the soil without compressing the soil with its front surface. Taking point A as the origin, the dotted line can be expressed by the equation,

$$x = r[\cos^{-1}(\frac{r-y}{r}) - \sqrt{1-(\frac{r-y}{r})^2}] \qquad (7)$$

With increasing slip, the length of soil masses between successive cuts made by the lugs decreases, down to a certain value called the minimum shear spacing when the soil suddenly shears off and the wheel starts spinning, giving a hundred percent slip. This minimum shear spacing, S is constant for a particular soil and wheel at constant load conditions.

The optimum lug spacing at zero slip condition, L is given by the equation,

$$L = 2X + S \qquad (8)$$

where x = X for y = Y, the lug height. Substituting into equation 7 we have,

$$X = r[\cos^{-1}(\frac{r-Y}{r}) - \sqrt{1-(\frac{r-Y}{r})^2}] \qquad (9)$$

Assuming L_i to be required lug spacing for wheel operation at maximum slip i, then by defination,

$$i = \frac{L_i - L}{L_i} \qquad (10)$$

From equations 8, 9 and 10, L_i is worked out to be given by the equation,

$$L_i = \frac{2}{(1-i)}(r\cos^{-1}(\frac{r-Y}{r}) - r\sqrt{1-(\frac{r-Y}{r})^2} + \frac{S}{2}) \qquad (11)$$

WHEEL DESIGN AND TRACTION PERFORMANCE STUDIES

The soil condition chosen was typical of one in which tractors with standard tyres often got bogged down. The top 15 cm. liquid layer was made up of a mixture of soft puddled soil and muddy water where resistance to cone penetration was virtually zero. The next 35 cm. was the deformable soil layer which was made up of a 15 cm. layer of soil of 1 kg/cm^2 bearing capacity and the remainder of 2kg/cm^2 and more. Wheel sinkage as obtained from previous field measurements was about 10 cm. into the soil layer. The shear strength of soil was measured to be 0.3 kg/cm^2 average.

Under these conditions we found through theoretical calculations (see Appendix on the Design of Wheel Parameters of a Pneumatic Tyre) the need for a different tyre tread, 7.8 cm. (3 in.) deep lugs spaced at about 30.5 cm. (12 in.) apart, so as not to shear off the soil. Tyres to this specifications were acquired from United States through the assistance of F.A.O. (Food and Agriculture Organisation of the United Nations).

Under field conditions tested in MARDI stations at Bumbong Lima and Parit, it was found that these tyres enable standard tractors to be used in places where soil resistance to cone penetration at 2 kg/cm^2 pressure was registered at less than 33 cm. below soil surface level. This therefore included some of those areas where even standard power tillers would become bogged. In marginal areas where soil resistance to cone penetration at 2 kg/cm^2 pressure was registered at deeper than 33 cm. but less than 40 cm. below soil surface, shearing of the soil and slipping took place. It was interesting to note that the soil did not clog up between the lugs. This self-cleaning ability was not observed in standard shallow lug tyres, commonly used in this country.

The most significant feature of this finding was that these tyres could easily be made locally using locally available rubber.

In contrast, the Dondi tracks that MADA (Muda Agriculture Development Authority) were currently testing, had to be imported and were quite expensive. Their working life was short (only about 500 hours) and were very much more difficult to extricate when become bogged.

CONCLUSION

The design parameters of a wheel operating in soft padi soil condition were evaluated and equations governing these parameters were developed and presented. The design specifications of the tyre that was derived using these equations subject to typical padi soil condition were 76.2 cm. x 35.6 cm. (or 30 in. x 14 in.) with lugs of 7.8 cm. (or 3 in.) depth and 30.5 cm. (or 12 in.) lug spacing. Tyres with these specifications were acquired and successfully field-tested, i.e. strongly indicating good correlation between the experimental results and the theory developed.

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SUMMARY

A literature review was made on the relation between physical properties of the soil and trafficability. The soil characteristics in the Muda area was studied. Effect of water table level on soil strength was noted to be significant. In the study on the traction phenomenon in soft paddy soil, it becomes obvious that both bearing and traction capacities of the soil must be considered in the design of the wheel. Design specifications of a tyre for typical soft padi soil condition were derived from theory and tyres meeting these specifications were acquired and field tested. The results obtained strongly indicate good correlation between the actual field performance of the tyre and the theory presented.

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APPENDIX

Design of Wheel Parameters of a Pneumatic Tyre

For a statio wheel with radius 76.2 cm. (30 in.) and width 35.6 cm. (14 in.), the total soil-wheel bearing area for a wheel sinkage of 10 cm. is approximately 2750 cm^2. Assuming an effective tractor load of 1300 kg. by each rear wheel on the soil, then the soil bearing stress at soil-wheel interface is about 0.47 kg/cm^2. For wheel sinkage less than 10 cm., the bearing area is smaller and consequently soil bearing stress is higher and vice versa. The effective normal load on each wheel furthermore decreases when wheel sinkage is deeper because of increase in buoyancy force as given by equation 1.

Consider a soil sample with a bearing capacity of 1 kg/cm^2 for the top 15 cm. layer below the muddy liquid and a shear strength of 0.3 kg/cm^2. Assuming Θ_1 and Θ_2 are 60° and 90° respectively, the bearing stress for the effective normal wheel load of 1300 kg. is about 0.95 kg/cm. On substitution for p in equations 2 and 3, we have,

$$R = 76.2 \times 35.6 \times 0.95 (\text{Sin } 90^\circ - \text{Sin } 60^\circ)$$
$$= 369 \text{ kg.}$$
$$\text{and } V = 76.2 \times 35.6 \times 0.95 (\text{Cos } 60^\circ - \text{Cos } 90^\circ)$$
$$= 1412 \text{ kg.}$$

The maximum tractive force obtainable under the above conditions is when t = 0.3 kg/cm^2 and on substitution for it in equations 4, 5 and 6, we have,

$$H = 76.2 \times 35.6 \times 0.95 (\text{Cos } 60^\circ - \text{Cos } 90^\circ)$$
$$= 434 \text{ kg.}$$
$$Q = 76.2 \times 35.6 \times 0.3 (\text{Sin } 90^\circ - \text{Sin } 60^\circ)$$
$$= 122.5 \text{ kg.}$$
$$\text{and } T = 76.2^2 \times 35.6 \times 0.3 \times \left(\frac{90-60}{180}\right)$$
$$= 29000 \text{ kg–cm.}$$

In order that the soil masses between successive cuts fail in shear and not in bearing at lug-soil interface, lugs should be high enough. Let the lug height be 7.8 cm. (3 in.), then maximum lug spacing at zero slip, L_{max} is given by,

$$1 \times 7.8 \times 35.6 = 0.3 \times 35.6 \times L_{max}$$

$$\text{i.e. } L_{max} = 26 \text{ cm.}$$

At maximum slip of 20 percent the lug spacing required is given by equation 10 as,

$$0.2 = \frac{L_{imax} - 26}{L_{imax}}$$

$$\text{i.e. } L_{imax} = 32.5 \text{ cm.}$$

Hence provide a lug spacing of 30.5 cm. (or 12 in.). From equation 11, it can be shown that the minimum shear spacing, S is 16 cm. Therefore the maximum horizontal tractive thrust that the soil can support at 20 percent slip is,

$$H_{max} = H + 16 \times 35.6 \times 0.3$$
$$= 434 + 171 \text{ kg.}$$
$$= \underline{\underline{605 \text{ kg.}}}$$

The drawbar pull, D_b is given by

$$D_b = H_{max} - R - D_v$$

where D_v is the drag force acting on the wheel. This drag force on a particular wheel is dependent on the viscousity of the muddy liquid and on the depth of the wheel below the liquid surface. A sharp increase in drag force would be expected when tractor axles and crankcase go below the liquid surface.

Assuming a drag force of 140 kg. (estimated from previous experiment) the drawbar drought available is,

$$D_b = 605 - 369 - 140$$
$$= 96 \text{ kg.}$$

This is sufficient for a rotary tiller to be used.