專　論

Walking Performace of A Chain-Driving Planetary Wheel for Uneven Hillside Vehicles

崎嶇坡地車輛用鏈條驅動行星式行走裝置之研究

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中　文　摘　要

為配合政府開發坡地資源，在水土保持保育利用原則下，供作農牧用途之長遠計畫，研究一種適用崎嶇多雨坡地條件之曳引機，於天然岩石植生坡地間爬行作業者，至有需要。

調查測知數處本省坡地土壤力學特性及地形特徵，並研究行走裝置之機動模式後，一種行星輪式驅動車體終被研製完成。行走特性線圖之測定結果顯示，此種由五只小輪成一梅花輪之行走性能，較之傳統之行走車輪為優異。由滑動率～轉矩之相關線圖顯示，其特性呈大小車輪行走特性之重疊效果。在一般平坦行走面，梅花輪與全輪驅動輪之作用雖相類似，但於崎嶇行走面，在土壓強度限度範圍內，可在滑動率極低之情況下，牽引係數及驅動係數呈直線增加，而牽引效率之下降率變化至為有限。

本文為有關梅花車輪行走特性及基礎理論之初步報告，對崎嶇田間牽引作業之最適機械設計條件，仍有待續行研究。

INTRODUCTION

In accordance with the generally known off-the-road locomotion theory, soil thrust is produced by rolling contacted wheel or moving track layer when relative deformation or slippage is simultaneously occured. In this case, the maximum propulsion of the vehicle is limited by local failure of stress-strain curve of the contacted soil.[5] Bekker's and Janosi-Hanamoto's expressions, and Yoshida's revised expression are all the same standpoints to calculate the soil thrust of vehicles.[2,4] However, in conventional traveling members' locomotion way , the wheel or track is not suitable for uneven hillside usage,[3] the plasto -elastic properties of soil would be causing an outflow of soil, and nose or belly. failures of vehicle in uneven ground would be a fatal fault in surface crossing.[1]

To correspond with the Government's long sight policy as to exploitating the the hillside lands, to develop a special form of vehicle which is able to climb up the naturaly constructed uneven terrain is studied in this University. Besides of general rolling locomotion , the vehicle is moved by the walking member if necessary in sted of rolling. A weighted 217 kg walking vehicle is produced to study the traveling characteristics. It is convinced that the planetary walking concept would spread out a new frontier in off-the-road locomotion.

MATERIALS AND METHODS

In order to understand the terra-mechanical properties of the hillside lands in Taiwan, a soil parameter measuring device, TN-4, is used. Also, a profilo-rule made in this University is drawn to take the topographical unevenness of the local

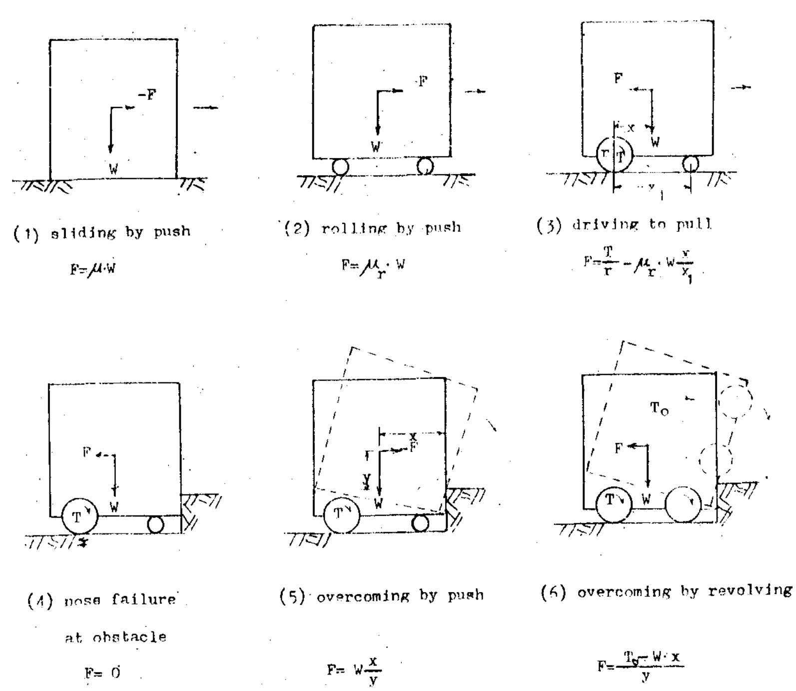


Fig. 1 Moving models of traveling member on surface crossing.

fields.

The moving models of traveling member on surface crossing is illustrated in Fig. 1. Nose failure would occured if driving torque could not overcome the passive earth pressure of its obstacle. Yet, it is possible to override the embankment or ditch by a turning over push force or revolving torque to its center

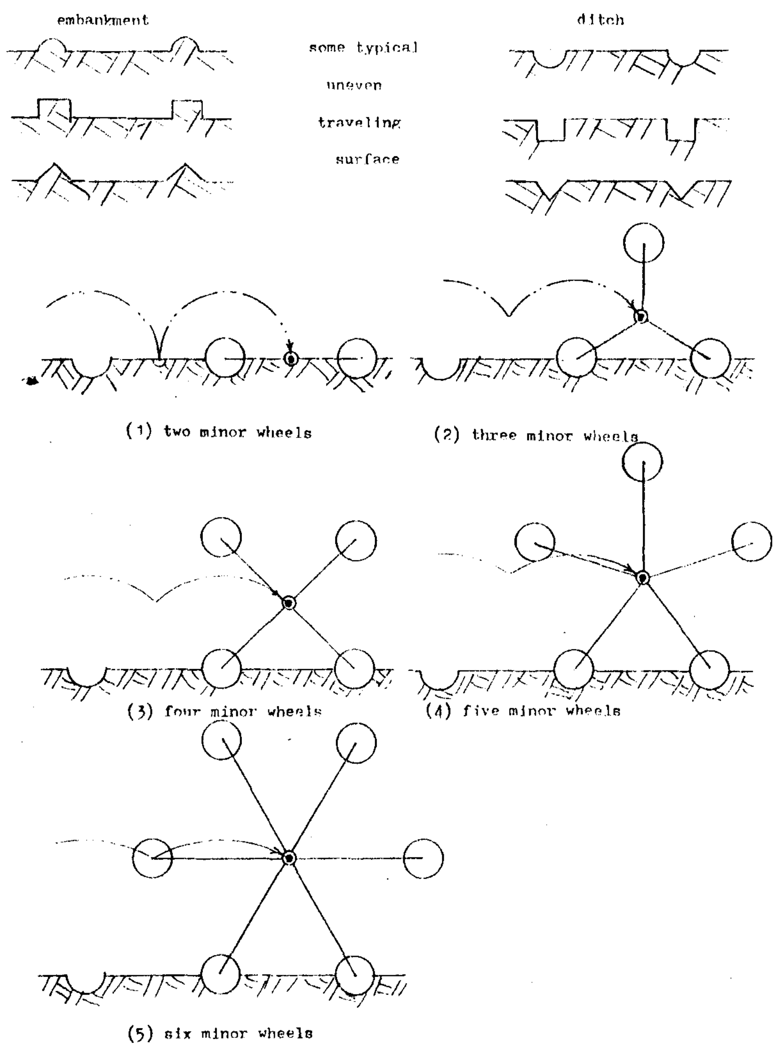


Fig. 2 Geometric illustration for walking trajectory of the planetary wheel's axle according to its minor wheel number.

of gravity. From the viewpoint of planetary wheel concept, plural minor wheels is necessary to constructed a walking wheel. As illustrated in Fig.2, above three minor wheel's planetary wheel is available. For the purpose to look forward the the transitional manner from self- rotation to planetary-revolution, an experimental walking vehicle with four planetary wheels in five minor wheels construction is produced. The effective radius of planetary wheel and minor wheel is 10.5 cm and 41.5 cm individually, a chain is driven by a 1/4 hp electric motor through a main shaft to these wheels. Table 1 shows the specification of the experimental vehicle.

Tab. 1 Specification of planetary wheel type experimented vehicle.

Item	Specification	Remarks
weight	217 kg	front wheels 126.5 kg { left wheel 60.32 kg; right wheel 56.18 kg }
length	182 cm	
wheel base	100 cm	
track	97 cm	
ground clearance	30 cm	
wheel diameter-rpm	planetary wheel: 83 cm-0.364 rpm, minor wheel: 21 cm-1.0345 rpm	
speed ratio	1 / 1710 (motor / minor wheel)	

The circumferential speed of minor wheel is nearly same as planetary ones by increasing the speed ratio between inside and outside sprockets. The torques on both the main shaft and the contacted minor wheel shaft are sensed by four pieces of strain gage through slip-ring , measured and recorded with Dynamic Amplifier, KYOWA DPM-3E6 and KYOWA RMS -11DPT "Rapicorder". The vehicle is traveled on flat concrete ground, saw-tooth shape uneven wooden surface and ditched soil field. Variable weight of load is hung over a wire-rope which is connected to the vehicle horizontally through pulleys to pull the vehicle backward as traction acted.

RESULTS AND DISCUSSIONS

Terramechanical Properties of Slopelands in Taiwan

Because of long period of expose in wind and rainfall, a great deal of gravel and unevenness are covered on most hillside surface. Except the failure loose slope, the general slopelands indicate fairy high penetrating resistance in limited depth, as shown in Fig. 3 (a),(b). Be notice that the soil friction angle ϕ shows quite large values in those shearing resistance diagrams.

The topograph of sandy slopeland soil presents a moderate unevenness in general. As indicated in Fig. 4 , the height of uneven is ranged 8 - 21 cm with the pitch of uneven at 25 ~ 35 cm. But however the degree of unevenness is increase with rock or gravel content, that is the problem for those off-the-road locomotion vehicles. Fig.5 shows one of the examples.

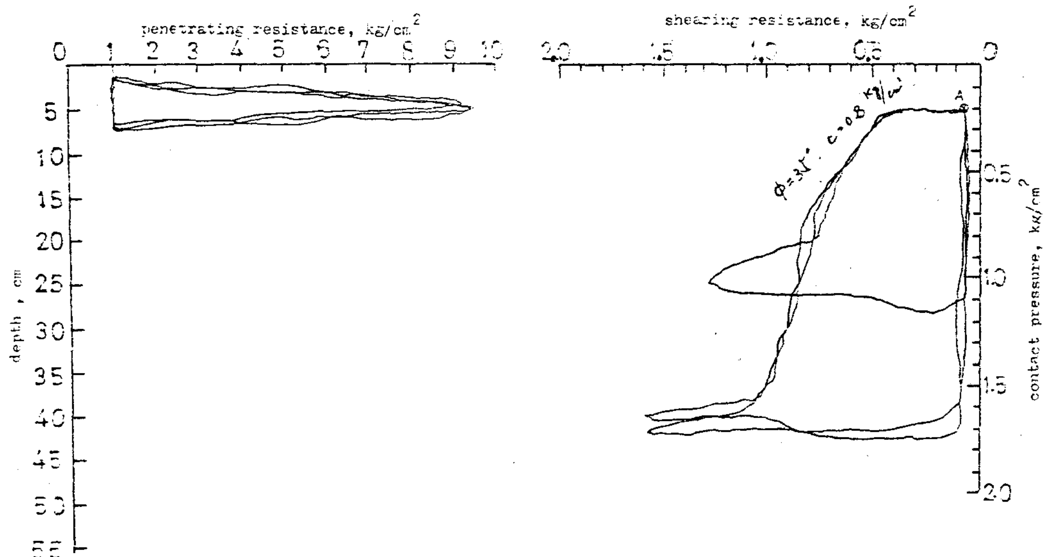
As Wong and Reece (1966) investgated the nature of the soil failure beneath wheels, they indicated that the flow of soil depends on the slip and causes rut filling behind the wheel and a bow wave in front[5]. Thus, the already made uneven ground may assist the wheel reducing slip , soil flow and failure. The available thrust H for a given ditch could be expressed as

$$H = (c + p \tan\phi) (1 - e^{-j\frac{p}{K}})$$

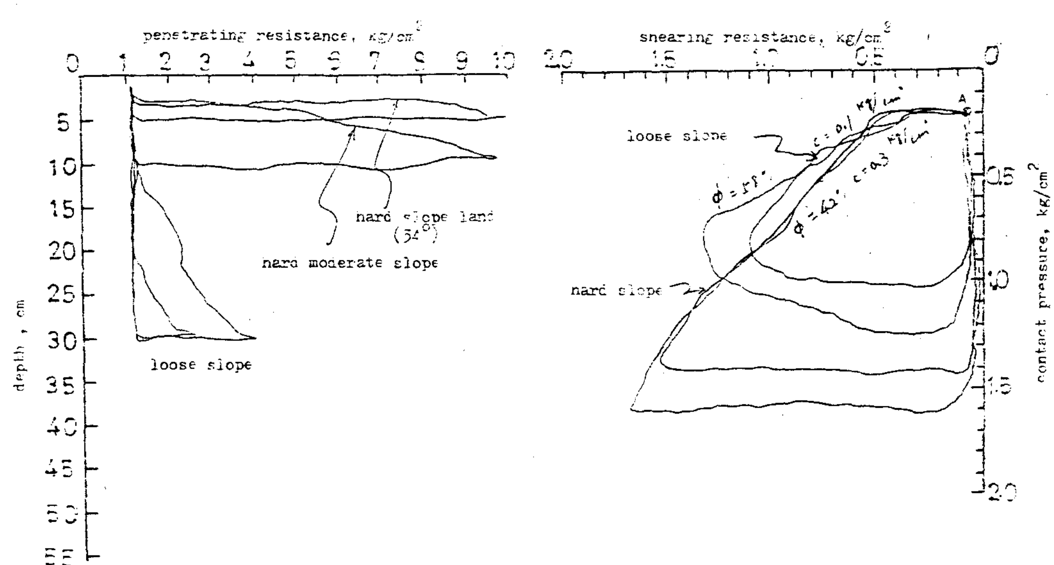
from the basis of Rankine's active earth pressure concept.

Chain-Driven Planetary Wheel For Uneven Slopeland Traveling

In normal low-resistance traveling surfaces, the minor wheels contacted by weight of the vehicle produce driving torques from main shaft ⑥, as shown in Fig. 6, making the vehicle propulsion in terms of contacted wheels 1,2, 1',2'. When the front contacted wheels rolling to the embankment or ditch, the pull force in chain ⑧ in relating to that contacted point, produce a driving torque in terms of the planetary wheel axle ①, then the minor wheels 3, 3' in sted of 1, 1' contact the ground as to continue travel. In general condition, the wheels slipping on that location even if producing continuous sinkage, if no planetary walking concept is considered.



(a) location :Hoo-ping, Tai-chung prefecture, the Central Traverse Highway
soil condition :gravel loam (slope 17 deg)
vegetation :miscellaneous trees
date :A.M. 11, Aug. 10, 1976



(b) location : Chi-lan san. the Northern Traverse Highway
soil condition : gravel loam
vegetation : cedar and cypress
date : P.M.2, Aug. 9, 1975

Fig.3 **Penetrating resistance and shearing resistance diagrams at hillside.**

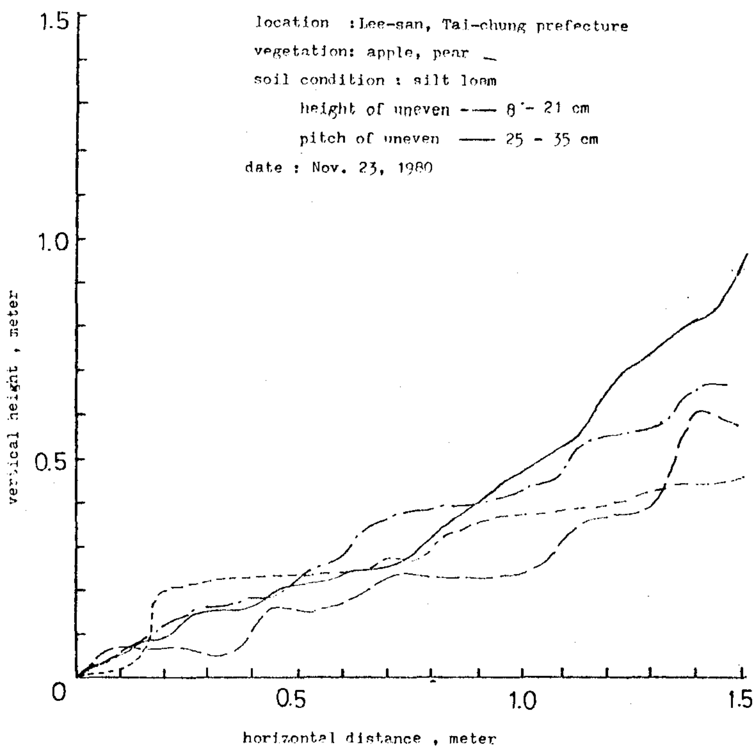


Fig. 4 Topographical uneven profile measured by profilo-rule on normal cultivated slopelands.

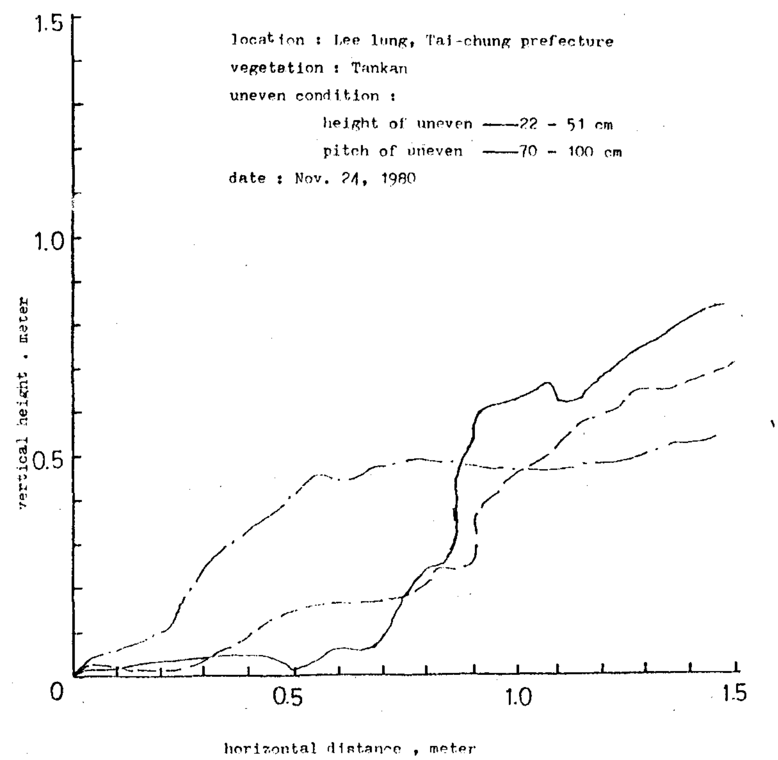


Fig. 5 Topogaphical uneven profile on classic gravel loam hillsides.

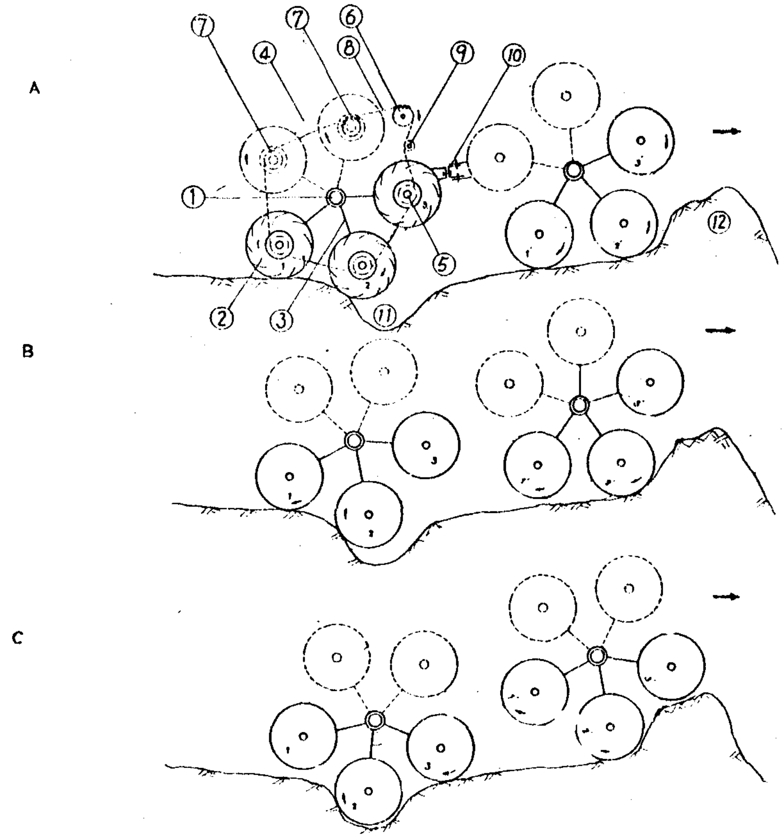


Fig. 6 Walking procedure from contacted minor wheels' rolling maner to turn over revolving of the chain-drivn planetary vehicle.

MECHANICS OF THE CHAIN-DRIVING PLANETARY WHEEL

A free body diagram of a chain-driving planetary wheel is shown in Fig. 7 The variables are defined as follows:

$\ddot{a}$=Angular acceleration of planetary wheel about the front axle A, rad/s^2

F=Horizontal tractive force, kg

H_7, H_8=Thrust produced by rear and front contacted wheel individually, kg

I_A=Moment of inertia about point A

R_7, R_8=Traveling resistance acting upon rear and front contacted wheel individually, kg

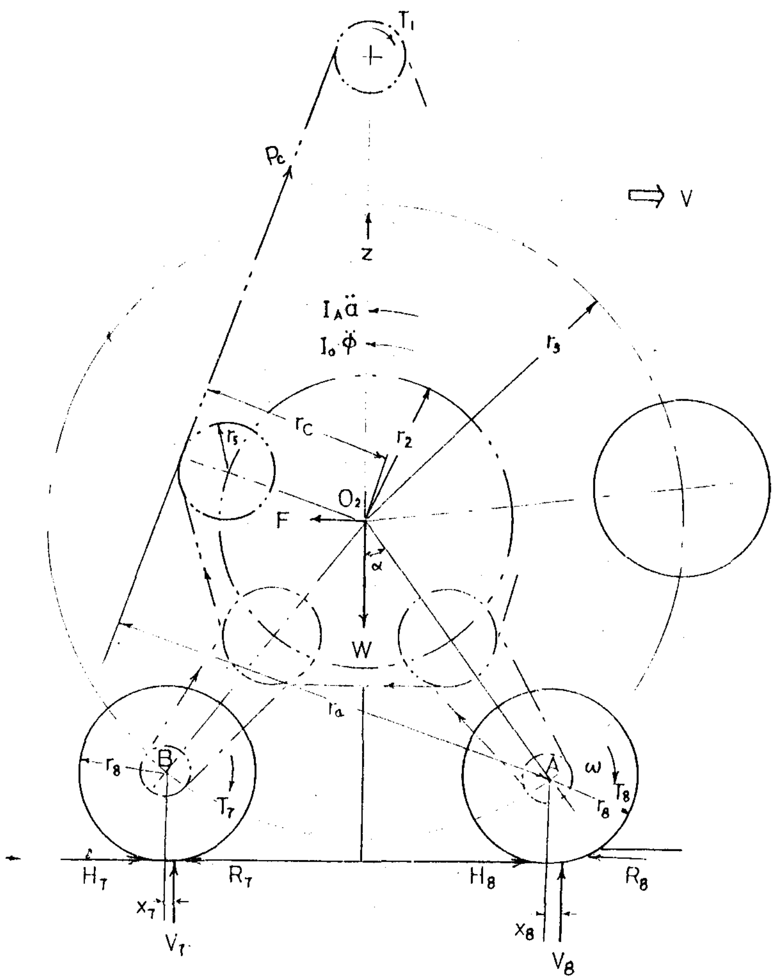


Fig. 7 Free body diagram of a chain-driving planetary wheel.

T_1, T_7, T_8=Torque developed by main shaft, rear and front contacted axle individually, kg-m

W=Static force on planetary wheel axle, kg

V_7, V_8=Vertical soil reaction against rear and front wheel individually, kg

x_7, x_8=Horizontal distance between vertical rear and front soil reaction and axle center line, m

r_a=Distance between front contactedwheel axle and driving chain, m

r_c=Distance between planetary wheel axle and driving chain, m

α =Angle between front contacted wheel spoke and vertical plane, deg

r_3, r_8= Diameter of planetary wheel and contacted wheel individulally, m

P_c = Tension force of driving chain, kg

M_w = Mass of the planetary wheel, $kg \cdot s^2/m$

V, $\dot{V}$ =Traveling speed and acceleration of planetary wheel, m/s, m/s^2

I_o = Moment of inertia of planetary wheel about its axle O_2

ϕ = Angular motion of planetary wheel about point O_2

ω = Angular speed of contacted wheel to its own axle

z = Vertical displacement of planetary wheel

At any instant, the following analysis can be developed from the dynamic equilibrium of planetary wheel, when it is traveled by the contacted two wheels revolving about their own axle A and B :

$$M_w \dot{V} = H_7 + H_8 - R_7 - R_8 - F \qquad (1)$$

$$M_w \ddot{z} = W - V_7 - V_8 \qquad (2)$$

$$I_o \ddot{\phi} = P_c \cdot r_c + V_7 (r_3 \sin\alpha - x_7) - V_8 (r_3 \sin\alpha + x_8) - (H_7 + H_8 - R_7 - R_8) \cdot (r_3 \cos\alpha + r_8) \qquad (3)$$

But when the planetary wheel is traveled by the front contacted wheel and the whole wheel revolving around the axles O_2 and A simultaneously, the dynamic equilibrium of the wheel may be ritten

$$M_w \dot{V} = H_8 - R_8 - F \qquad (4)$$

$$M_w \ddot{z} = W - V_8 \qquad (5)$$

$$I_A \ddot{a} = P_c \cdot r_a - W \cdot r_3 \cdot \sin\alpha - V_8 \cdot x_8 - F r_3 \cdot \cos\alpha - (H_8 - R_8) \cdot r_8 \qquad (6)$$

Equation (1) and (4) govern the foward translational motion of the planetary wheel. However, the soil thrust H_7 and H_8 are seen to be the only forces acting to propel the wheel foward. It is known that $x_i = \frac{R_i}{V_i} r_i$ and $T_i = H_i r_i$, (i = 7, 8), then equations (3) and (6) may be written as :

$$I_o \ddot{\phi} = P_c \cdot r_c + (V_7 - V_8) \cdot r_3 \cdot \sin\alpha - (H_7 + H_8 - R_7 - R_8) \cdot r_3 \cdot \cos\alpha - (T_7 + T_8) \qquad (7)$$

$$I_A \ddot{a} = P_c \cdot r_a - W \cdot r_3 \cdot \sin\alpha - F \cdot r_3 \cdot \cos\alpha - T_8 \quad (8)$$

The slippage of the planetary wheel is defined as follows :

$$S = 1 - \frac{V}{r_8\, \omega} \quad (9)$$

$$S = 1 - \frac{V}{(r_3 + r_8)\, \dot{a}} \quad (10)$$

Walking Performance on Concrete Ground

The traveling characteristics of planetary wheel on the horizontal flat concrete ground is shown in Fig. 8. The wheel is moved by the torques of contacted minor wheels in S = 0 - 42 % at coefficient of traction C_f = 0 - 26 %. The diagram is somehow resembled with normal four (all) wheel tractor's. Up to S = 42 %, the dynamic behaviour of the wheel becomes into planetary revolving, increasing further traction till C_f = 63 %. The maximum traction efficiency is around 58 % at slippage of 3 %.

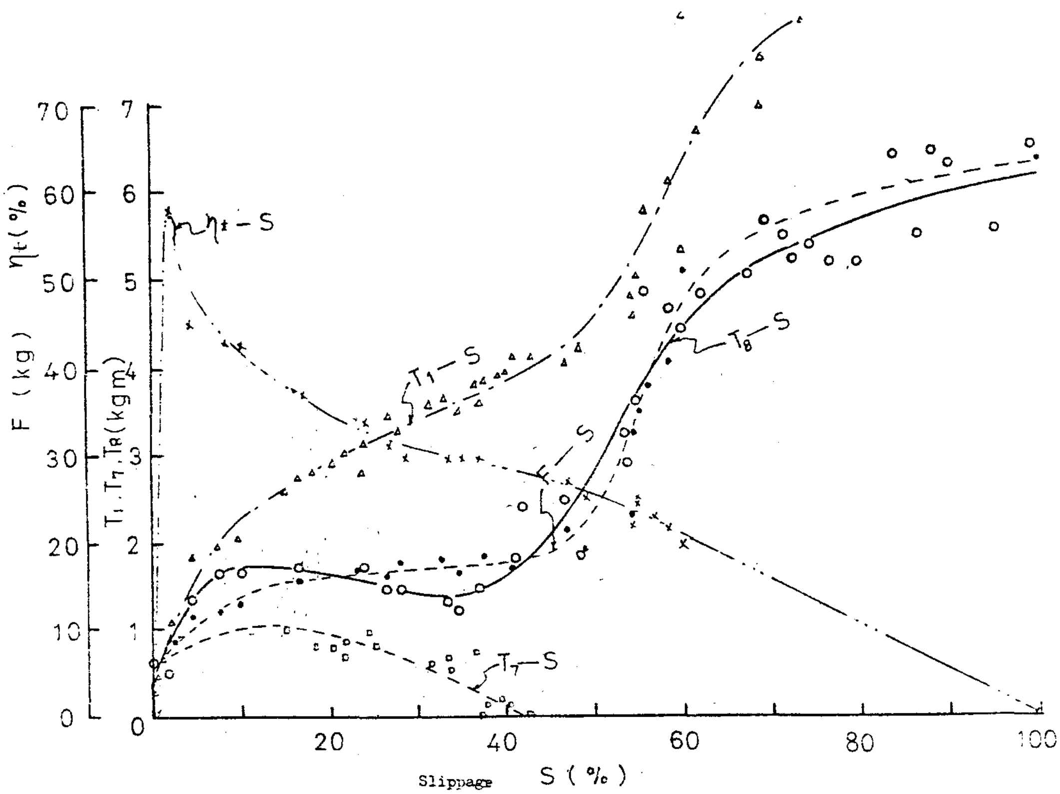


Fig. 8 Traveling characteristics of planetary wheel on flat concrete ground.

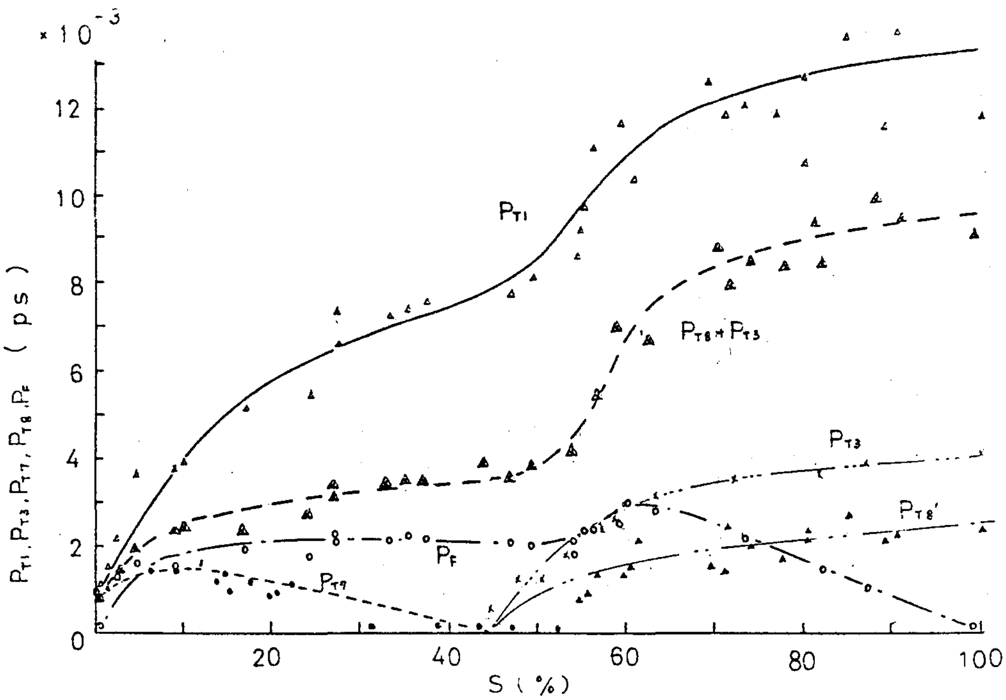


Fig. 9 Power requirement of planetary wheel and tractive pull versus slippage.

The PS horsepower to slippage relationship is shown in Fig. 9. It is obiously that the curve presents superposition effect of both minor wheel and planetary one

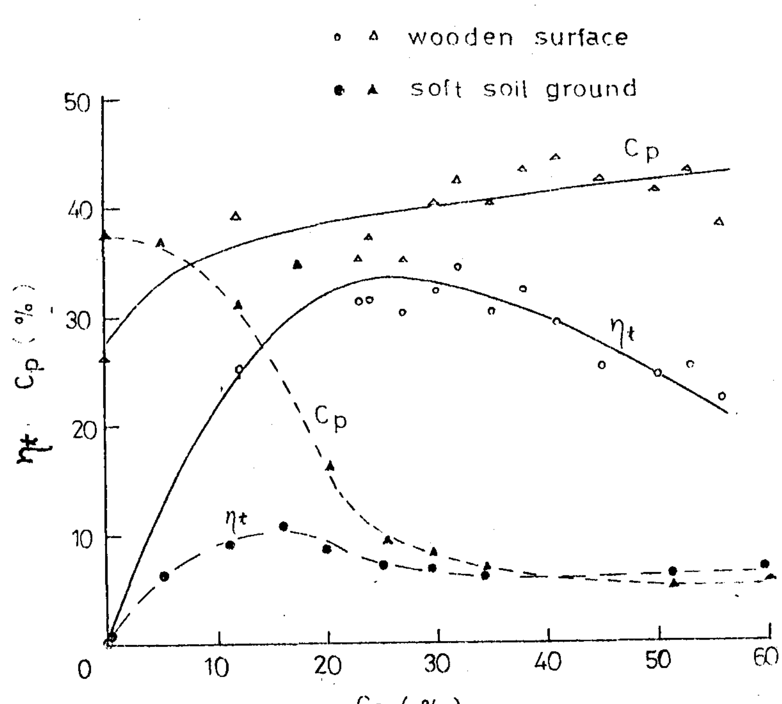


Fig. 10 Performance of planetary wheel of uneven traveling surface.

in planetary traveling field. The difference between P_{T1} and $P_{T8}+P_{T3}$ may be considered the power consumed by traveling resistance.

Walking Performance on Uneven Traveling Surface

Coefficient of traction C_f versus coefficient of driven power C_p $(=\frac{P_{T8}}{P_{T1}}\times 100\ \%)$, and traction efficiency $\eta_t(=\frac{P_F}{P_{T1}}\times 100\ \%)$ relations are shown in Fig. 10 . On hard uneven surface, C_p and η_t show rather high values than on soft uneven surface ones. Be careful the C_f values are no limitation in its range even if above 100 % of C_f for the sake of nothing completely slippage of the wheel is occured, except the pull load is far above the shearing resistance of whole embankment or ditch .

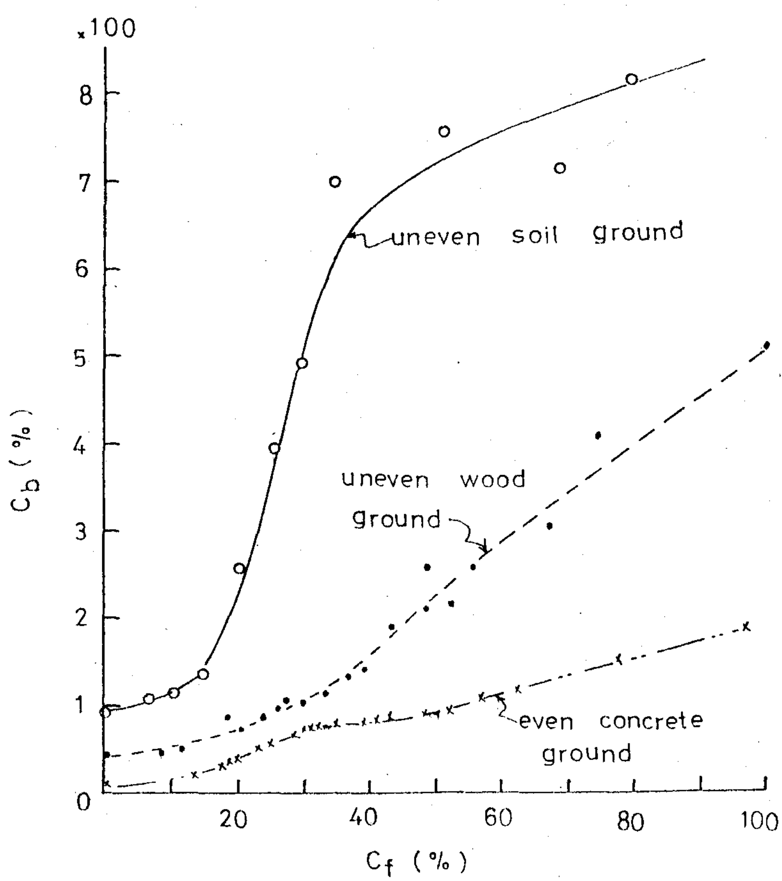


Fig. 11 Driving torque performance of planetary wheel on different grounds.

C_f versus C_b ($= \frac{P_{T1}}{W \cdot v/75} \times 100$ %) relations of uneven grounds to even ground is shown in Fig. 11 . More torque is exerted to overcome traveling resistance and traction on uneven soil ground crossing, however on the occasion of normal surface crossing , no additional torque could be exerted because of the limit of cohesion. The wheel moves in planetary manner above C_f= 24 % area in these diagrams,though under C_f = 24 % area it plays the same role in uneven ground cases.

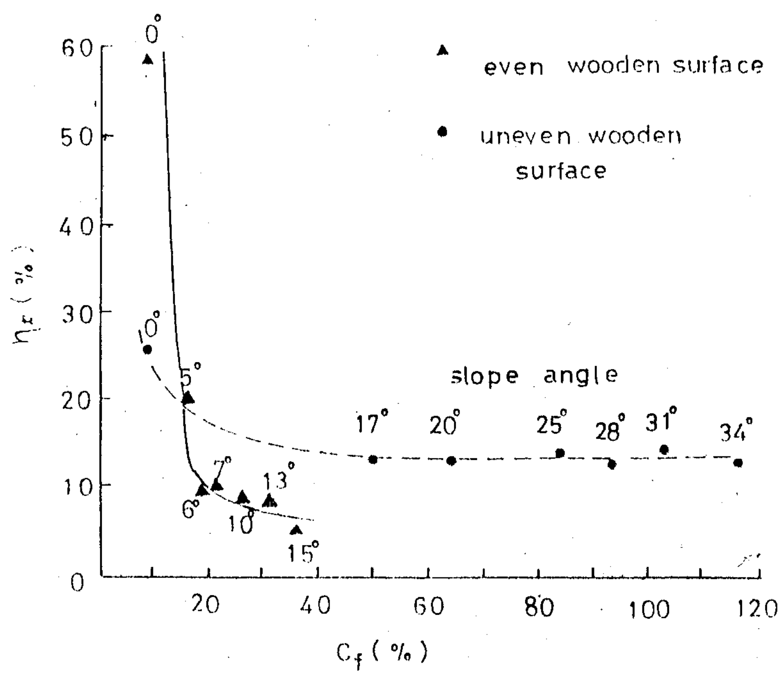


Fig. 12 Relation between the coefficient of traction (C_f) and the traction efficiency (ηt) at different slope degree.

Climbing Slope Performance

Fig. 12 shows C_f - ηt diagram difference between even wooden surface and uneven wooden surface by ploting different slope gradients. It is obiously shown that ηt value is nearly about 13 % at C_f ones above 24 % range in the case of uneven traveling on wooden different slope degrees. The critical angle of contacted wheel climbing up the flat wood board, transiting to planetary wheel's climbing is 6 deg. of gradient. Whereas a fairly high slippage is produced hereafter in revolving upon above 6 deg. of slope climbing up, and the maximum gradient of walking up is 15 deg.

ACKNOWLEDGEMENT

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SUMMARY

To correspond with the Government's long sight policy as to exploitating the hillside lands, to develop a kind of hillside tractor which is able to walk and climb up the naturaly vegetated uneven terrain fields is urgently necessary. The vehicle weighted of 217 kg, driven by four planetary type walking wheels is used to study the running performance. Also the driving torques on each shafts were measured for the necessity to desigh the tractor.

The experiment concluded the results that its walking performance is superior to those conventional running wheels, especially on the indent uneven ground. Because of mechanically constructed by two different diameter wheels into one walking member, the performance obviously presents the effect of superposition. Traction efficiency curve is fairly flattened across the whole slippage values (S). The transit point from minor wheel rotation to major wheel planetary rotation is at S=42% on concrete ground running.

A study on hillside soil strength investigation showed that most of the penetrating resistance and the shearing resistance values were at the safty ranges from the viewpoint of soil-vehicle system evaluation.

Though a great deal of studies about hillside tractor were made up to date, but this is the first report which concerned on the major-minor wheel concept walking member characteristics. It is expected the off-the-road locomotion researches would be lead into a new frontier.

REFERENCES

1. Bekker, M.G., 1969. Introduction to Terrain-Vehicle Systems. The Univ. of Michigan, 158-180.
2. Fijikawa, T. and Yoshida, I., 1972. On the Soil Thrust of Bulldozer at the Surface Soil Removing Work. Sci. Bull. Agr. Kyushu Univ. 26, 1-4.
3. Gilfillan, G., 1970. Tractor Behavior During Motion Uphill. Agri. Engng. Research, 15, 3, 236-243.
4. Janosi, Z and Hanamoto, B. The Analytical Determination of Drawbar Pull as a Function of Slip for Tracked Vehicles in Deformable Soils. Proc. 1st Int. Conf. Mech. Soil-Vehicle Systems, Torino-Saint Vincent, 1961.
5. Jo-Yung Wong and Reece, A.R., 1966. Soil Failure Beneath Rigid Wheels. Proc. 2nd Int. Conf. Mech. Soil-Vehicle Systems, 424-445.
6. Machine Design, 1978. Holocaust Buggy, 24-25.