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A Theoretical Study on the use of Passive Soil Resistance in Winch Anchor Design

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RINGKASAN

Kertas kerja ini memperihalkan kajian yang dibuat dalam menentukan panjang dan dalam suatu bilah yang diperlukan sebagai alas pada jentarik yang dipasang dengan rantai. Analisis yang dijalankan lebih berhubung kepada penyesuaian ukuran bilah yang diperlukan. Reka bentuk ini berpusatkan kepada teori bilah lebar dengan pergerakan yang berserenjang untuk kemudian perkiraan bagi keadaannya yang dua dimensi. Pendekatan yang diambil berasaskan kaedah pengiraan rintangan tanah pasif ke atas bilah lebar yang mencecah permukaan bumi, mempunyai sudut cakar tertentu di samping kebebasan untuk berpusing sama ada ke atas atau ke bawah.

SUMMARY

This paper describes work being carried out to determine the length and depth of a cutting blade required to support a rescue vehicle fitted with a winch. Analytical work described relates mostly to the suitability of blade used. The design was confined to the case of the wide cutting blade moving in a direction perpendicular to the breadth of the blade because of its two dimensional simplicity. The approach adopted was based on a method already presented for the rapid calculation of passive soil resistance on a plane wide structure extending to the soil surface and having any rake angle as well as a wide range of directions of interface motion.

KEY TO SYMBOLS.

A = Actual tangential adhesion force per unit width of interface.
P = Frictional soil resistance component per unit width of interface.
R = Resultant soil resistance per unit width of interface.
SN = Sc = cohesion number (dimensionless group).
x,y,r = angles < OBA, < BOA, < BAO respectively.
Ca = Constrained adhesion Ca = c $\tan \delta \cot \phi$.
Z = Depth of interface below horizontal soil surface.
Δ = $\sin^{-1} (\sin \delta / \sin \phi)$.
τ = Shear stress.
σ = Normal stress.
θ = Angle between one slip direction and the interface.
$\kappa\omega$ = Kinematic wedge.
b = Width of soil structure interface = 0.7 m.
e = Base of natural logarithm.
K = Dimensionless soil resistance coefficient.
α_{kw} = Rake angle of interface measured from direction of translation and designated apparent rake angle $(\alpha - \beta)$.

Key to author's name: D Ahmad.

α = Rake angle of interface measured from the horizontal.
β = Direction of translation of interface with horizontal (positive downwards).
γ = Soil bulk density.
g = Acceleration due to gravity.
δ = Mobilized angle of soil interface friction.
a = Apparent adhesion = c tan δ cot ϕ.
ϕ = Angle of friction in Coulomb's equation.
L = Length of blade.
n = Ratio of δ to ϕ (δ / ϕ).
$K_{c\ \delta=o}$ = Value of coefficient K_{ca} being interpolated at δ = o,
$K_{c\ \delta=\phi}$ = Value of coefficient K_{ca} being interpolated at $\delta = \phi$,
$K_{\gamma\ \delta=o}$ = Value of coefficient K_γ being interpolated at δ = o,
$K_{\gamma\ \delta=\phi}$ = Value of coefficient K_γ being interpolated at $\delta = \phi$,
$K_{s\ \delta=o}$ = Value of coefficient K_s being interpolated at δ = o,
$K_{s\ \delta=\phi}$ = Value of coefficient K_s being interpolated at $\delta = \phi$.

INTRODUCTION

A winch anchor is one of the necessary tools used in overcoming the problem of earthmoving machines which tend to sink while in operation on wet and spongy ground.

Early work on the design of an anchor resulted from drainage work where pulls of 20,000 to 30,000 lb (about 89–134 kN) were required from a medium powered wheel tractor fitted with a winch. The development of a new design was spurred by the fact that the conventional anchor was somewhat too large to take the reaction besides causing unnecessary soil disturbance (Payne, 1956). Payne improved the conventional anchor by attaching a horizontal plate to it such that it covered the soil surface. In this way, the tractor weight can be mobilized as surcharge through weight transfer obtained by controlling winch cable height.

In the analysis to determine the resultant reaction of the soil, which in this case, can be represented by

$$R = (P^2 + A^2 + 2PA \sin\delta)^{\frac{1}{2}} \qquad (1)$$

where

$$P = czK_{c\delta} + \gamma_{gz}{}^2 K_{\gamma\delta} - \gamma_z{}^2 K_{s\delta} e^{-sc} \qquad (1)$$

$$A = az \operatorname{cosec} \alpha \qquad (3)$$

and

$$a = c \tan\delta \cot\phi \qquad (4)$$

Payne assumed that adhesion was zero whilst other parameters were assigned certain values. This is quite inappropriate because even though the cohesive part is by far the bigger component in comparison with the adhesive part, adhesion does affect soil resistance in two ways, namely by

i) its influence on the magnitude of the adhesive force along the anchor unless the anchor is smooth and

ii) the fact that the frictional force is a function of adhesion (Hettiaratchi *et al.*, 1966; Hettiaratchi and Reece, 1974).

From results of laboratory experiments and field work on seven different occasions Payne concluded that a significant increase in anchorage could be obtained on frictional soils by arranging for the resultant of the rope tension and the weight of the tractor and winch to act on the shear surface. However, on soils of low bearing capacity the actual increase was not as great as predicted. The limiting condition for the new design occurred when the tractor was about to rear and the rope tension was fully sustained up to this value causing only the slightest soil disturbance in contrast to the conventional design which showed continuous soil failure during pulls thus causing extensive soil disturbance. Payne also concluded that where horizontal pulls of the order of twice the weight of the tractor were required on soils other than very wet clays, the new design had great advantages. Where anchorage required was of the same order as the weight of the tractor the conventional design was preferred for its simplicity.

This paper is an attempt at designing a winch anchor for given soil parameters, pulling force and vehicle weight. The anchor suggested has to be able to penetrate under the action of winching force only. This is achieved by first forcing it into the lowered position causing partial penetration using the hydraulic system of the tractor, while the winch pull does the rest. This type of connection can be simulated by bolting the anchor firmly to the vehicle of stated size and weight in its lowered position.

The coheisve value given falls under plastic clay region while the winching force suggested was four times the tractor weight.

The design was confined to the case of the wide cutting blade moving in a direction perpendicular to the blade because of its two dimensional simplicity (Osman, 1964). The approach adopted was based on a method presented for the rapid calculation of passive soil resistance on plane wide structure extending to the soil surface and having any rake angle in addition to the wide range of directions of motion of the interface (Hettiaratchi, *et al.,* 1966). Calculations involved turned out to be tedious and recourse to a computer was made.

ASSUMPTIONS

For the design analysis the following have been considered:

(1) Soil failure occurs in a two dimensional field.

(2) Soil is assumed to be a rigid Coulomb material having cohesion, self weight, angle of internal friction and the soil interface properties of tangential adhesion and friction.

(3) Any surcharge pressure applied to the soil surface is uniformly distributed over an area at least as great as the rupture zone and no shear stresses act at this boundary.

(4) The free surface is horizontal.

(5) The soil structure interface translates at an angle $\pm\beta$ with the horizontal without rotating.

(6) In the development of the shape of the slipline field it is assumed that $a = c \tan \delta \cot \phi$.

Cutting Process

As a straight blade is pulled along, it compresses the soil until its maximum shear strength is reached. When failure occurs a wedge shaped mass of soil is sheared from the soil bulk. The sheared wedge moves upwards along the interface of the blade by the successive newly formed wedges resulting from further travel of the blade. The soil will pile upon the surface and increase in height until it collapses and falls behind the blade.

Hettiaratchi and Reece (1966, 1974, 1975) have shown that there are three distinct modes of failure depending upon the failure geometry controlled by rake angle, α, direction of interface motion β, soil internal friction angle ϕ and the soil interface friction angle δ. Hettiaratchi and Reece (1975) also pointed out that the shape of the wedge changes as the direction of motion is varied. The limit to the analysis occurs when $\beta = -(45-\phi/2)$ while the shape of the wedge depends upon θ_+ which is kinematically determined by $\theta_+ = 180-\alpha + \beta$. Hence as the shape of the wedge changes so does the extent to which the friction and adhesion between the wedge and the interface is mobilized.

Since the independent variable governing δ (for specified ϕ) is the apparent rake angle $\alpha_{K\omega} = (\alpha-\beta)$, the limiting factor for the kinematic wedge has been generalised in terms of this apparent rake angle given as: –

$$\alpha_{K\omega} \text{ or } (\alpha-\beta) = 135° - \phi/2 - \delta/2 - \Delta/2 \qquad (5)$$

For this design, an analysis has been carried out on the basis that if α is fixed the remaining β is changed through various limits, or otherwise. For instance if α is known, β can be determined. Since the soil resistance of an interface depends only on its rupture surface geometry and if all variables are held constant, the soil resistance of the interface with a kinematic wedge will be identical to the case which consists only of a basic Sokoloski's failure pattern without a kinematic wedge (Sokoloski, 1960). Therefore, basic Sokoloski's theory can be used to predict soil resistance of interface with a kinematic wedge and this can be solved quite easily by using the set of charts given in Hettiaratchi and Reece (1974).

The soil resistance, R, per unit width of the interface can be broken into two parts namely P, the frictional component acting at an angle δ with the normal to the interface and the 'adhesive' component A, acting along the interface. The magnitude of the adhesive component is simply given by $A = az \operatorname{cosec} \alpha$. (See equations 1, 2, 3).

For the proposed design, the two basic unknown factors are length of blade and its rake angle. The rest could be solved once these factors are determined. Since the soil resistance is known, therefore the only problem is to find the correct depth of blade (i.e. blade length × sin α) and the blade rake angle.

THEORY INVOLVED

From *Fig. 1,* for condition $\delta = 0$, the resultant force (i.e. soil resistance) is perpendicular to the

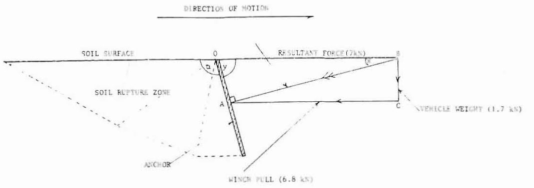

Figure 1.

blade giving a large value of rake angle with a wedge of soil fixed to the interface. Since the resultant force is acting at a constant angle x with the horizontal, therefore, as δ is varied the only angle that changes is y which corresponds to the change in angle α as shown in *Fig. 2.*

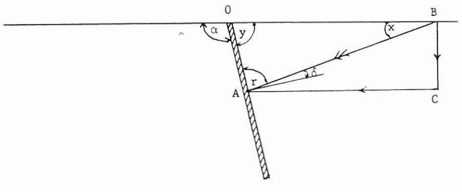

Figure 2.

Referring to *Fig. 2.*

$$y = 180 - \alpha \tag{6}$$

and

$$y = 180 - x - z \tag{7}$$

hence

$$180 - \alpha = 180 - x - z$$

or

$$\alpha - x - z = 0 \tag{8}$$

But

$$z = 90 - \delta \tag{9}$$

Substituting (8) into (9) gives

$$\delta = 90 + x - \alpha \tag{10}$$

Now

$$x = \sin^{-1} \frac{BC}{AB}$$

$$= \sin^{-1} \frac{1.7}{7.0}$$

$$= 14.05^\circ \tag{11}$$

Substituting (9) into (10) gives

$$\delta = 90 + 14.05 - \alpha$$

or

$$\delta = 104.05 - \alpha \tag{12}$$

Hence for δ = 5, 10, 15, 20 25 and 30 the corresponding values of α are 99.05°, 94.05°, 89.05°, 84.05°, and 74.05° respectively. From the above, the corresponding β values can be calculated using equation (5), the depth of blade determined and various soil resistance coefficients interpolated.

COMPUTER ANALYSIS

A method based on trial and error was used by varying the angle of soil interface friction, δ, from 5° to 30° at an assumed initial length of blade. Iteration at a small increment was carried out to obtain the designed value of soil resistance. This was determined in such a way that for each increment the six apparent rake angles were successively substituted into the general passive resistance equation.

For example, results of various variables β, z, Sc and corresponding soil resistance coefficients (Table 1) at a blade length of 55 mm and with a rake angle of 99° were determined as follows:—

TABLE 1
Results from Programme A.
Soil Parameters $c = 20\ \mathrm{kN/m^2}$, $\phi = 30^\circ$, $\gamma = 1800\ \mathrm{kG/m^3}$ and $g = 9.81\ \mathrm{m/s^2}$

	Soil Resistance Coefficients:—					
$(\alpha)^\circ$	$K_{c\,\delta=0}$	$K_{c\,\delta=\phi}$	$K_{\gamma\,\delta=0}$	$K_{\gamma\,\delta=\phi}$	$K_{s\,\delta=0}$	$K_{s\,\delta=\phi}$
99.03	4.5000	10.0000	1.9000	4.9000	0.0400	0.8000
94.03	4.0000	9.0000	1.7000	4.0000	0.0049	0.5500
89.03	3.4000	8.0000	1.5000	3.5000	0.0049	0.4200
84.03	2.9000	7.0000	1.3000	3.1000	0.0120	0.3200
82.03	2.7000	6.6000	1.3000	3.0000	0.0150	0.3000
79.03	2.5000	6.0000	1.2500	2.8000	0.0260	0.2600
74.03	2.2000	5.5000	1.1000	2.4000	0.0500	0.2500

TABLE 2
Soil Passive Resistance

Length of Blade (m)	$\alpha°$	$\delta°$	$\beta°$	z (m)	SN	P (kN/m)
0.055	99.03	5	−18.3826	0.0543	20.8517	3.9903
	94.03	10	−20.7964	0.0549	20.6444	4.1101
	89.03	15	−23.2112	0.0549	20.5963	4.1000
	84.03	20	−25.6279	0.0547	20.7056	4.0821
	79.03	25	−28.0474	0.0539	20.9466	4.0080
0.0949	99.03	5	−18.3829	0.0938	12.0721	6.9943
	94.03	10	−20.7964	0.0948	11.9520	7.2049
	89.03	15	−23.2112	0.0949	11.9242	7.1909
	84.03	20	−25.6279	0.0945	11.9875	7.1588
	79.03	25	−28.0479	0.09336	12.1444	7.0337
	74.03	30	−30.4700	0.0913	12.4011	7.2801

TABLE 3
Soil Passive Resistance

Length of Blade (m)	$\alpha°$	$\delta°$	$\beta°$	z (m)	SN	P (kN/m)
0.09099	94.03	10	−20.7964	0.0908	12.4774	6.8914
	89.03	15	−23.2112	0.0909	12.4483	6.8779
	84.03	20	−25.6279	0.0905	12.5144	6.8470
	82.03	22	−26.5954	0.0901	12.5679	6.8022
	89.03	25	−28.0474	0.0893	12.6782	6.7269
	74.03	30	−30.4700	0.0875	12.0462	6.9636
0.09199	94.03	10	−20.7964	0.0918	12.3418	6.9697
	89.03	15	−23.2112	0.0919	12.3130	6.9561
	84.03	20	−25.6279	0.0915	12.3784	6.9249
	82.03	22	−26.5954	0.0911	12.4313	6.8796
	79.03	25	−28.0474	0.0903	12.5404	6.8036
	74.03	30	−30.4700	0.0884	12.3055	7.0427
	94.03	10	−20.7964	0.0928	12.2090	7.0481
	89.03	15	−23.2112	0.0929	12.1806	7.0343
	84.03	20	−25.6279	0.0925	12.2453	7.0028
	82.03	22	−26.5954	0.0921	12.2976	6.9571
	79.03	25	−28.0474	0.0913	12.4055	6.8802
	74.03	30	−30.4700	0.0894	12.6678	7.1218
0.09399	94.03	10	−20.7964	0.0938	12.6792	7.1264
	89.03	15	−23.2112	0.0939	12.0510	7.1126
	84.03	20	−25.6279	0.0935	12.1150	7.0807
	82.03	22	−26.5954	0.0931	12.1668	7.0346
	79.03	25	−28.0474	0.0923	12.2736	6.9569
	74.03	30	−30.4700	0.0904	12.5329	7.2009

TABLE 4
Soil Passive Resistance

Length of Blade (m)	α°	δ°	β°	z (m)	SN	P (kN/m)
0.0809	99.03	5	−18.3829	0.0799	14.1586	5.9506
	94.03	10	−20.7964	0.0808	14.0178	6.1816
	89.03	15	−23.2112	0.0809	13.0951	6.2560
	84.03	20	−25.6279	0.0806	14.0594	6.3517
	82.03	22	−26.5954	0.0802	14.1195	6.3710
	79.03	25	−28.0474	0.0765	13.1104	6.9765
0.0889	99.03	5	−18.3829	0.0879	12.8859	6.5574
	94.03	10	−20.7964	0.0887	12.7578	6.8114
	89.03	15	−23.2112	0.0889	12.7281	6.8939
	84.03	20	−25.6279	0.0885	12.7956	6.999
	82.03	22	−26.5954	0.0881	12.8504	7.0208

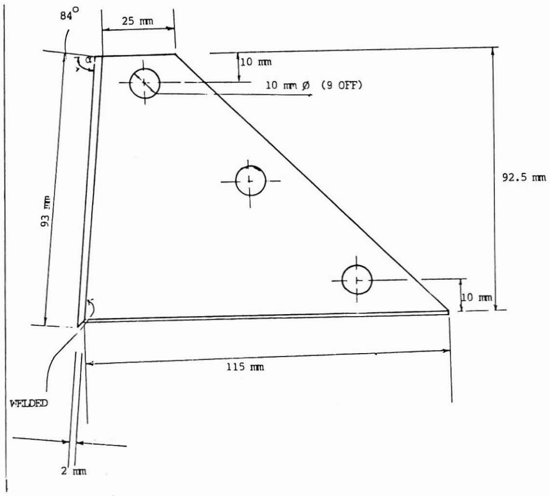

Fig. 3. Side view of anchor. Scale 1:1.

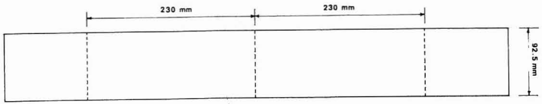

Fig. 4. Front view of anchor. Scale 1: 3.

$$\delta = 104.03 - \alpha \tag{13}$$

$$\beta = \alpha + \phi/2 + \delta/2 + \Delta/2 - 135^\circ \tag{14}$$

$$K_{c}\delta = K_{c\,\delta=0}\left[K_{c}\delta{=}\phi/K_{c}\delta{=}0\right]^{n} \tag{15}$$

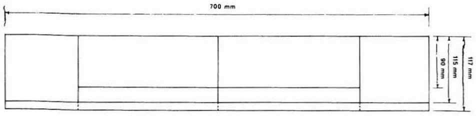

Fig. 5. Plan view of anchor. Scale 1:3.

$$K_{\gamma}\delta = K_{\gamma}\delta{=}0\left[K_{\gamma}\delta{=}\phi/K_{\gamma}\delta{=}0\right]^{n} \tag{16}$$

$$K_{s}\delta = K_{s}\delta{=}0\left[K_{s}\delta{=}\phi/K_{s}\delta{=}0\right]^{n} \tag{17}$$

$$z = L\sin\alpha \tag{18}$$

$$Sc = c/\gamma_{zg} \tag{19}$$

The values obtained from those formulas were later substituted into the passive soil resistance equation given earlier as

$$P = czK_{c}\delta + \gamma_{gz}{}^{2}K_{\gamma}\delta - \gamma z^{2}K_{s}\delta\, e^{-Sc} \tag{2}$$

If the value of P calculated for this particular rake angle was far from the required value, a similar procedure was repeated for the remaining rake angles. However when none of the rake angle values gave the required value, the next length of blade was assumed and the iteration repeated. The whole procecure has been worked out and reported in another paper (Desa Ahmad, 1978). Additional calculation was also carried out taking into consideration the adhesive force A acting along the interface. Results of the additional computation are presented in Table 4.

RESULTS

Both of the methods used showed that for a given vehicle weight of 1.7 kN, a winching force of 6.8 kN, c = 20 kN/m², $\phi = 30°$ and $\gamma =$ 1800 kg/m³, the soil passive resistance was 7 kN. When adhesive force A was excluded, the value was obtained when the rake angle was 84.03° (Tables 2 and 3). Addition of adhesive force, however, was not significant since the required value with accuracy to 3 decimal places was also achieved at the rake angle but at a shorter blade length (Table 4).

Hence, at a rake angle of 84.03°, the following can be summarised:—

(a) For P = 7.00 kN, the length of blade was 93 mm
δ = 20°
β = −25.6°
z = 92.5 mm
S = 12.2

(b) For R = 6.999 kN, the length of blade was 89 mm
δ = 20°
β = −25.6°
z = 88.1 mm
S = 12.9

Models of the initial design are presented in *Figures 3, 4* and *5*. Furtherwork will be carried out to test the validity of the theory using various loads at different positions while applying the winching force at several heights. Comparison with a modified design as proposed by Payne will also be made.

CONCLUSIONS

For the proposed design, the actual length of blade should be between 89 mm to 93 mm and positioned at a rake angle of 84° to the soil surface when $\delta = 20°$, $\beta = -25.6°$, z from 88.1 to 92.5 mm, Sc from 12.2 to 12.9 and P = 7 kN/m.

For a fixed length of blade, decreasing the rake angle would decrease the value of passive soil resistance.

For a fixed rake angle, increasing the length of blade would increase the value of passive soil resistance.

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