EXPERIMENTAL AND ANALYTICAL INVESTIGATION OF SOIL CUTTING

by

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CERTIFICATION

THIS IS TO CERTIFY THAT THE THESIS -

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SUBMITTED TO THE SCHOOL OF POSTGRADUATE STUDIES UNIVERSITY OF LAGOS FOR THE AWARD OF THE DEGREE OF

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IS A RECORD OF ORIGINAL RESEARCH CARRIED OUT BY

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DEDICATION

This thesis is dedicated to the Honour and Glory of the Holy Trinity, The Alfa and The Omega.

It is also dedicated to the cherised memory of my father, Prince Oyewoga and mother, Princess Tinuola.

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LIST OF SYMBOLS

Ac	Final triaxial sample area
b	Blade width
C,c	Apparent cohesion
d	Depth of cut (cm)
D_i,D	The particle size diameter (mm), of the i^{th} section
$D_{max.}$	Maximum soil particle size (mm)
$D_{min.}$	Minimum soil particle size (mm)
Dv	Triaxial sample volume change
e_o,e	Initial and final voids ratio respectively
f	Horizontal rupture distance from the blade
F_a,F_{ac}	Acceleration force due to inertia effect
g	Acceleration of gravity
$H'=c \cot \phi$	Normal compressive stresses
Hc	Final triaxial sample height
H_H,H_V	Horizontal and vertical components of passive force H_p.
H_o,H_f	Initial force intercept and horizontal force component respectively (N)

$H_p, H_{p1}, H_{p2}, H_{p3}, H_{p4}$ Passive force causing deformation

H_{v1}, H_{v2} Empirical vertical force component

H_1, H_2, H Empirical horizontal force component

I_D Density index

k, k_o Constants

K Constant

K_a Coefficient of active pressure

K_o Coefficient of pressure at rest

$\ln = \log_e$ Natural logarithm

m, n, a Triad constants of blade width, depth of cut and particle size distribution

ma Product of mass (m) and acceleration (a)

N_a, N_c, N_q, N_γ Dimensionless soil resistance coefficient for gravitational, cohesion, surcharge and adhesion respectively

p Mean stress acting on a system from x,y,z axes

p' Effective consolidation pressure

$\bar{p}$ Mean percent particle size passing

p_i Percent passing at the i^{th} section

P_q Stress acting on the top face of the boundary 0c

r, θ Polar coordinate axis

$r, r_o, r_\theta, r_\beta$ Radial distance

S Coefficient of force transmission (cm)

S_a, S_c, S_q Soil numbers for adhesion, cohesion and surcharge respectively.

SPI Soil particle index

SCI Soil cutting index

Sin Δ Ratio of sin δ and sin ϕ

$S(\theta)$ Stress function

V, v Tool operating velocity

V_b Velocity of the soil along the blade

Vc Final triaxial sample volume

V_f Final blade velocity in y direction

V_o Initial blade velocity in y direction

V_s Velocity of the soil along the slip line

W Width of the cutting blade (cm)

W_d Work dissipated along log - spiral slip line

W_1, W_2, W_3 Weights of soil wedges 0ab, 0bc and 0ae respectively (see Figure 3.4)

x, y, z Rectangular coordinate axis

z	Blade cutting depth
α	Inclination blade angle to horizontal
β	Angle of inclination of the blade to the vertical x axis
$\gamma=\rho g$	Unit weight of soil medium
δ	Angle of soil-interface friction for cohesionless soils
δ'	Angle of soil-interface friction for soils possessing both cohesion and friction
θ_+, θ_-	Inclination of I characteristics slip directions with the interface respectively
κ	Soil constant, defined as the gradient of the rebound curve in the e:$\log_e$ p' space
λ	Soil constant, defined as the gradient in the e:$\log_e$p' space
$\mu = \frac{\pi}{4} - \phi/2$	Angle between the failure plane and the horizontal, or the direction of maximum principal stress, (see Figure 3.1)
μ	Coefficient of soil-to-metal friction, dimensionless, (see Appendix D)
ν, λ	Angle between the normal n to the element area and x and y axis respectively
ρ	Mass density of soil medium

ρ_{max}	Maximum density
ρ_{min}	Minimum density
$\sigma=\rho gr\ S(\theta)$	Mean stress in polar co-ordinate system. Also it can be expressed in equivalent cartesian coordinates
σ_o, σ_f	Initial and final stresses respectively
σ_r, σ_θ	Stress components in radial and tangential directions of the polar axis
σ_1', σ_3'	Effective major and minor principal stresses respectively
τ	Shear stress
$\tau_{r\theta}, \tau_{\theta r}$	Shear stresses acting on the differential element
ϕ	Angle of mobilised soil friction
ϕ_a	Angle of soil friction (air dry samples)
ϕ_d	Angle of soil friction (drained tests)
ψ'	Angle of major principal stress to the polar radius making angle β^0 with the vertical x axis
ω	Angle of major principal stress to the vertical x axis

Suffices:

a	Adhesive
c	Cohesive
f	Failure or limiting
p	Plastic
q	Surcharge
r	Recoverable
γ	Gravitational

Abbreviation:

SCA	Soil Cutting Apparatus

Summary

The objective of this work is firstly to determine experimentally the horizontal and vertical force components of the operative forces during soil cutting. Since previous work in soil cutting had been empirical and involved curve fitting techniques, therefore the second objective to predict these horizontal and vertical force components. In order to achieve these objectives a special apparatus was designed and fabricated for experimentation. It comprises the soil bin, the horizontal and vertical carriages, the proving rings, carriage seat frame, soil hopper, manually operated jack, and the blades. In order to reduce cost and weight of the apparatus, and also because of the limited space available, the carriages and the cutting blades were made of aluminium.

In order that this investigation can be applied to a variety of soils, Ogun river sand and beach sand were chosen because they are granular materials, but with different angles of internal friction ϕ. Black cotton soil was chosen because it is a cohesive soil which possesses both cohesion C and angle of internal friction ϕ. All the soil samples were air dried, in order to have a good control to obtain repetative results. In order to predict accurately, the horizontal and vertical operative forces in soil cutting it is essential that some specific properties of the soil be known. The soil properties chosen for this work are cohesion, C, and angle of internal friction, ϕ. These soil properties were determined using triaxial apparatus. Also the shear box apparatus, imposing directional horizontal

failure plane was used to determine the ϕ values of cohesionless soils.

The cutting blades inclination β^{o} to the vertical was varied from 0^{o} to 75^{o} in increments of 15^{o}. The soil bin was filled with soil by the soil hopper, whilst the blade was inserted and pushed horizontally by manually operated 10 tonne (98.07 kN) jack, at a horizontal speed of about 0.11 cm/sec. The soil bin perspex glass enabled the tests to be observed visually. The horizontal and vertical force components operating during soil cutting was measured by standard Wykeham-Ferrance proving rings, with maximum load of 200 kgf (1962 N) and with E.L.E dial gauge of 0.001"/ division (0.0254 mm/division).

It was found that the soil properties C and ϕ used by Coulomb and Terzaghi in the expression, $\tau = C + \sigma' \tan \phi$ were found to be true. However the soil plasticity slip line configurations in soil cutting show that whereas 100% of the angle of internal friction, is mobilised for cohesive soil, typified by black cotton soil at failure, only about 80% of the angle of internal friction ϕ, is mobilised for cohesionless soils, Ogun river sand and beach sand, at failure. The mobilised ϕ values of the soils were therefore used to evaluate the horizontal and vertical components of operative forces in soil cutting. Other soil parameters like void ratio e, and a new soil particle size distribution parameter index (SPI)

$$SPI = \left| \frac{(D_{max} - D_{min})100}{\Sigma D \times \% \text{ distribution}} \right|^{0.025}$$

derived from grading tests, are found to be true in evaluating these horizontal and vertical components of operative forces. From these findings, empirical formulae were derived, which will be of great benefit and advantage to design engineers, who can quickly estimate the horizontal and vertical components of the operative forces during soil cutting. It was found that as blade inclination β^{o}, and width-to-depth of cut ratio $\frac{w}{d}$, increased, the horizontal component of force in soil cutting, decreased. The horizontal force decreased by 93%, when width-to-depth of cut ratio $\frac{w}{d} = 1$, and blade inclination β° increased from 0^{o} to 75^{o}. The passive Rankine force is less than the horizontal components of the forces in soil cutting. These forces like the Rankine forces are proportional to the square of depth of cut. For vertical blades, that is, blades with inclination $\beta = 0^{o}$, the horizontal components of the forces can be evaluated by multiplying the Rankine force by constant K, which is 7.25 for cohesionless soils and 1.06 for cohesive soils. The present work also shows that the optimum performance of the blades occurred at an angle of inclination $\beta = 57^{o}$ for cohesionless soils. Whilst the optimum performance of the blade for cohesive soils occurred at a blade inclination $\beta = 45^{o}$.

A theoretical solution of the boundary energy theory which considers the kinematics of the soil-blade system, predicts most accurately the horizontal and vertical components of operative forces in soil cutting, than any other theory hitherto in use. The maximum and minimum errors in horizontal components of forces for Ogun river sand, at blade inclination β^0 from zero up to the optimum performance of the blade, were 10.6% and -5% respectively. Similarly the maximum and minimum errors in horizontal components of forces at same blade inclination, for beach sand and black cotton soil, taken in pairs were (9.2%, -23.2%) and (2.8%, -0.47%) respectively. At a blade inclination of $\beta = 30^o$, and $\delta = \frac{1}{2}\phi$, the experimental and theoretical horizontal components of forces, taken in pairs for Ogun river sand were (130N, 126N) an error of 3%. Whilst for beach sand and black cotton soil, at the same blade inclination, the values were (100N, 101N) an error of -1% and (135N, 135N) an error of 0% respectively. Similarly experimental and theoretical vertical components of forces, taken in pairs, at blade inclination $\beta = 30^o$ and $\delta = \frac{1}{2}\phi$, for Ogun river sand were (37N, 29N). Whilst for beach sand and black cotton soil, at same blade inclination, the values were (40N, 27N) and (58N, 55N) respectively.

CHAPTER 1

1. INTRODUCTION

1.1 General Introduction

The significance of this study of soil cutting is three-fold as regards the design of implements in civil engineering, agricultural engineering and military tracted vehicles, to suit our local soil conditions. In civil engineering construction where large volumes of soil are cut and moved, it is necessary to know the influence of angle of blade inclination $\beta°$ and depth of cut on the horizontal and vertical components of operative forces during soil cutting. The maximum blade inclination at the draft with optimum performance can therefore be determined. The bulldozer cutting blades at inclinations, to give optimum performance can be designed to suit local soil conditions. The agricultural implements which use blades or combinations of cutting edges with moleboard and discs can better be designed for minimum soil resistance to suit local soil conditions, and guard against breakages. The larger area of contact of the tracts compensates for many irregularities in the terrain that make wheeled vehicles less desirable. The design parameters utilised in tracks for armoured military vehicles are track width, track length, grouser shape, grouser spacing, sinkage, and slip. These military vehicles can be designed to suit local conditions and terrain, for greater mobility of these vehicles with high efficiency and performance.

This study will help in the design of shape and type of material used for soil engaging implements, which will also cope with the induced bending moments.

1.2 Earth Moving

There is a significant difference between the aims when solving stability problems in soil mechanics, and when predicting the horizontal and vertical components of the operative forces during soil cutting. A soil engineer when designing foundations, slopes, etc. must ensure that failure does not occur. Though he analyses failure conditions, he then imposes sufficiently large factor of safety, to ensure that he is protected against any errors in his assessment of the failure conditions. In soil cutting problems, soil failure must occur and the whole problem is to assess accurately the conditions at failure. There are two basic methods for solving soil stability problems. The first method entails kinematically admissible solution, by presuming a number of sizes and shapes for individual potential sliding surfaces. Each surface is then considered in turn. The point of application of the load applied by the wall, or foundation, on the soil is presumed known, and its direction is assumed to be defined by an angle of wall friction δ. By considering the overall equilibrum of the soil sector between the assumed failure surface and the wall, it is then possible to determine the magnitude of the applied load that will just cause failure of the soil along this surface. This calculation is repeated for all the assumed failure surfaces, and the true surface is taken to be that which corresponds to the smallest value of the applied load. The second method uses the limiting equilibrium and theory of plasticity to assess forces acting on an interface of various inclinations $\beta°$, for soils possessing internal friction angle ϕ, cohesion C and unit weight γ.

1.3 Objective of this Study

The objective of this study is to formulate boundary energy theory to predict the horizontal and vertical components of the operative forces during soil cutting. The boundary energy theory takes into account the Kinematics of the soil-blade system. In achieving this objective it is essential to design and fabricate a special apparatus for experimentation. The apparatus consists of soil bin, horizontal carriage, vertical carriage, proving rings, carriage seat frame, soil hopper, hydraulic jack and cutting blades. A comparison will be made of test results with the corresponding theoretical values, and also with the work of other researchers.

CHAPTER 2

2. LITERATURE REVIEW

2.1 Review of Previous Work

Most of the work by researchers, on previous investigation on cutting of soil, had been empirical and involved curve fitting techniques. Also limiting equilibrium had been used to determine the passive soil resistance on cutting blades. The methods of characteristics and plasticity had also been used to determine the force acting on the cutting blades. The soil was regarded as rigid plastic material which obeys the Mohr-Coulomb yield criteria.

Coulomb (16 , 1776), derived the coefficient of passive earth pressure for retaining walls of variable inclinations to the horizontal. Coulomb assumed that the failure surface is plane and that the soil interface friction δ is less than a third of the angle of soil friction ϕ ($\delta < \frac{\phi}{3}$). For $\delta > \frac{\phi}{3}$ Coulomb's assumption leads to large errors in the evaluation of the passive forces on the retaining structures and is therefore unsafe.

Rankine (50, 1857) considered the soil in a state of plastic equilibrium and used essentially the same assumptions as Coulomb, except that he assumed no wall cohesion or wall friction, which although simplifies calculations, it gives lower values for the coefficient of passive pressure.

This leads to underestimation of passive forces acting during soil cutting.

Kötter (36,1903) derived the equations of limiting equilibrium giving the changes of stresses along the characteristic lines for a material possessing unit weight γ, angle of internal friction ϕ , but without cohesion C. A good deduction from his work is that the ratio of the stresses along a radial fan characteristics and another is equal to the exponent of the product of twice the angle between them and tanϕ, the angle being the counterclockwise rotation of the characteristics. However Kötter's work can only be applied to cohesionless materials.

Terzaghi (59, 1947) used limiting equilibrium to derive bearing capacity of foundations for soil possessing angle of internal friction ϕ , cohesion C and unit weight γ. The resistance of the soil to the movement of the plate, acting normally to the plate thus results in bearing capacity of a shallow foundation with blade inclination $\beta = -90°$. At blade inclination $\beta = +90°$, pull out capacity of vertically loaded horizontal plate uplift ground anchors occurs. Brinch Hansen (12, 1953), Meyerhof and Hanna (40, 1978) made use of the general foundation configuration, base conditions, shape and depth factors which include inclined load effects in the bearing capacity equations. Balla (9, 1961), estimated the bearing capacity of foundations with uplift or tension forces. Byrne and Liam Finn (13, 1978) used the bearing capacity equations to estimate the pull out force on submerged structures buried in a shallow depth, in which suction effect predominates. The test conditions in soil cutting rule out suction effect.

Kawamuwa (35, 1953) used plastic equilibrium in developing the cutting resistance on blade in soil cutting. Although Kawamura did not obtain analytical solution, he summed the tangential stresses on the slip surface and equated the horizontal component of draft force. Kawamura solution is therefore approximate.

Payne and Tanner (48, 1959) investigated the relationship between rake angles and cutting tool performance. However the failure surface is arbitrary and has to be further subjected to trial computation of minimisation to obtain a final value.

Siemens <u>et</u> <u>al</u>. (54, 1964) found that failure geometry was in accordance with the logarithmic spiral solution for retaining walls. Osman (45, 1964) used the dimensional analysis and presented charts to predict the draft force on cutting blades. This work was extended by Wismer and Forth (64, 1969) for cohesionless soils and Wismer and Luth (65, 1970) for cohesive soil. They applied the curve fitting technique to their experimental data and obtained a functional relationship of the draft force. Although the assumption of angle of friction ϕ and soil metal friction μ to be constant simplied the empirical formula for the draft force, errors occur in evaluating these draft forces because for cohesionless soils the values of ϕ and μ are large. The empirical formula takes into account the inertial effect in soil cutting. Since for the clays tested the values of ϕ were small, and therefore the non explicit inclusion of ϕ in the empirical formula would lead to small errors. However for large values of ϕ, errors occur in the determination of the horizontal and vertical components of operative forces during soil cutting

O'Callaghan and Farrely (41,1964) and also O'Callaghan and McCullen (42,1965) derived a simplified expression for the draft per unit width, on the basis that two distinct regimes of deformation occur in vertical and horizontal planes. This expression gave good correlation for cohesive soils, but bad correlation for cohesionless soils.

Reece (51,1965) postulated that the soil acting on a plane loaded interface could be written in form of additive equation of the bearing capacity to represent the gravitational, cohesive, adhesive and surcharge components of the soil reaction per unit width of interface respectively. He called the bearing capacity factors "N - factors" which are pure numbers which describe the shape of the soil failure surface and are thus functions of ϕ and δ and the geometry of the loaded surface. Reece employed a logarithmic spiral solution for passive pressure, and by taking moments about the pole of the logarithmic spiral, the "N - factors" can easily be determined. The determination of these factors is time consuming and also Reece additive equation applies to all forms of soil failure where deformation takes place slowly, so that inertia forces due to velocity effects can be neglected. Hettiaratchi *et al*. (25,1966), Hettiaratchi and Reece (26,1967), assumed the soil as rigid plastic, and obtained curves for "N - factors" which were of considerable advantage for design purposes. Hettiaratchi and Reece (27, 1974) introduced dimensionless scale numbers, and obtained dimensionless passive coefficients which were substituted into the additive equation. They obtained charts which were very useful for design purposes. Hettiaratchi and Reece

(28, 1975) analysed the effect of the boundary wedges imposed by kinematics of the interface on the interface stress. They found that influence of the wedge effect was noticeable only in sharply raked cutting blades, but it can be ignored in acute raked cutting blades. It should however be noted that Sokolovski's (55, 1965) derived equations using the method of characteristics and finite difference should strictly be used for cohesionless soils and cohesive soils respectively. Errors would therefore be introduced in the values of the dimensionless soil resistance coefficients of Hettiaratchi and Reece, when applied to C-ϕ materials, that is soil possessing both cohesion C and friction ϕ Karafiath (34, 1972) applied theory of plasticity and Kotter's (36, 1903) equation to bearing capacity problems. Rosenfarb and Chen (52, 1973) developed a closed form solution using plasticity theory which also solves the earth-pressure problem for active and passive pressure. They considered several failure surfaces, and the combination of a so-called "log sandwich" mechanism gave results which compared favourably with the Sokolovski solution. It should be noted that maximisation of the expressions of the active and passive pressure coefficients must be carried out to obtain a final solution. This is labourious and in some cases maximum values may not be found. Godwin and Spoor (22, 1977) and also Spoor (57, 1969), (58, 1983) developed expressions for draft force when crescent failure occurs in vertical plane and lateral failure in horizontal plane. They were able to estimate the position of the critical depth, that is, the depth at which crescent failure terminates and lateral failure begins, for a wide range of blade aspect ratios. Their work is similar to work by Hettiaratchi and Reece (28, 1975).

Yong et al. (68, 1969), (69, 1972) obtained solution to the problems of blade moving horizontally in a soil possessing both cohesion C, and angle of friction ϕ, by adopting Sokolovski method. They substituted Coulomb yield conditions into Kötter's equation and applied the method of characteristics to solve for the stresses acting on the blade interface, and hence calculate the horizontal and vertical components of forces in soil cutting. Yong et al. assumed that the direction of the maximum principal stress ψ' along the blade interface is constant. Fan et al. (21, 1986), however assumed that in slope stability problems the function describing direction of the interslice forces is bell shaped, with the peak occurring approximately at mid slope. In soil cutting, since the interface is rigid and maintains continuity when flexible, the direction of the maximum principal stress along the blade is taken as constant. Yong et al. assumed the soil to be rigid plastic material, but in nature soil is elasto-plastic material. Errors will therefore occur in their values of the horizontal and vertical components of forces during soil cutting.

Yong and Hanna (70, 1977) used the finite element method to determine the forces developed by the blade during soil cutting. They used a combination of constant strain triangular elements developed by Zienkiewicz (72, 1971), and joint elements developed by Goodman et al. (23, 1968). The coefficients of the hyperbolic tangential stress versus displacement curves were determined experimentally. The finite element method was formulated in terms of these coefficients and not in terms of the material properties, cohesion C and angle of friction ϕ . Hence their results are peculiar to their soil type and test conditions. Inertial effects were not considered only the displacements at the boundaries were specified. This formulation cannot give the displacements at which the maximum horizontal components of force occur.

2.2 Previous Researchers

The previous researchers in soil cutting used mostly artificial soils and regarded soil as a rigid plastic material, that obeys Mohr-Coulomb failure conditions. This means that when the soil is deformed, it does not undergo any strains, until suddenly it fails. This restriction on the soil property, although simplified analytical solutions, yet does not depict the actual stress-strain conditions of the soil. In order to predict more accurately the forces acting on the blade during soil cutting, inertial forces in soil cutting should be taken into account. Hence the need for this research to develop analytical solutions in soil cutting using local soils, and considering inertial forces.

CHAPTER 3

3. THEORETICAL ANALYSIS

3.1 Fundamental Basis for this Work

Coulomb (16, 1776) assumed a straight failure plane abc, as in Figure 3.1, at an angle $(\frac{\pi}{4} - \frac{\phi}{2})$ to the horizontal. Terzaghi (59, 1947) assumed ab as log-spiral curve and bc as a straight plane, making angle $(\frac{\pi}{4} - \frac{\phi}{2})$ with the horizontal. Coulomb and Terzaghi failure criterion will be used in this work. Hill (30, 1950) and Kachanov (32, 1974) confirmed the latter by the theory of plasticity. Sokolovski (55, 1965) in polar coordinates derived that the curve ab is log-spiral. For this work, the slip lines derived from the theory of plasticity will be used, and the geometry of the analytical model in soil cutting is as in Figures 3.1, 3.2 and 3.3 respectively, as regards soil plasticity. The passive Rankine zone in 0bc and the radial shear zone is 0ab, of which 0a is the blade interface. Yavorsky and Detlaf (67, 1980) energy principle, that work done by conservative forces along an arbitrary closed path or boundary is zero, will also be used in this work for cohesionless soils. For cohesive soils where hysterisis predominates, [Wroth and Zytynski (66, 1977)] the work done by forces along the closed boundary is not zero. Therefore the work done by applied forces is equated to the work done by resisting forces along the failure plane, neglecting work done by thermodynamic effects.

The failure criterion used is the Coulomb and Terzaghi criterion. Theoretical equations in soil cutting are developed in this work by energy principles. The elastic and plastic work due to volume change were derived using, Terzaghi (59, 1947) theory of consolidation, Wroth and Zytynski (66, 1977) work hardening principle.

3.2 Boundary Energy Theory

The general equation in soil cutting is such that the horizontal components of operative forces are functions of, blade geometry and velocity, initial and final soil conditions. The failure plane ab (see Figure 3.4) is assumed to be logarithmic spiral. The soils obey Mohr-Coulomb yield criteria.

Terzaghi (59, 1947), gave the equation of the logarithmic spiral ab as follows:

$$r = r_o e^{\theta \tan \phi} \tag{3.1}$$

Haythornthwaite (24, 1961), gave the velocity V, along the log-spiral as follows:

$$V = V_o e^{\theta \tan \phi} \tag{3.2}$$

Kötter (36, 1903), gave the stress σ on a radial slip line as follows:

$$\sigma = \sigma_o e^{2 \theta \tan \phi} \tag{3.3}$$

The velocity diagram is as shown in Figure 3.5. By applying the sine rule, the velocity, V_b of the soil along the blade, is expressed as follows:

$$V_b = V_s \frac{\sin(\frac{\pi}{4} - \frac{\phi}{2})}{\cos \beta} \qquad (3.4)$$

Similarly, the velocity of the soil, V_s along the slip line is expressed as follows:

$$V_s = V_o \frac{\cos \beta}{\cos(\frac{\pi}{4} - (\beta + \frac{\phi}{2}))} \qquad (3.5)$$

Since change in the velocity of the blade causes acceleration of the soil, Newton's accelerating force, F_a due to inertial effect is written as follows:

$$F_a = ma \qquad (3.6)$$

where a, is the acceleration due to change of velocity at time t, along the slip line.

The mass, m of the soil accelerated in time t, is given from the volume of soil disturbed in time t, so that

$$m = \frac{\gamma}{g} bdV_o t \qquad (3.7)$$

Assuming that the soil mass, m is moved along the slip line with velocity V_s, and the blade initial velocity was zero the acceleration force F_a is derived by substituting m, in equation (3.7) into equation (3.6). The acceleration force, F_a

is expressed as follows:

$$F_a = \frac{\gamma \, bdV_o^{\,2} \cos\beta}{g \cos\left(\frac{\pi}{4} - \left(\beta + \frac{\phi}{2}\right)\right)} \qquad (3.8)$$

The work, W_d dissipated along the log-spiral ab is as follows:

$$W_d = \int_o^\theta crVd\theta \qquad (3.9)$$

Substitute r, in equation (3.1) and V, in equation (3.2) into equation 3.9, and integrate. After simplification, the work, W_d is expressed as follows:

$$W_d = \tfrac{1}{2} \; c r_o V_o \cot\phi \left(e^{2\theta\tan\phi} - 1\right) \qquad (3.10)$$

The product of force and velocity on a boundary, gives the rate of work on that boundary. By summing all work done on boundaries ab, bc, 0a, including work done by inertial effect within the closed boundary 0abc0 and equating to zero, the following expression of passive force H_{p1} is obtained for cohesionless soils as follows:

$$H_{p1} = \left(b\left(W_1 + \frac{W_2}{2} - W_3\right) \frac{\sin\phi\cos\beta}{\cos\left(\frac{\pi}{4} - \left(\beta + \frac{\phi}{2}\right)\right)}\right.$$

$$+ \; bW_2 \cos\left(\frac{\pi}{4} - \frac{\phi}{2}\right) \frac{\tan\phi\cos\beta}{2\cos\left(\frac{\pi}{4} - \left(\beta + \frac{\phi}{2}\right)\right)}$$

$$+ \quad bW_3 \cos\left(\frac{\pi}{4} - \frac{\phi}{2}\right) \frac{\tan\delta \sin\left(\frac{\pi}{4} - \frac{\phi}{2}\right)}{\cos\left(\frac{\pi}{4} - \left(\beta + \frac{\phi}{2}\right)\right)}$$

$$+ \quad \frac{b\gamma r_o V_o^2 \cos^3\beta}{g \cos^2\left(\frac{\pi}{4} - \left(\beta + \frac{\phi}{2}\right)\right)} \Bigg) \frac{\cos\left(\frac{\pi}{4} - \left(\beta + \frac{\phi}{2}\right)\right)}{\sin\delta \sin\left(\frac{\pi}{4} - \frac{\phi}{2}\right)} \tag{3.11}$$

Work done by forces causing blade horizontal displacement is the product of the horizontal component of the force and the blade velocity, V_o. By equating the work done by forces causing deformation to work resisting deformation including work W_d dissipated along log-spiral ab, the following expression of passive force, H_{p2} is obtained for cohesive soil as follows:

$$H_{p2} \quad = \quad \left(\tfrac{1}{2} r_o bc \cot\phi \left(e^{2\theta\tan\phi} - 1\right)\right.$$

$$+ \quad b\left(W_1 + \frac{W_2}{2} - W_3\right) \frac{\sin\phi\cos\beta}{\cos\left(\frac{\pi}{4} - \left(\beta + \frac{\phi}{2}\right)\right)}$$

$$+ \quad bW_2 \cos\left(\frac{\pi}{4} - \frac{\phi}{2}\right) \frac{\tan\phi\cos\beta}{2\cos\left(\frac{\pi}{4} - \left(\beta + \frac{\phi}{2}\right)\right)}$$

$$+ \quad \frac{r_o bc \cos\beta e^{\theta\tan\phi}}{\cos\left(\frac{\pi}{4} - \left(\beta + \frac{\phi}{2}\right)\right)}$$

$$+ \quad bW_3 \cos\left(\frac{\pi}{4} - \frac{\phi}{2}\right) \frac{\tan\delta\sin\left(\frac{\pi}{4} - \frac{\phi}{2}\right)}{\cos\left(\frac{\pi}{4} - \left(\beta + \frac{\phi}{2}\right)\right)}$$

$$+ \frac{br_o c_a \sin(\frac{\pi}{4} - \frac{\phi}{2})}{\cos(\frac{\pi}{4} - (\beta + \frac{\phi}{2}))}$$

$$+ \frac{br_o \gamma V_o^2 \cos^3\beta}{g\cos^2(\frac{\pi}{4} - (\beta + \frac{\phi}{2}))}) \sec(\beta - \delta) \qquad (3.12)$$

The horizontal force component H_H, is expressed as follows:

$$H_H = H_p \cos(\beta - \delta) \qquad (3.13)$$

The vertical force component H_V, is expressed as follows:

$$H_V = H_H \tan(\beta - \delta) \qquad (3.14)$$

The first term in equation (3.11) is the force component due to friction on ab (see Figure 3.4. Similarly the second term is the force component on bc. Whilst the third term is the force component on 0a. The fourth term is the force component due to intertial effect in 0a bc. The first term in equation (3.12) is the force component on ab due to cohesion. The second term is the force component on ab due to friction. Similarly the third term is the force component on bc and the fifth term is the force component on 0a. The fourth term is the force component on bc due to cohesion. Whilst the sixth term is the force component due to adhesion. The soils used in this thesis do not have adhesive properties, and hence the adhesion c_a is zero. The seventh term is the force component due to inertial effect.

Since work is required to change the volume of a medium in compression, the boundary energy equation derived by summation of work done along the boundary will be less than the summation of work done along the boundary and the internal work done due to volume change. The work done along the boundary is regarded as the least work, whilst the total work done on the system is regarded as the greatest work.

3.2.1 Boundary Energy Theory (Upper bound)

The work done is the product of the stress increment dp, and volume change of the system.

The elastic work done in soil cutting is as follows:

$$W_E = \frac{bdV_o \kappa}{1+e} dp \qquad (3.15)$$

Similarly the plastic work done is as follows:

$$W_p = \frac{bdV_o (\lambda - \kappa)}{1+e} dp \qquad (3.16)$$

The force on 0a is H_p and acts at an angle $(\beta - \delta)^o$ to the horizontal. During plastic work, H_p is assumed to act horizontally in y direction. The average stress perpendicular surface 0ac is $\frac{1}{2}K_o\gamma d$. The stress on oc is P_q. The mean stress increment dp is one third the sum of the stresses on 0a, 0ac and 0c. The stress increment dp can be substituted in equations (3.15) and (3.16). By combining elastic work given by equation (3.15) and plastic work given by equation (3.16), with the passive force H_{p1} of the boundary work in equation (3.11) the following expression of the total passive force H_{p3} is obtained for cohesionless soils as follows:

$$H_{p3} = (b(W_1 + \frac{W_2}{2} - W_3) \frac{\sin\phi\cos\beta}{\cos(\frac{\pi}{4} - (\beta + \frac{\phi}{2}))}$$

$$+ \quad bW_2\cos(\frac{\pi}{4} - \frac{\phi}{2}) \frac{\tan\phi\cos\beta}{2\cos(\frac{\pi}{4} - (\beta + \frac{\phi}{2}))}$$

$$+ \quad bW_3\cos(\frac{\pi}{4} - \frac{\phi}{2}) \frac{\tan\delta\sin(\frac{\pi}{4} - \frac{\phi}{2})}{\cos(\frac{\pi}{4} - (\beta + \frac{\phi}{2}))}$$

$$+ \quad \frac{b\gamma r_o V_o^2 \cos^3\beta}{g\cos^2(\frac{\pi}{4} - (\beta + \frac{\phi}{2}))}$$

$$+ \quad \frac{\kappa\gamma b r_o^2 \cos^2\beta K_o}{6(1 + e)}$$

$$+ \quad \frac{(\lambda - \kappa)\gamma b r_o^2 \cos^2\beta K_o}{6(1 + e)}$$

$$+ \quad \frac{\kappa b r_o \cos\beta\, P_q}{3(1 + e)}$$

$$+ \quad \frac{(\lambda - \kappa) b r_o \cos\beta P_q}{3(1 + e)})/$$

$$\left(\frac{\sin\delta\sin(\frac{\pi}{4} - \frac{\phi}{2})}{\cos(\frac{\pi}{4} - (\beta + \frac{\phi}{2}))} - \frac{\kappa\cos(\beta - \delta)}{3(1 + e)} - \frac{\lambda - \kappa}{3(1 + e)}\right) \quad (3.17)$$

The first four terms of equation (3.17) of the force components and their planes of action are as previously defined in section 3.2. The fifth term is the force component due to elastic work done in 0abc0 in figure 3.4. The sixth term is the force component due to plastic work done in 0abc0. The seventh term is the force component due to elastic work done by a stress P_q applied on boundary 0c in 0abc0. Similarly the eight term is the force component due to plastic work done by stress P_q applied on boundary 0c in 0abc0. In this experiment of soil cutting, no boundary stress P_q was applied, and hence P_q is equal to zero. In the denominator of equation (3.17), the first term is a factor of passive force H_{p3}, of work done along the boundary 0a. The second and third terms are factors of the passive force H_{p3}, of internal work done in soil cutting.

Similarly by combining the elastic and plastic work in equations (3.15) and (3.16) respectively, with the passive force of the boundary work in equation (3.12) the following expression of the total passive force H_{p4} is obtained for cohesive soils as follows:

$$H_{p4} = (\tfrac{1}{2}r_o bc\cot\phi(e^{2\theta\tan\phi} - 1)$$

$$+ b(W_1 + \frac{W_2}{2} - W_3)\frac{\sin\phi\cos\beta}{\cos(\frac{\pi}{4} - (\beta + \frac{\phi}{2}))}$$

$$+ \quad bW_2 \cos\left(\frac{\pi}{4} - \frac{\phi}{2}\right) \frac{\tan\phi \cos\beta}{2\cos\left(\frac{\pi}{4} - \left(\beta + \frac{\phi}{2}\right)\right)}$$

$$+ \quad \frac{r_o bc \cos\beta e^{\theta \tan\phi}}{\cos\left(\frac{\pi}{4} - \left(\beta + \frac{\phi}{2}\right)\right)}$$

$$+ \quad bW_3 \cos\left(\frac{\pi}{4} - \frac{\phi}{2}\right) \frac{\tan\delta \sin\left(\frac{\pi}{4} - \frac{\phi}{2}\right)}{\cos\left(\frac{\pi}{4} - \left(\beta + \frac{\phi}{2}\right)\right)}$$

$$+ \quad \frac{br_o c_a \sin\left(\frac{\pi}{4} - \frac{\phi}{2}\right)}{\cos\left(\frac{\pi}{4} - \left(\beta + \frac{\phi}{2}\right)\right)}$$

$$+ \quad \frac{br_o \gamma V_o^2 \cos^3\beta}{g\cos^2\left(\frac{\pi}{4} - \left(\beta + \frac{\phi}{2}\right)\right)}$$

$$+ \quad \frac{\kappa\gamma b r_o^2 \cos^2\beta\, K_o}{6(1+e)}$$

$$+ \quad \frac{(\lambda - \kappa)\gamma\, b r_o^2 \cos^2\beta K_o}{6(1+e)}$$

$$+ \quad \frac{\kappa b r_o \cos\beta\, P_q}{3(1+e)}$$

$$+ \quad \frac{(\lambda - \kappa) b r_o \cos\beta\, P_q}{3(1+e)}) \;/$$

$$\left(\cos(\beta - \delta) - \frac{\kappa\cos(\beta - \delta)}{3(1+e)} - \frac{\lambda - \kappa}{3(1+e)}\right) \quad (3.18)$$

The first seven terms of equation (3.18) of the force components and their planes of action are as previously defined in section 3.2. The eighth term is the force component due to elastic work done in 0abc0 in figure 3.4. The ninth term is the force component due to the plastic work done in 0abc0. The tenth term is the force component due to elastic work done by stress P_q applied on boundary 0c in 0abc0. Similarly the eleventh term is the force component due to plastic work done by stress P_q applied on boundary 0c in 0abc0. In this experiment of soil cutting, the boundary stress P_q is zero. In the denominator of equation (3.18), the first term is a factor of the passive force H_{p4}, of work done along the boundary 0a. The second and third terms are the factors of the passive force H_{p4}, of internal work done in soil cutting.

3.3 Analytical Solution of Blade Cutting of Soil

The boundary energy theory will be used to evaluate the horizontal and vertical components of forces in soil cutting. Experimental data, theory and work by other researchers will be compared.

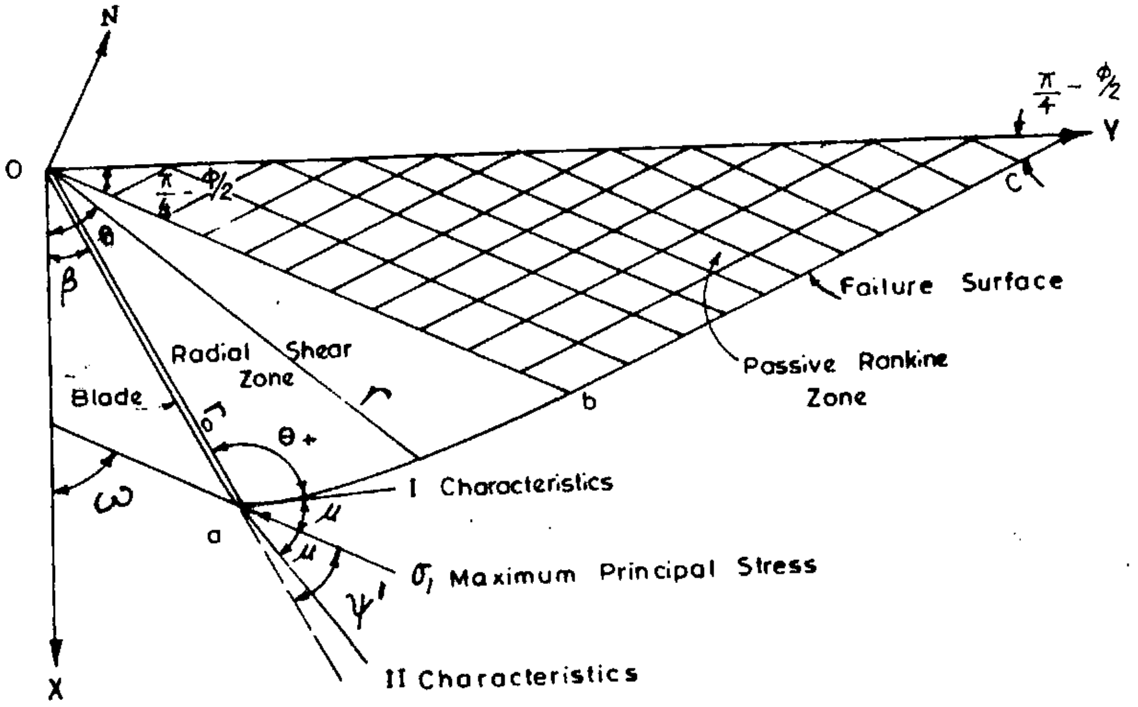

FIG. 3·1 GEOMETRY OF ANALYTICAL MODEL FOR DESCRIBING BOUNDARY CONDITIONS

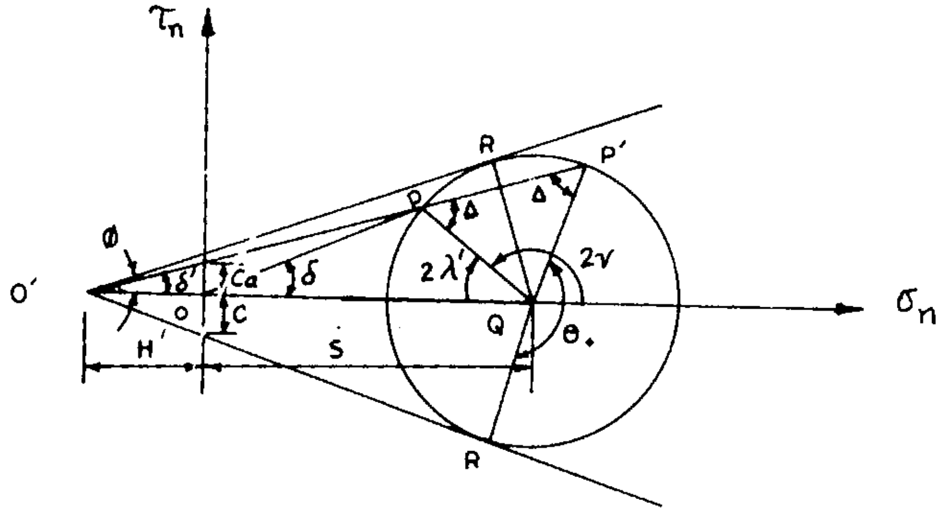

FIG. 3·2 MOHRS DIAGRAM OF A POINT P IN ELEMENT AREA OF SOIL MEDIUM

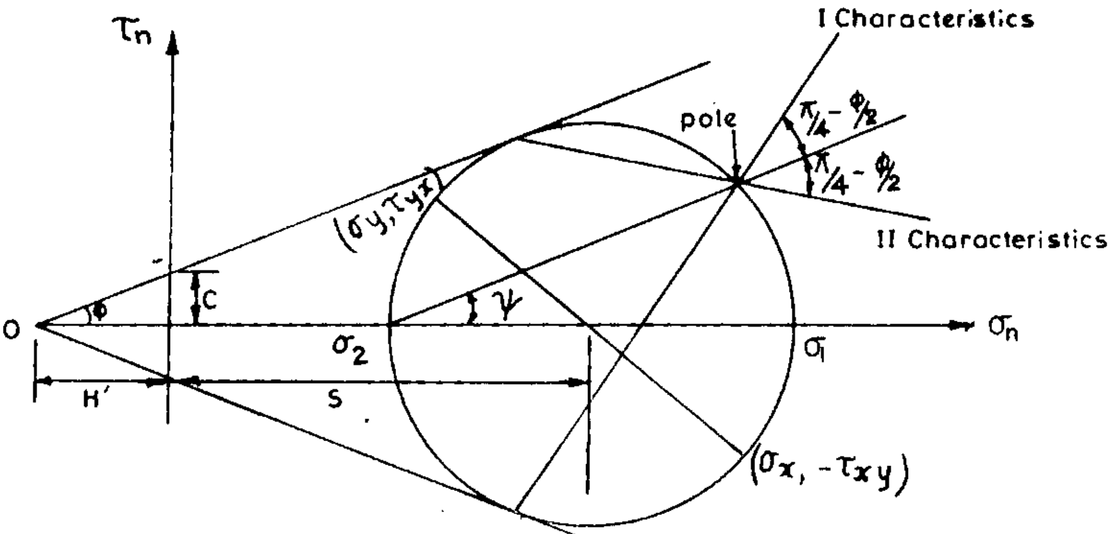

FIG. 3·3 DIAGRAM OF MOHRS CIRCLE AND CHARACTERISTICS

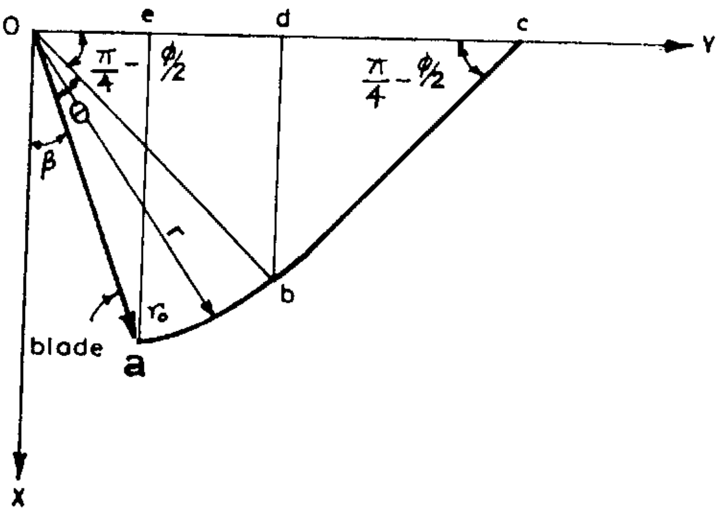

FIG 3·4 DIAGRAM FOR CALCULATING HORIZONTAL AND VERTICAL FORCES ON BLADE Oa, BY BOUNDARY ENERGY METHOD

V_o = Velocity of the blade in y direction

V_s = Velocity of the soil along the slip line abc

V_b = Velocity of the soil along the blade Oa

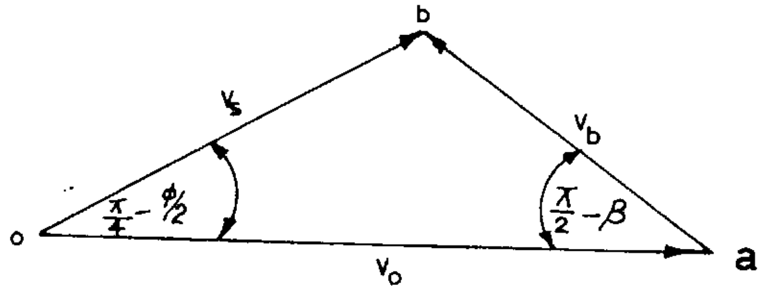

FIG. 3·5 VELOCITY DIAGRAM OF THE KINEMATICS OF BLADE – SOIL MOTION AT FAILURE

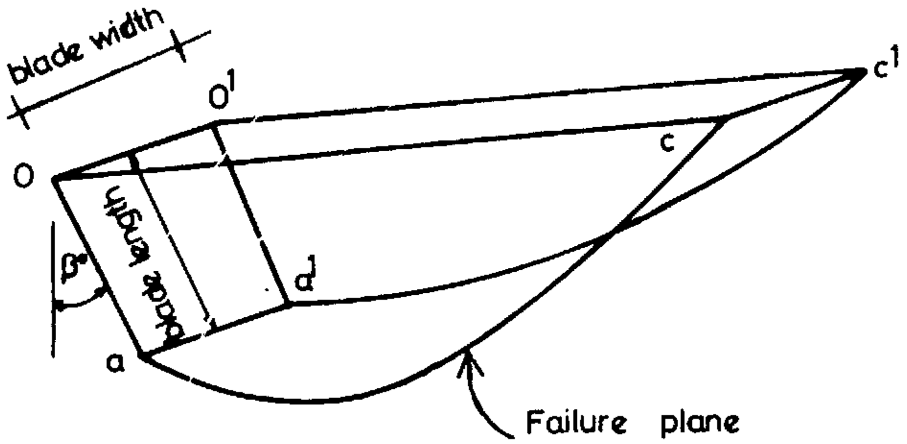

Figure. 3·6 Schematic Diagram of soil cutting blade and Failure plane.

CHAPTER 4

4. THE APPARATUS

4.1 General Description of the Apparatus

The general arrangement of the soil cutting apparatus (SCA) is as in Figure 4.1. It comprises the soil bin, horizontal and vertical carriages, proving rings, carriage seat frame, soil hopper, hydraulic jack, and the blades.

The longitudinal and transverse sectional details of the apparatus SCA, showing line of application of operative horizontal and vertical forces are as in figures 4.6 and 4.7 respectively.

4.2 Soil Bin

The soil bin is made of an aluminium alloy of 50mm x 50mm x 4mm thick angles, 865mm in length and also 50mm x 50mm x 4mm thick angles, 595mm in length. These were made into rectangular frames 865mm long, 595mm high and stayed by aluminium angle brackets 50mm x 50mm x 4mm. The inner flanges of the angle frames were chamfered at 45^{o}. The angle brackets were riveted to the main angle frame by Kling Klik T 80 riveter. The soil bin has aluminium frame on either side. The two frames were spaced by 100mm x 50mm x 4mm thick aluminium channels, 595mm in length, placed vertically and a 100mm x 50mm x 4mm thick aluminium channel, 765mm length, placed horizontally at the bottom. The vertical channels were stayed to the horizontal channels by 100mm x 50mm x 4mm thick, angle brackets and riveted. A perspex glass 865mm long x 595mm high x 6mm thick was placed on either face of the soil bin, between the angle frames and channel frames. These components were bolted together to form a rigid soil bin, by 100mm diameter steel bolts with hexagonal nuts. Two bolts were on the left side and two bolts were on the right side of the soil bin respectively.

In order to reduce cost and weight of the apparatus, and also because of the limited space available, the carriages and the cutting blades were made of aluminium. By using visual perspex glass, the boundary conditions at the sides can be assumed to be frictionless. The perspex glass also allowed the deformation of the soil to be monitored visually.

4.3 Horizontal Carriage

The carriage is 385mm long by 313mm wide on four rollers with two rollers on either side. The carriage is made of 50mm x 50mm x 4mm thick, aluminium box sections, joined by 100mm x 50mm x 5mm thick plates and riveted. The vertical sleeve in which the vertical carriage traverses was made of 50mm x 25mm x 4mm thick aluminium channel 150mm long. The back column is made of 50mm x 50mm x 4mm aluminium box sections, joined by 100mm x 50mm x 5mm thick plates and riveted. The vertical sleeve in which the vertical carriage traverses was made of 50mm x 25mm x 4mm thick aluminium channel 150mm long. The back column is made of 50mm x 50mm x 4mm aluminium box, 305mm long, with an overhang 50mm x 50mm x 4mm thick aluminium box, 129mm long. This was riveted by 100mm x 50mm x 5mm aluminium flats to the back column. The lower end of the back column has a 10 mm diameter hole with 4mm deep recess by which the load from the hydraulic jack can be applied on the proving ring. The overhang is connected by 50mm x 25mm x 4mm aluminium channel, 200mm long with 100mm x 50mm x 4mm thick flats and riveted. A 10mm diameter hole was drilled through the channel to allow for connection of the proving ring for measuring the vertical forces.

The design considerations for the horizontal carriage are that, it could travel horizontally with very little friction resistance and also rigid enough as not to introduce errors in the measured horizontal and vertical components of the operative forces during soil cutting. Assuming the Young's modulus of the aluminium alloy is $E = 70 kN/mm^2$, the maximum deflection of the channel on which the horizontal carriage seats is calculated to be 47×10^{-3}mm. This is equivalent to 1.86 divisions of the dial gauge. The deflection of the vertical overhang of the carriage, of 22×10^{-3}mm, is equivalent to 0.86 divisions of the dial gauge. Errors due to deflections are therefore negligible.

4.4 Vertical Carriage

The vertical carriage is as in Figure 4.2. It is made of two 50mm x 25mm x 4mm thick aluminium box sections, 100mm long, and spaced by 100mm wide x 150mm long x 4 thick aluminium flat, joined together by 30mm x 20mm x 4mm angle brackets and riveted. A roller 10mm in diameter is centrally placed on either side of the aluminimum box. Two 6mm diameter holes were drilled on the 100mm x 150mm x 4mm thick, aluminium flat for connection to the cutting blades.

The vertical carriage was designed such that little or no friction existed between the rollers and the vertical sleeve of the horizontal carriage. The vertical carriage was allowed to move freely vertically. In order to reduce frictional resistance on the rollers, the rollers and the tracks were well greased by silicone grease. The maximum deflection of the vertical overhang of the carriage was 22×10^{-3}mm. This is equivalent to 0.86 divisions of the dial gauge. Errors due to the vertical deflection are therefore negligible.

4.5 Carriage Seat Frame

The carriage seat frame is as in Figure 4.1. It comprises two 80mm x 40mm x 4mm aluminium channel joists, 1620mm long. These seat centrally on four 100mm x 50mm x 4mm thick aluminium boxes, 770mm long, spaced longitudinally at 1225mm centres and transversely at 350mm centres. They are braced transversely at top and bottom by 45mm x 45mm x 4mm aluminium box sections 305mm long. The 80mm x 40mm x 4mm thick vertical boxes individually seat on 200mm x 100mm x 6mm aluminium flat plates, connected by 50mm x 50mm x 4mm angle brackets to the boxes and riveted. The channel flange seats for the carriages are connected to the four vertical boxes by 160mm x 100m x 6mm aluminium flats and riveted. The carriage rollers roll between the flange of 80mm x 40mm x 4mm thick channels, and 30mm diameter, galvanised iron pipe, 690mm long 3mm thick. The pipes are connected to the flanges of the channels by 20mm diameter x 3mm thick and 20mm long bushing, by 5mm diameter bolts, with nuts.

4.6 Proving Rings

The proving rings are as in Figure 4.2. They are standard Wykeham - Ferrance proving rings with maximum load of 200 kgf (1962 N), and with E.L.E dial gauge of 0.001"/division (0.0254mm/division). These were used to measure the horizontal and vertical components of the operative forces on the blade.

4.7 Hydraulic Jack

The hydraulic jack is as in Figure 4.1. The jack was of 10 tonne-capacity (98.07 kN), with patent number 8103 and manually operated so as to give an average speed of 0.11 cm/sec.

4.8 Soil Hopper

The soil hopper is as in Figure 4.3. It was designed to produce uniform density within the soil mass in the soil bin. It was designed like an inverted regular pyramid, with top, 410mm square and bottom 135mm square and height of 395mm. The slanting corners are 30mm x 30mm x 4mm aluminium angles, which form the edges of the hopper on which 6mm thick perspex glasses seat, and were riveted. The hopper centrally seats on 100mm wide x 390mm long x 4mm aluminium plate, which was securely riveted to the base of the hopper. There were 9mm diameter perforations at the bottom of the hopper, for discharge of the soil. The soil hopper was manually traversed across the length of the bin forward and backward, until the soil bin reached the predetermined marked height of 85mm from the top of the soil bin. Black cotton soil was placed in dry form. This is a limitation since black cotton soil is a plastic material when it is wet.

4.9 Cutting Blades

The blades are as in Figure 4.4. The blades were made of aluminium flats of widths 50mm, 75mm and 100mm respectively. The overall length and thickness of the blades were 250mm and 8mm respectively. The cutting length was 100mm. Each blade had two 9mm diameter holes for connection to the vertical carriage. The inclination $\beta°$ to the vertical, of blades vary from 0° to 75°, in increment of 15°. The depth of cut to lift ratio $\frac{z}{\ell \cos\beta}$ is made unity. See Figure 4.5. The maximum deflection of the cutting tip of the blade was 0.24mm. This is equivalent to an error of $0° 8' 15''$ in measuring the actual inclination of the blade angle either to the horizontal $\alpha°$ or to the vertical $\beta°$.

4.10 Mechanism of Application of the Horizontal and Vertical Forces

The longitudinal and transverse sections of the soil cutting apparatus (SCA), showing the fabrication details and the mechanism of application of the horizontal and vertical forces are as in Figures 4.6 and 4.7 respectively. The schematic diagram of soil cuttting blade and failure plane is as in Figure 3.6. The horizontal force is applied on the horizontal carriage by the hydraulic jack which moves the blade horizontally. The induced vertical force during soil cutting, lifts the blade, through the vertical carriage. The vertical thrust is measured by the gauge.

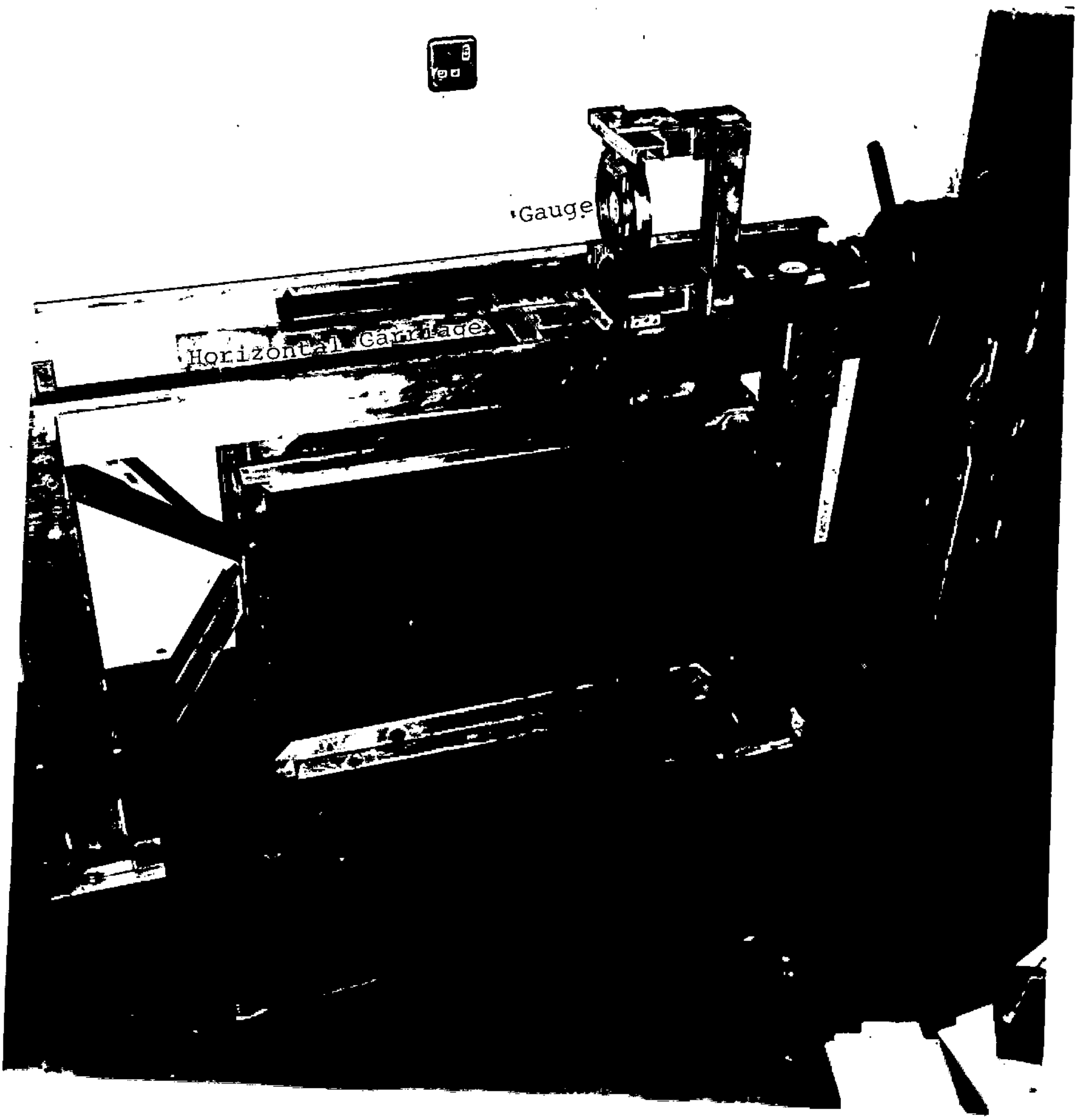

FIGURE 4.1: General Arrangement of soil cutting Apparatus (SCA).

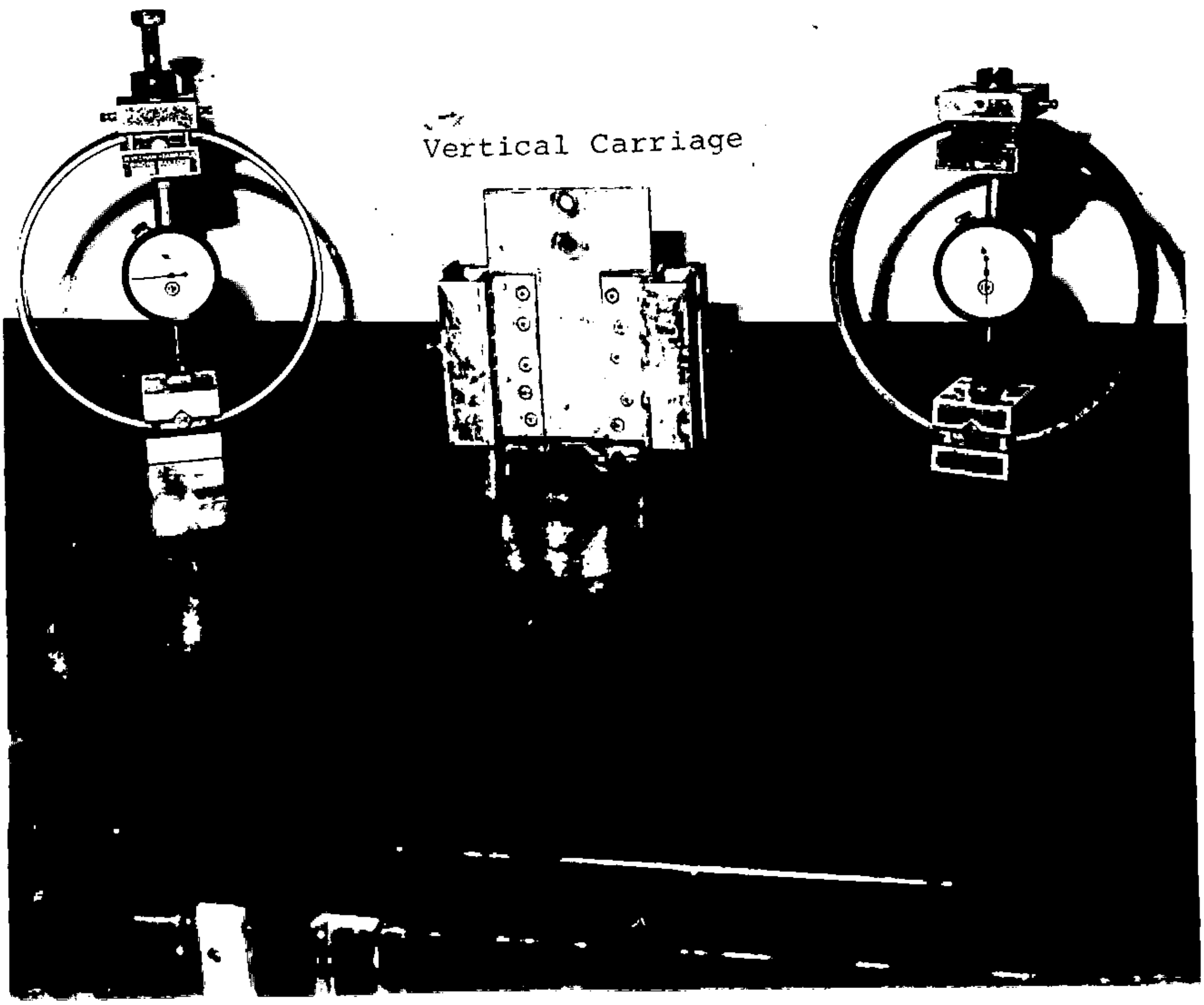

FIGURE 4.2: Gauges and vertical carriage.

FIGURE 4.3: Preparation of soil bed for soil cutting using hopper.

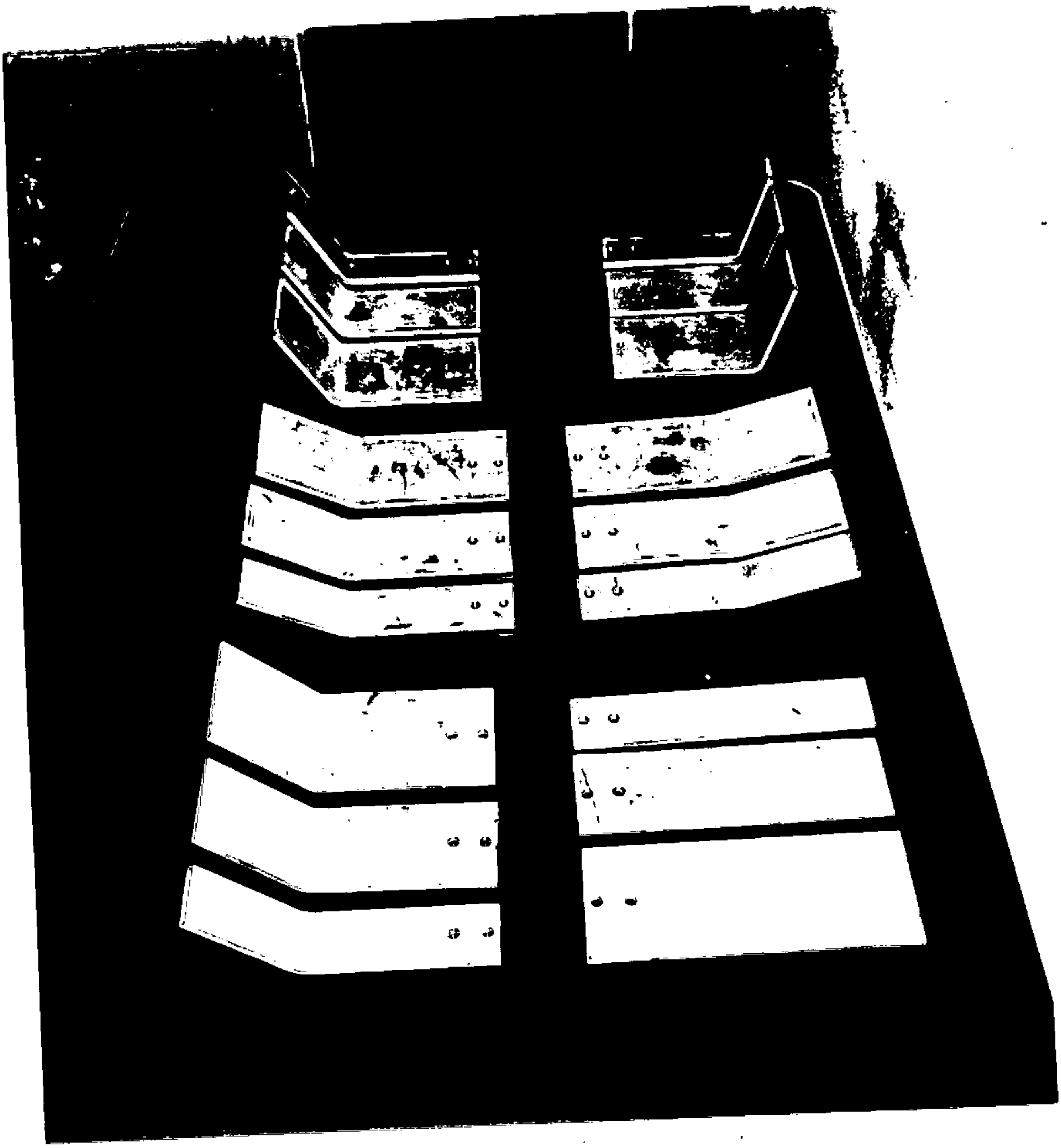

FIGURE 4.4: Soil cutting blades.

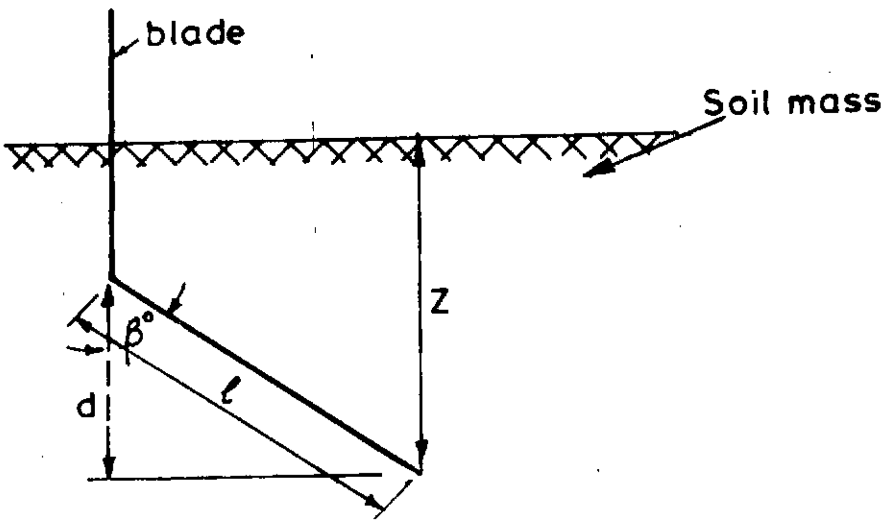

FIG 4·5 DEPTH OF CUT TO LIFT RATIO $\frac{Z}{\ell \cos\beta}$

NOTES

1. All aluminium materials are manufactured to BS
2. Aluminium is riveted by KLING KLIK T80 riveter.
3. The modulus of Elasticity of the aluminium is 70 KN/m²
4. Rivet size 6mm ϕ.

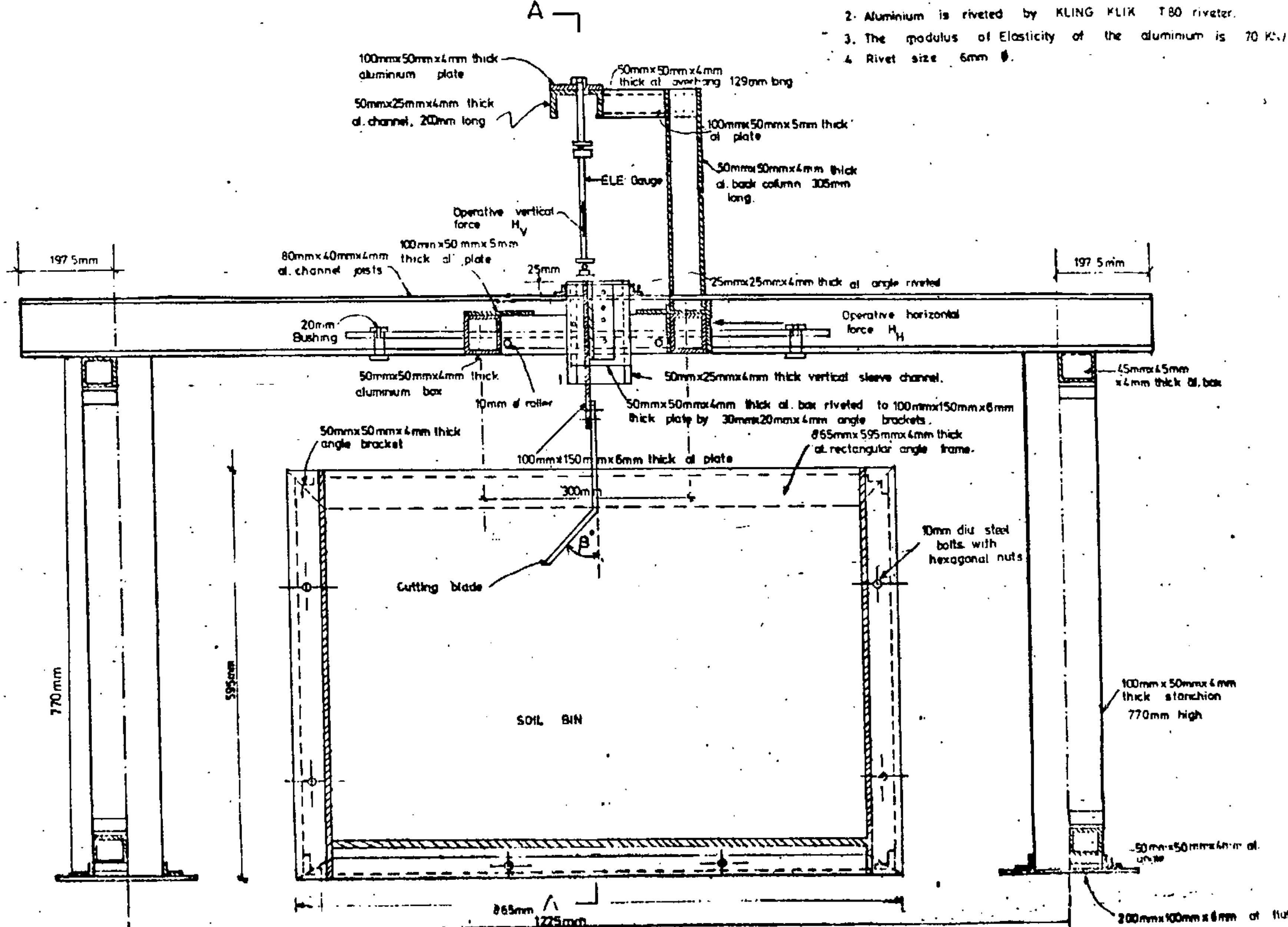

Fig. 46 : Longitudinal section through the soil cutting apparatus SCA

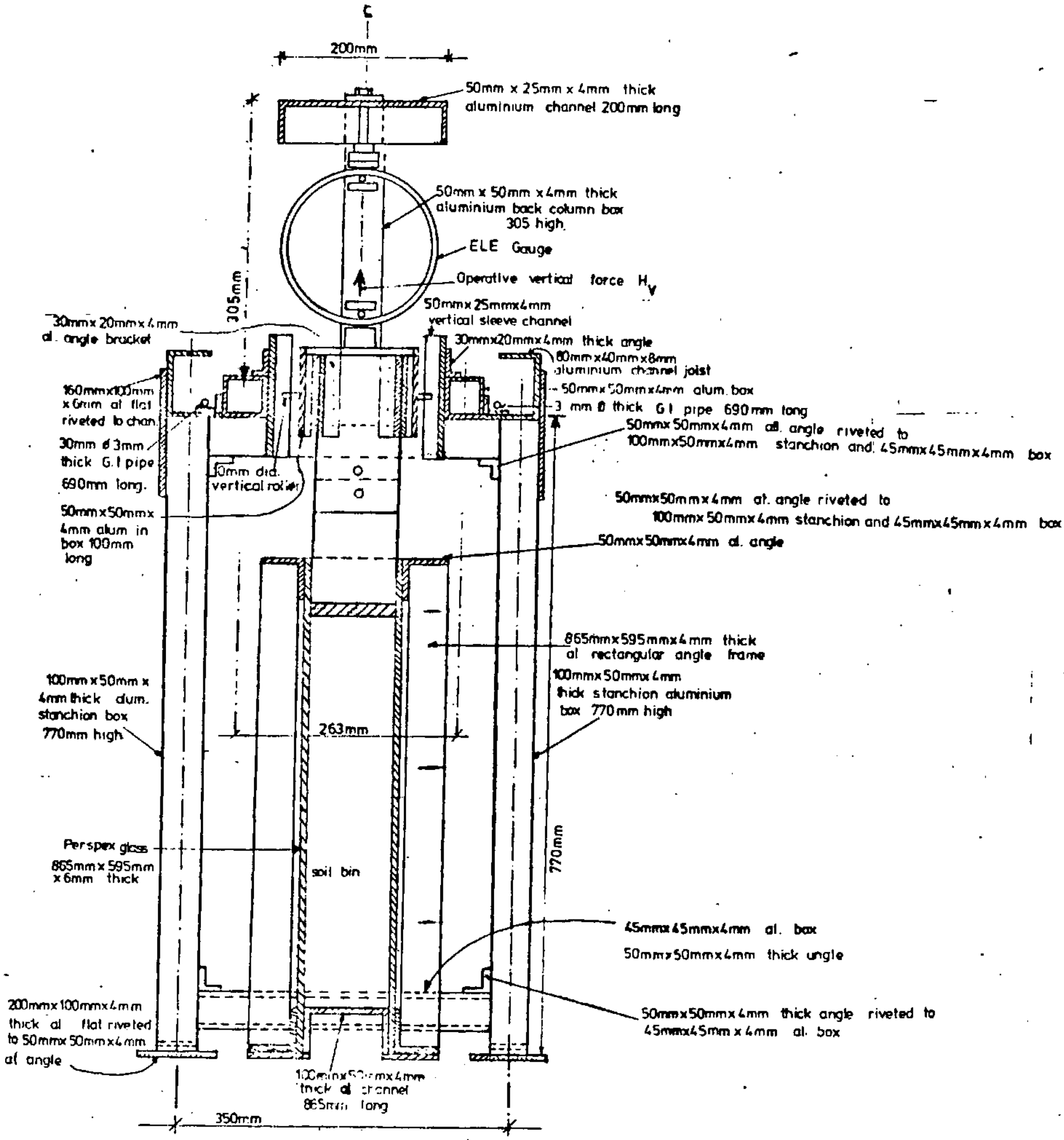

Figure . 47 :- Transverse section A-A through the soil cutting apparatus SCA

CHAPTER 5

5. Experimental Tests, Procedure, Objectives and Scope

The objective of the experimental part of this study, is to measure the horizontal and vertical components of the operative forces required to cut Ogun river sand, beach sand and black cotton soil respectively. In achieving this experimental objective, the proving rings Wykeham - Ferrance, (1962 N) load capacity gauges were calibrated, to measure these components of force during soil cutting. The soil properties cohesion C, and angle of friction ϕ, were determined by triaxial and direct shear tests. Grain size tests were also carried out on these soils.

5.1 Calibration of Gauges

The proving ring gauges used were standard Wykeham - Ferrance 200 kgf (1962 N) load capacity, with dial gauge of 0.0254mm/division. The gauges were standard calibrated.

5.2 Atterberg Limits, and Grain Size Tests

The Atterberg limits tests were performed on black cotton soil as specified in B.S 1377 (1975). The grain size and specific gravity tests were carried out according to the same specification, on Ogun river sand, beach sand and black cotton soil respectively. Also density index tests were carried out on Ogun river sand and beach sand respectively.

5.3 Triaxial Tests

Standard triaxial tests were performed on black cotton soil samples at a density of 1.64 Mg/m^3. Consolidated drained triaxial tests were carried out on Ogun river sand at densities of 1.50 Mg/m^3, 1.94 Mg/m^3 and 1.99 Mg/m^3 respectively. Also consolidated drained triaxial tests were carried out on beach sand at densities of 1.61 Mg/m^3, 1.91 Mg/m^3 and 2.05 Mg/m^3 respectively.

5.4 Shear Box Test

Direct shear tests using shear box apparatus were carried out on Ogun river sand and beach sand. These tests were carried out on the soil samples with same densities as in the triaxial tests.

5.5 Soil Cutting Tests:

The factors considered pertinent in soil cutting experiments relate to,

(a) Soil type: Density, and shear resistance parameters.

(b) Cutting tool: Geometry, depth of cut, speed of travel and interfacial characteristics

(c) Forces: Developed forces which are classified as horizontal and vertical components.

In general the variations with regards to the above for a given soil, are concerned with the specification of the desired conditions, that is;

(1) Specific constant speed and constant depth of cut. This will yield developed operative forces on the tool, which may be resolved into horizontal and vertical components.

(2) Specified constant horizontal force component and constant depth of cut. The measured variables in this instance are speed and developed vertical force component.

(3) Specified constant horizontal and vertical force components. In this particular case both speed and depth of cut are the measured variables.

To allow for a rational approach in the analysis of results in soil cutting, the experiments performed in this study are limited to the first condition, of measuring the horizontal and vertical components of operative forces, in soil cutting. The blade inclination β^0 to the vertical vary between 0^o and 75^o in increment of 15^o. The soil bin was filled by soil dropping from the hopper by gravity. The blades pushed by manually operated, 98.07kN jack travelled horizontally at an average speed of 0.11cm/sec, in a soil bin bed of Ogun river sand, beach sand and black cotton soil respectively. The horizontal and vertical components of the operative forces were then measured.

CHAPTER 6

6 Results

The results of experiments carried out in this work are given in relation to, calibration of proving rings, determination of engineering soil properties, and soil cutting characteristics.

6.1 Proving Ring Constant

The results of the calibration of gauges are as shown in Figures 6.1a and 6.1b respectively. The gauge constants are the same, and have a value of 393.70 N per mm deflection.

6.2 Soil Properties

The particle grading curves for Ogun river sand, beach sand and black cotton soil are as shown in Figure 6.2. The plots of angle of internal friction ϕ versus porosity n% are as shown in Figure 6.3. Test results of Ogun river sand are as shown in Table 6.1. Similar test results of beach sand and black cotton soil are as shown in Tables 6.2 and 6.3 respectively.

6.3 Soil Cutting

Graphs of horizontal force and vertical force versus blade displacement are as shown in Figures 6.4 and 6.5

respectively for Ogun river sands. Whilst for beach sand the horizontal force and vertical force versus blade displacement are as shown in Figures 6.6 and 6.7 respectifully. The black cotton soil horizontal force and vertical force versus blade displacement are as shown in Figures 6.8 and 6.9 respectively. The graphs of maximum horizontal force versus blade inclination β^o, for various blade widths are as shown in Figure 6.10 for Ogun river sand. Whilst graphs of maximum horizontal force versus angle of blade inclination β^o, for various blade widths for beach sand and black cotton soil are as shown in Figures 6.11 and 6.12 respectively. The graph of maximum horizontal force versus blade width for Ogun river sand is as shown in Figure 6.13. Whilst the graphs of maximum horizontal force versus blade width for beach sand and black cotton soil are as shown in Figures 6.14 and 6.15 respectively. The graphs of maximum horizontal force versus blade inclination β^o, for Ogun river sand, beach sand, and black cotton soil are as shown in Figure 6.16. The graphs of maximum vertical force versus angle of blade inclination β^o, for various widths of blade, and soil types, are as shown in Figure 6.17. Results of soil cutting tests for Ogun river sand are as shown in Table 6.4. Whilst the results for beach sand and black cotton soil are as shown in Tables 6.5 and 6.6 respectively.

Graphs of horizontal force versus blade inclination β^o, with varying soil-blade friction δ^o, for Ogun river sand are as shown in Figure 6.18. Similarly graphs of horizontal force versus blade inclination β^o, for varying soil-blade friction δ^o, for beach sand and black cotton soil are as shown in Figures 6.19 and 6.20 respectively. Graphs of vertical force versus blade inclination β^{o}, for varying soil-blade friction δ^{o}, for Ogun river sand are as shown in Figure 6.21. Whilst the graphs of vertical force versus blade inclination β^{o}, with varying soil-blade friction δ^{o}, for beach sand and black cotton soil are in Figures 6.22 and 6.23 respectively. Graphs of experimental and theoretical forces versus angle of blade inclination for Ogun river sand are as shown in Figure 6.24. Whilst graphs of experimental and the theoretical horizontal forces versus angle of blade inclination β^{o}, for beach sand and black cotton soil, are as shown in Figures 6.25 and 6.26 respectively. Graphs of experimental and theoretical forces versus angle of blade inclination β^{o}, for Ogun river sand and beach sand are as shown in Figures 6.27 and 6.28 respectively. Whilst graph of experimental and theoretical vertical forces versus angle of blade inclination β^{o}, for black cotton soil, is as shown in Figure 6.29. Theoretical horizontal and vertical components for forces and measured values are as shown in Tables 6.7 to 6.12. The graph of horizontal force versus square of depth of cut is as shown in Figure 6.30. Graph of maximum horizontal force versus ratio of blade width and depth of cut, for Ogun river sand is as shown in Figure 6.31. Whilst graphs of maximum horizontal force versus ratio of blade width and depth of cut, for beach sand and black cotton soil are as shown in Figures 6.32 and 6.33 respectively. Gradients of maximum horizontal force versus ratio of blade width to depth of cut are as shown in Table 6.13. Graph of horizontal force increment per blade width to depth of cut ratio, versus inverse of depth of cut is as shown in Figure 6.34. Graph of $\log_e(\log_e H_f)$ versus $\log_e \frac{(D_{max} - D_{min})\ 100}{\Sigma D \times \%\ \text{distribution}}$ is as shown in Figure 6.35. Graph of $\ln H_f$ versus $\ln b$ for Ogun river sand, is as shown in Figure 6.36. Whilst graphs of $\ln H_f$ versus $\ln b$, for beach sand and black cotton soil are as shown in Figures 6.37 and 6.38 respectively. Graph of $\log_e H_f$ versus $\log_e d$ for different soil types is as shown in Figure 6.39. Graph of maximum horizontal force versus soil cutting index (SCI),

$$SCI = \gamma b d^2 \exp\left\{\left|\frac{(D_{max} - D_{min})\ 100}{\Sigma D \times \%\ \text{distribution}}\right|^{0.025} - e\right\}$$

is as shown in Figure 6.40. Graph of maximum vertical force versus maximum horizontal force for 100mm width blade is as shown in Figure 6.41. Graph of maximum vertical force versus maximum horizontal force for 75mm width blade is as shown in Figure 6.42. Graph of maximum vertical force versus maximum horizontal force for 50mm width blade is as shown in Figure 6.43. Graphs of energy per unit volume applied to cut soil versus depth of cut, of 100mm width blade is as shown in Figure 6.44. Graphs of energy per unit volume applied to cut soil versus depth of cut of 75mm width blade is as shown in Figure 6.45. Graph of energy per unit volume applied to cut soil, versus depth of 50mm width blade is as shown in Figure 6.46.

6.4 Characteristics of the Failure Plane

The observed failure boundary for 100mm width vertical blade in Ogun river sand is as shown in Figure 6.47. The ruptured boundaries for beach sand and black cotton soil are as shown in Figures 6.48 and 6.49 respectively.

6.5 Active and Passive Rankine Pressure and Displacement

The Mohr diagram of active and passive pressures for cohesionless soils are as shown in Figure 6.50. The graphs of passive Rankine forces and maximum horizontal forces versus blade horizontal displacement, are as shown in Figure 6.52 for Ogun river sand, whilst the graphs of passive Rankine forces and maximum horizontal displacement versus blade horizontal displacement for beach sand and black cotton soil are as shown in Figures 6.53 and 6.54 respectively. The graph of void ratio e versus

$$\frac{(D_{max} - D_{min})100}{\Sigma D \times \%\ \text{distribution}}$$ is as shown in Figure 6.51

Blade horizontal displacement to develop passive Rankine zone, for 100mm width blade is as shown in Table 6.14. Similar graphs for 75mm width blade and 50mm width blade are shown in Tables 6.15 and 6.16 respectively. The mobilised angle of friction Ø, are as shown in Table 6.17

6.6 Effect of Angle of Soil-metal Friction δ^{o} on Operative Horizontal and Vertical Forces

The graphs of horizontal force versus blade inclination β^{o}, with varying soil-blade friction δ^{o}, for Ogun river sand is as shown in Figure 6.55. Whilst similar graphs for beach sand and black cotton soil are as shown in Figures 6.56 amd 6.57 respectively. The graphs of vertical force versus blade inclination β^{o}, with varying soil-blade friction δ^{o}, for Ogun river sand are as shown in Figure 6.58. Whilst similar graphs for beach sand and black cotton soil are as shown in Figures 6.59 and 6.60 respectively. The horizontal operative forces in soil cutting for varying soil metal friction δ^{o}, for Ogun river sand are as shown in Table 6.18. Whilst the horizontal operative forces for varying friction $\emptyset$, and varying soil metal friction δ^{o}, for beach sand and black cotton soil are as shown in Tables 6.20 and 6.22 respectively. The vertical operative forces in soil cutting, for varying angle of friction $\emptyset$, and varying soil metal friction δ^{o} for Ogun river sand is as shown in Table 6.19. Whilst the vertical operative forces for varying angle of friction $\emptyset$ and varying soil metal friction δ^{o}, for beach sand and black cotton soil are as shown in Tables 6.21 and 6.23 respectively.

Table 6.1: Soil Properties for Ogun river sand

Specific gravity, S.G.	=	2.52
Maximum density, ρ_{max}	=	1.99 Mg/m^3
Minimum density, ρ_{min}	=	1.51 Mg/m^3
Test density, ρ	=	1.94 Mg/m^3
Moisture content, w	=	0.5%
Coefficient of Uniformity	=	2.40
Coefficient of Curvature	=	1.22
Density Index, I_D	=	0.92
Angle of friction:		
Triaxial test, ϕ_d	=	42^o
Shearbox test, ϕ_d	=	40^o
Classification	=	A - 1 (0)

Table 6.2: Soil properties for beach sand

Specific gravity, S.G.	= 2.65
Maximum density, ρ_{max}	= 2.05 Mg/m^3
Minimum density, ρ_{min}	= 1.61 Mg/m^3
Test density, ρ	= 1.91 Mg/m^3
Moisture content, w	= 0.5%
Coefficient of Uniformity	= 3.15
Coefficient of Curvature	= 1.33
Density Index, I_D	= 0.73
Angle of friction	
Triaxial test, ϕ_d	= 40^o
Shear Box test, ϕ_d	= 40^o
Classification	= A - 3 (0)

Table 6.3: Soil properties for black cotton soil

Liquid limit, w_L	=	63%
Plastic limit, w_p	=	23%
Plasticity index, I_p	=	40%
Free swell	=	75%
Shrinkage limit	=	21%
Linear Shrinkage	=	10%
Specific gravity, S.G.	=	2.27
Activity	=	0.47
Cohesion, C	=	6.9 kN/m^2
Moisture content, w	=	6.1%
Angle of friction:		
Triaxial, ϕ_d	=	16^o
Test density, ρ	=	1.64 Mg/m^3
Classification:	=	A-7-6 (20)

Table 6.4: Soil Cutting test results, for Ogun river sand

Soil Material	Blade Angle (β^{o})	Blade Width (cm)	Maximum Horizontal Force (N)	Failure Plane Distance f (cm)	Maximum Vertical Force (N)	Blade Horizontal displacement, At maximum		Force at variable width blade / Force at 100mm width blade	
						Horizontal Force (cm) (cm)	Vertical Force (cm) (cm)	Horizontal %	Vertical %
Ogun River sand	0	10.0	250	17.5	Not measured	3.4	Not measured		
		7.5	195	17.5	"	3.4	"	78.0	Not measured
		5.0	150	17	"	3.2	"	60.0	"
	15	10.0	180	21.5	"	3.4	"		
		7.5	150	20.5	"	4.0	"	83.5	"
		5.0	100	20.5	"	3.7	"	55.5	"
	30	10.0	130	20.5	37.5	2.75	1.75		
		7.5	100	20.5	32.5	2.4	1.75	76.9	86.6
		5.0	75	20.0	25.5	2.2	1.50	57.6	68.0
	45	10.0	75	19.5	47.5	1.75	1.1		
		7.5	65	19.5	40.0	2.2	1.75	86.6	84.2
		5.0	45	19.0	30.0	2.2	3.0	60.0	68.8

..../2

Table 6.4

Soil Material	Blade Angle (β^o)	Blade Width (cm)	Maximum Horizontal Force (N)	Failure Plane Distance f (cm)	Maximum Vertical Force (N)	Blade Horizontal displacement, At maximum		Force at variable width blade / Force at 100mm width blade	
						Horizontal Force (cm)	Vertical Force (cm)	Horizontal %	Vertical %
Ogun River Sand	60	10.0	50	15.0	35.0	1.75	1.1		
		7.5	40	15.0	30.0	1.5	1.1	80.0	83.3
		5.0	30	14.5	25.0	1.5	1.75	60.0	71.4
	75	10.0	35	15.5	30.0	1.75	1.1		
		7.5	30	15.5	25.5	1.75	1.75	85.7	83.3
		5.0	25	15.5	15.5	1.5	1.2	71.4	51.6

Table 6.5: Soil cutting test results, for beach sand

Soil Material	Blade Angle (β^{o})	Blade Width (cm)	Maximum Horizontal Force (N)	Failure Plane Distance r (cm)	Maximum Vertical Force (N)	Blade Horizontal displacement At maximum		Force at variable width blade / Force at 100mm width blade	
						Horizontal Force (cm)	Vertical Force (cm)	Horizontal %	Vertical %
Beach sand	0	10.0	205	17.5	Not measured	2.8	Not measured		
		7.5	190	170	"	2.5	"	92.6	Not measured
		5.0	125	17.0	"	3.5	"	60.9	Not measured
	15	10.0	125	20.0	"	3.5	"		
		7.5	110	19.0	"	3.5	"	88.0	"
		5.0	85	19.0	"	2.5	"	68.0	"
	30	10.0	100	17.0	40	2.5	2.2		
		7.5	90	17.0	35.0	3.5	1.75	90.0	87.5
		5.0	60	13.5	25.0	1.75	1.75	60.0	62.5
	45	10.0	75	18.0	50.0	2.2	2.2		
		7.5	60	16.0	40.0	2.75	2.2	80.0	80.0
		5.0	45	15.0	30.0	1.75	1.75	60.0	60.0

..../2

Table 6.5

Soil Material	Blade Angle (β^{o})	Blade Width (cm)	Maximum Horizontal Force (N)	Failure Plane Distance f (cm)	Maximum Vertical Force (N)	Blade Horizontal displacement At maximum: Horizontal Force (cm)	Blade Horizontal displacement At maximum: Vertical Force (cm)	Force at variable width blade / Force at 100mm width blade: Horizontal %	Force at variable width blade / Force at 100mm width blade: Vertical %
Beach sand	60	10.0	50	17.5	40.0	1.7	1.6		
		7.5	40	15.5	35.0	2.1	2.5	80.0	87.5
		5.0	30	15.5	22.5	1.4	1.5	60.0	56.2
	75	10.0	35	17.5	25.0	1.7	1.2		
		7.5	25	15.0	20.0	2.1	1.1	71.1	80.0
		5.0	20	15.0	15.0	1.1	1.1	57.1	60.0

Table 6.6: Soil Cutting Test Results, for Black Cotton Soil

Soil Material	Blade Angle (β^o)	Blade Width (cm)	Maximum Horizontal Force (N)	Failure Plane Distance f (cm)	Maximum Vertical Force (N)	Blade Horizontal displacement, At maximum		Force at variable width blade / Force at 100mm width blade	
						Horizontal Force (cm)	Vertical Force (cm)	Horizontal %	Vertical %
Black Cotton Soil	0	10.0	210	21.5	Not measured	3.4	Not measured		
		7.5	190	18.0	"	4.5	"	90.4	Not measured
		5.0	150	17.0	"	3.5	"	71.4	"
	15	10.0	175	16.0	25	4.0	3.2		
		7.5	150	13.5	30	3.7	3.7	85.7	85.7
		5.0	100	12.0	22	3.5	3.5	57.1	62.8
	30	10.0	135	19.0	57.5	4.0	2.7		
		7.5	105	16.5	50.0	4.1	3.2	77.7	86.9
		5.0	70	15.0	33.7	2.5	2.7	51.8	58.6
	45	10.0	105	16.0	71.5	2.4	2.4		
		7.5	80	15.0	55.0	2.7	2.7	76.1	76.9
		5.0	55	15.0	47.5	2.4	2.7	52.3	66.4

..../2

Table 6.6

Soil Material	Blade Angle (β^o)	Blade Width (cm)	Maximum Horizontal Force (N)	Failure Plane Distance f (cm)	Maximum Vertical Force (N)	Blade Horizontal displacement, At maximum		Force at variable width blade / Force at 100mm width blade	
						Horizontal Force (cm)	Vertical Force (cm)	Horizontal %	Vertical %
Black cotton soil	60	10.0	75	13.5	76.5	3.5	3.5		
		7.5	57.5	12.5	65.0	2.5	2.0	76.6	84.9
		5.0	40.0	13.5	46.0	2.0	2.7	53.3	60.1
	75	10.0	45	15.0	77.5	4.0	2.7		
		7.5	35	15.0	59.0	2.2	2.2	77.7	76.1
		5.0	30	14.5	47.5	1.6	1.1	66.6	61.2

Table 6.7: Theoretical horizontal and vertical components of forces and measured values for Ogun river sand

Soil Material	Theory	Blade angle (β°)	HORIZONTAL FORCE					VERTICAL FORCE				
			Theoretical (N)	Measured (N)	Error %	Avg. error %	Std. Deviation %	Theoretical (N)	Measured (N)	Error %	Avg. error %	Std. Deviation %
Ogun River Sand	Boundary Energy Theory	0°	228	250	8.8			-66.0				
		15°	189	180	-5			-5.0				
		30°	126	130	3			29.1	37.5	22.4		
		45°	67	75	10.6			35.4	47.5	25.4		
		60°	26	50	48			25	35.0	28.6		
		75°	6	35	82	24.5	30.6	8	30.0	73.3	37.4	20.8
	Wismer et al.	0°	210.10	250	13.6			-64.0				
		15°	153.8	180	14.5			-4.1				
		30°	99.7	130	23.3			23.5	37.5	37.3		
		45°	51.1	75	31.8			27.8	47.5	41.4		
		60°	20.2	50	59.6			19.5	35.0	44.2		
		75°	4.2	35	88	38.4	29.5	6.8	30.0	77.3	50	18.3
	Reece and Hettiaratchi	0°	110.0	250	56			-32.5				
		15°	82.1	180	54.3			-2.2				
		30°	60.0	130	53.8			14.4	37.5	61.6		
		45°	39.0	75	48.0			21.0	47.5	55.7		
		60°	21.2	50	57.6	53.9	3.6	20.1	35.0	42.5	53.2	9.7
		75°										

* % Error = $\frac{\text{Measured value} - \text{Theoretical value}}{\text{Measured value}} \times 100$ %

Blade width = 100mm

Table 6.8: Theoretical horizontal and vertical components of forces and measured values, for Ogun river sand

Soil Material	Theory	Blade angle (β^o)	HORIZONTAL FORCE Theoretical (N)	Measured (N)	Error %	Avg. error %	Std. Deviation %	VERTICAL FORCE Theoretical (N)	Measured (N)	Error %	Avg. error	Std. Deviation %
Ogun river sand	Yong et al.	0^o	195.2	250	21.9			-100				
		15^o	120.1	180	33.2			-40				
		30^o	75.0	130	42.3			-10.0	37.5			
		45^o	45.5	75	39.3			4.9	47.5	89.6		
		60^o	25.0	50	50			8.0	35	77.1		
		75^o	17.5	35	50	39.4	10.7	11.8	30.0	60.6	75.7	14.5

$$* \ \% \text{ Error} = \frac{\text{Measured value} - \text{Theoretical value}}{\text{Measured Value}} \times 100 \ \%$$

Blade width = 100mm

Table 6.9: Theoretical horizontal and vertical components of forces and measured values, for beach sand.

Soil Material	Theory	Blade angle (β^{o})	HORIZONTAL FORCE: Theoretical (N)	HORIZONTAL FORCE: Measured (N)	HORIZONTAL FORCE: Error %	HORIZONTAL FORCE: Avg. Error %	HORIZONTAL FORCE: Std. Deviation %	VERTICAL FORCE: Theoretical (N)	VERTICAL FORCE: Measured	VERTICAL FORCE: Error %	VERTICAL FORCE: Avg. error %	VERTICAL FORCE: Std. Deviation %
Beach Sand	Boundary Energy Theory (Osho)	0^{o}	186	205	9.2		-	-48.5				
		15^{o}	154	125	-23.2			0				
		30^{o}	101	100	-1			26.5	40	33.8		
		45^{o}	54	75	28			29	50.0	39.6		
		60^{o}	21	50	58			20	40.0	47.5		
		75^{o}	5	20	85.7	26.1	36.5	8	25.0	67.2	48.6	11.2
	Wismer et al.	0^{o}	173.0	205	15.6			-43.6				
		15^{o}	121.8	125	2.5			2.1				
		30^{o}	76.5	100	23.5			22.4	40	44		
		45^{o}	38.8	75	48.2			24.8	50.0	50.4		
		60^{o}	16.0	50	60			17.0	40.0	57.5		
		75^{o}	3.3	20	86.8	39.4	31.3	6.1	25.0	75.6	56.7	13.64
	Reece and Hettiaratchi	0^{o}	85.7	205	58.1			-21.4				
		15^{o}	65.2	125	47.8			1.14				
		30^{o}	47.2	100	52.5			13.5	40	66.3		
		45^{o}	32.8	75	56.2			19.1	50.0	60.6		
		60^{o}	18.0	50	64.	55.7	6.1	18.7	40.0	53.2	60	5.4
		75^{o}	-									

$$* \ \% \ \text{Error} = \frac{\text{Measured value} - \text{Theoretical value}}{\text{Measured value}} \times 100$$

Blade width = 100mm

Table 6.10: Theoretical horizontal and vertical components of forces and measured values for beach sand.

Soil Material	Theory	Blade angle (β^o)	HORIZONTAL FORCE					VERTICAL FORCE				
			Theoretical (N)	Measured (N)	Error %	Avg. Error %	Std. Deviation %	Theoretical (N)	Measured	Error %	Avg. error %	Std. Deviation %
Beach sand	Yong et al.	0^o	125.0	205	39.0			-90.5				
		15^o	82.5	125	34.0			-35.0				
		30^o	50.5	100	49.5			-10.0	40			
		45^o	26.5	75	64.6			5.0	50.0	90		
		60^o	20.0	50	60.0			7.5	40.0	81.2		
		75^o	10.0	20	71.4	53.1	14.7	6.5	25.0	74	81.7	8.0

$$* \ \% \text{ Error} = \frac{\text{Measured value} - \text{Theoretical value}}{\text{Measured value}} \times 100\%$$

Blade width = 100mm

Table 6.11: Theoretical horizontal and vertical components of forces and measured values, for black cotton soil

Soil Material	Theory	Blade angle (β^o)	HORIZONTAL FORCE					VERTICAL FORCE				
			Theoretical (N)	Measured (N)	Error %	Avg. Error %	Std. Deviation %	Theoretical (N)	Measured	Error %	Avg. error %	Std. Deviation %
Black cotton soil	Boundary Energy Theory (Osho)	0^o	211.0	210	-.47			-29.6				
		15^o	170.0	175	2.8			21.00	25.0	16.0		
		30^o	135.0	135	0			55.00	57.5	4.3		
		45^o	105.0	105	0			79.00	71.5	-10.5		
		60^o	76.0	75	-1.3			97.00	76.5	26.8		
		75^o	46.0	45	-2.2	-0.19	1.5	109.00	77.5	-40.6	-11.52	20.4
	Wismer et al.	0^o	203.1	210	3.2			-51.1				
		15^o	166.7	175	4.7			70.5	25.0	-182		
		30^o	134.2	135	0			113.9	57.5	-98		
		45^o	104.3	105	0			110.0	71.5	-53.8		
		60^o	74.8	75	0			88.3	76.5	-15.4		
		75^o	42.5	45	5.5	2.2	2.5	60.2	77.5	22.3	-65.38	79.03
	Reece and Hettiaratchi	0^o	196.1	210	6.6			-12.0				
		15^o	140.7	175	19.6			28.6	25.0	-14.4		
		30^o	105.9	135	21.5			52.8	57.5	8.1		
		45^o	67.0	105	36.1	20.9	12.0	59.3	71.5	17.1	3.6	16.2
		60^o	-									
		75^o	-									

* % Error = $\frac{\text{Measured value - Theoretical value}}{\text{Measured Value}} \times 100\%$

Blade Width = 100mm

Table 6.12: Theoretical horizontal and vertical components of forces and measurd values, for black cotton soil

Soil Material	Theory	Blade angle (β°)	HORIZONTAL FORCE					VERTICAL FORCE				
			Theoretical (N)	Measured (N)	Error %	Avg. Error %	Std. Deviation %	Theoretical (N)	Measured	Error %	Avg. error %	Std. Deviation %
Black cotton soil	*Yong et al.*	0°	120.0	210	42.8			-97.5				
		15°	82.5	175	52.8			-40.5	25.0			
		30°	52.5	135	61.1			-10.0	57.5			
		45°	42.5	105	59.5			5.5	71.5	92.3		
		60°	27.5	75	63.3			7.5	76.5	90.1		
		75°	25.0	45	44.4	53.9	8.7	8.5	77.5	89.0	90.8	2.2

$$* \ \% \text{ Error} = \frac{\text{Measured value} - \text{Theoretical value}}{\text{Measured value}} \times 100\%$$

Blade Width = 100mm

Table 6.13: Gradients of maximum horizontal force H, versus ratio of blade width to depth of cut, $\frac{w}{d}$.

Soil Material	Blade Inclination (β^o)	Gradient of maximum H versus $\frac{w}{d}$ (Degrees)
Ogun River sand	0	61
	15	60
	30	50
	45	24
	60	12
	75	4
Beach Sand	0	60
	15	39
	30	30
	45	23
	60	10
	75	5
Black cotton soil	0	44
	15	43
	30	43
	45	36
	60	20
	75	5

<u>Table 6.14</u>: Blade horizontal displacement to develop passive Rankine zone, for 10mm width blade.

Soil Material	Blade Incli- nation β°	Passive Rankine force (N)	Blade horizon- tal dis- placement (cm)	Retain- ing wall displa- cement at passive failure (Terzaghi, 1947) (cm)	K- Factor	Maximum horizon- tal force (N)	Blade horizon- tal dis- placement (cm)
Ogun river sand	0	33.6	0.9	0.02	7.5	250	3.4
	15	24	1.2	0.019	7.52	180	3.4
	30	17	0.6	0.0173	7.73	130	2.75
	45	11.2	0.1	0.014	6.7	75	1.75
	60	6.6	0.1	0.01	7.56	50	1.75
	75	2.9	0.1	0.005	12.0	35	1.75
Beach sand	0	29.5	0.6	0.02	7.0	205	2.8
	15	21.5	1.4	0.019	5.82	125	3.5
	30	16	0.4	0.0173	6.4	100	2.5
	45	11	0.5	0.014	7.1	75	2.2
	60	6.5	0.15	0.01	7.9	50	1.7
	75	2.8	0.1	0.005	12.47	35	1.7
Black cotton soil	0	197.29	3.3	0.3	1.06	210	3.4
	15	142.4	2.4	0.29	1.22	175	4.0
	30	102.2	2.6	0.26	1.32	135	4.0
	45	70.4	1.7	0.21	1.49	105	2.4
	60	39.9	1.9	0.15	1.87	75	3.5
	75	18.52	0.9	0.08	2.43	45	4.0

Table 6.15: Blade horizontal displacement to develop passive Rankine zone, for 75mm width blade.

Soil Material	Blade Inclination β^0	Passive Rankine force (N)	Blade horizontal displacement (cm)	Retaining wall displacement at passive failure (Terzaghi, 1947) (cm)	K-Factor	Maximum horizontal force (N)	Blade horizontal displacement (cm)
Ogun river sand	0	25.2	1.4	0.02	7.74	195	3.4
	15	18	1.2	0.019	6.38	150	4.0
	30	12.75	0.2	0.0173	8.7	100	2.4
	45	8.4	0.3	0.014	8.67	65	2.2
	60	4.95	0.2	0.01	8.8	40	1.5
	75	2.18	0.05	0.005	15.78	30	1.75
Beach sand	0	22.1	0.4	0.02	8.60	190	2.5
	15	16.13	0.7	0.019	7.64	110	3.5
	30	12	0.9	0.0173	8.18	90	3.5
	45	8.25	0.2	0.014	8.0	60	2.75
	60	4.88	0.1	0.01	8.89	40	2.1
	75	2.1	0.05	0.005	13.16	25	2.1
Black cotton soil	0	147.97	3.0	0.03	1.28	190	4.5
	15	106.8	3.3	0.29	1.4	150	3.7
	30	76.65	4.0	0.26	1.37	105	4.1
	45	52.8	1.6	0.21	1.52	80	2.7
	60	29.93	1.0	0.15	1.92	57.5	2.5
	75	13.89	0.8	0.08	2.52	35	2.2

Table 6.16: Blade horizontal displacement to develop passive Rankine zone, for 50mm width blade.

Soil Material	Blade Inclination β^0	Passive Rankine force (N)	Blade horizontal displacement (cm)	Retaining wall displacement at passive failure (Terzaghi, 1947) (cm)	K-Factor	Maximum horizontal force (N)	Blade horizontal displacement (cm)
Ogun river sand	0	16.8	0.9	0.02	8.92	150	3.2
	15	12	0.5	0.019	8.33	100	3.7
	30	8.5	0.2	0.0173	8.82	75	2.2
	45	5.6	0.2	0.014	8.04	45	2.2
	60	3.5	0.1	0.01	8.57	30	1.5
	75	1.5	0.05	0.005	16.67	25	1.5
Beach sand	0	14.8	1.8	0.02	8.45	125	3.5
	15	11	0.2	0.019	7.73	85	2.5
	30	8	0.3	0.0173	7.5	60	1.75
	45	5.5	0.2	0.014	8.18	45	1.75
	60	3.7	0.1	0.01	8.1	30	1.4
	75	1.4	0.05	0.005	14.28	20	1.1
Black cotton soil	0	98.65	2.9	0.3	1.52	150	3.5
	15	71.2	3.4	0.29	1.4	100	3.5
	30	51.1	2.4	0.26	1.37	70	2.5
	45	35.2	2.0	0.21	1.56	55	2.4
	60	19.9	0.9	0.15	2.0	40	2.0
	75	9.26	0.5	0.08	3.24	30	1.6

Table 6.17: Mobilised angle of friction Ø, as derived by plasticity theory, from ruptured boundary for vertical 100mm width blade in Figures 6.47 - 6.49.

Soil Material	Ruptured boundary inclination to the horizontal (45° - Ø/2)	Calculated mobilised angles of friction Ø
Ogun river sand	28°	34°
Beach sand	29½°	31°
Black cotton soil	37°	16°

Table 6.18: Horizontal Operative Forces in Soil Cutting for varying angles of friction ϕ and varying soil metal friction δ^o (Ogun river sand)

Soil Material	Theory	Blade Inclination β^o	Horizontal Force (N) $\phi = 34^o$, $\delta = 17^o$	Horizontal Force (N) $\phi = 34^o$, $\delta = 20^o$	Horizontal Force (N) $\phi = 34^o$, $\delta = 23^o$
Ogun River Sand	Boundary Energy Theory (Osho) (least work)	0	228.04	183.74	160.06
		15	189.42	158.08	141.22
		30	125.96	108.89	99.71
		45	66.49	59.83	56.30
		60	26.25	24.87	24.21
		75	66.12	6.27	6.42
	Boundary Energy Theory (Osho) (Upper bound)	0	233.4	186.01	161.77
		15	193.12	160.66	143.26
		30	128.4	110.72	101.24
		45	67.51	60.65	57.03
		60	26.5	25.1	24.43
		75	6.15	6.3	6.45

Blade Width = 100mm

Table 6.19: Vertical Operative Forces in Soil Cutting, for varying angle of friction Ø and varying soil metal friction δ°. Ogun river sand.

Soil Material	Theory	Blade Inclination β°	Vertical force (N)		
			Ø = 34° δ = 17°	Ø = 34° δ = 20°	Ø = 34° δ = 23°
Ogun River Sand	Boundary Energy Theory (Osho) (least work)	0	-69.72	-68.33	-67.22
		15	- 6.61	-14.94	-11.29
		30	29.08	18.42	12.63
		45	35.35	27.39	23.00
		60	24.48	20.57	18.39
		75	9.79	8.83	8.28
	Boundary Energy Theory (Osho) (Upper bound)	0	-71.36	-69.17	-67.94
		15	- 6.74	-15.19	-19.58
		30	29.64	18.73	12.83
		45	35.89	27.77	23.30
		60	24.72	20.76	18.55
		75	9.84	8.87	8.32

Blade Width = 100mm

Table 6.20: Horizontal Operative Forces in Soil Cutting, for varying angles of friction $\emptyset$, and varying soil metal friction δ^{o}. (Beach Sand)

Soil Material	Theory	Blade Inclination β^{o}	Horizontal force (N)		
			$\emptyset = 31^{o}$, $\delta = 15\frac{1}{2}^{o}$	$\emptyset = 31^{o}$, $\delta = 18^{o}$	$\emptyset = 31^{o}$, $\delta = 20\frac{1}{2}^{o}$
Beach Sand	Boundary Energy Theory (Osho) (Least work)	0	185.64	150.46	131.61
		15	153.42	128.44	115.07
		30	101.55	87.89	80.58
		45	53.42	48.04	45.21
		60	21.02	19.87	19.33
		75	4.84	4.94	5.05
	Boundary Energy Theory (Osho) (Upper bound)	0	191.48	154.26	134.56
		15	159.61	132.79	118.56
		30	105.55	90.92	83.13
		45	55.11	49.4	46.42
		60	21.44	20.24	19.68
		75	4.85	4.99	5.10

Blade Width = 100mm

Table 6.21: Vertical Operative Forces in Soil Cutting, for varying angles of friction ϕ, and varying soil metal friction δ°. (Beach Sand)

Soil Material	Theory	Blade Inclination β°	Vertical force (N)		
			$\phi = 31^{\circ}$, $\delta = 15\frac{1}{2}^{\circ}$	$\phi = 31^{\circ}$, $\delta = 18^{\circ}$	$\phi = 31^{\circ}$, $\delta = 20\frac{1}{2}^{\circ}$
Beach Sand	Boundary Energy Theory (Osho) (least work)	0	-51.48	-50.63	-49.95
		15	- 1.34	- 8.08	-11.63
		30	26.26	17.72	13.10
		45	30.22	23.85	20.35
		60	20.66	17.52	15.78
		75	8.22	7.44	7.01
	Boundary Energy Theory (Osho) (Upper bound)	0	-53.10	-51.92	-51.05
		15	- 1.39	- 8.35	-11.98
		30	27.31	18.33	13.51
		45	31.18	24.52	20.89
		60	21.07	17.85	16.06
		75	8.30	7.51	7.07

Blade Width = 100mm

Table 6.22: Horizontal Operative forces in soil cutting for Varying angles of friction Ø, and Varying Soil metal friction δ^{o}. (Black Cotton Soil).

Soil Material	Thory	Blade Inclination (β^{o})	Horizontal Force (N)		
			Ø = 16^{o}, $\delta = 8^{o}$	Ø = 16^{o}, $\delta = 10^{o}$	Ø = 16^{o}, $\delta = 11^{o}$
Black Cotton Soil	Boundary Energy Theory (Osho) (least work)	0	210.93	210.87	210.81
		15	170.08	170.15	170.19
		30	135.25	135.86	135.91
		45	105.16	105.27	105.34
		60	76.20	76.27	76.32
		75	46.28	46.30	46.32
	Boundary Energy Theory (Osho) (Upper bound)	0	243.07	249.22	253.74
		15	193.11	197.12	200.01
		30	154.55	157.63	159.83
		45	122.49	125.18	127.08
		60	94.47	97.15	99.02
		75	70.35	73.69	75.91

Blade width = 100mm

Table 6.23: Vertical Operative Forces in Soil Cutting for Varying Angles of friction ϕ, and varying soil metal friction δ^{o}. (Black Cotton Soil).

Soil Material	Theory	Blade Inclination β^{o}	Vertical Force (N)		
			$\phi = 16^{o}$, $\delta = 8^{o}$	$\phi = 16^{o}$, $\delta = 10^{o}$	$\phi = 16^{o}$, $\delta = 11^{o}$
Black Cotton Soil	Boundary Energy Theory (Osho) (least work)	0	-29.64	-35.67	-39.91
		15	20.88	16.08	12.74
		30	54.85	50.53	47.55
		45	79.25	74.81	71.81
		60	97.53	92.19	88.66
		75	109.02	101.14	96.17
	Boundary Energy Theory (Osho) (Upper bound)	0	-34.16	-42.15	-48.04
		15	23.71	18.63	14.97
		30	62.44	58.62	55.91
		45	92.30	88.96	86.62
		60	120.91	117.44	115.04
		75	165.73	160.95	157.72

Blade width = 100mm

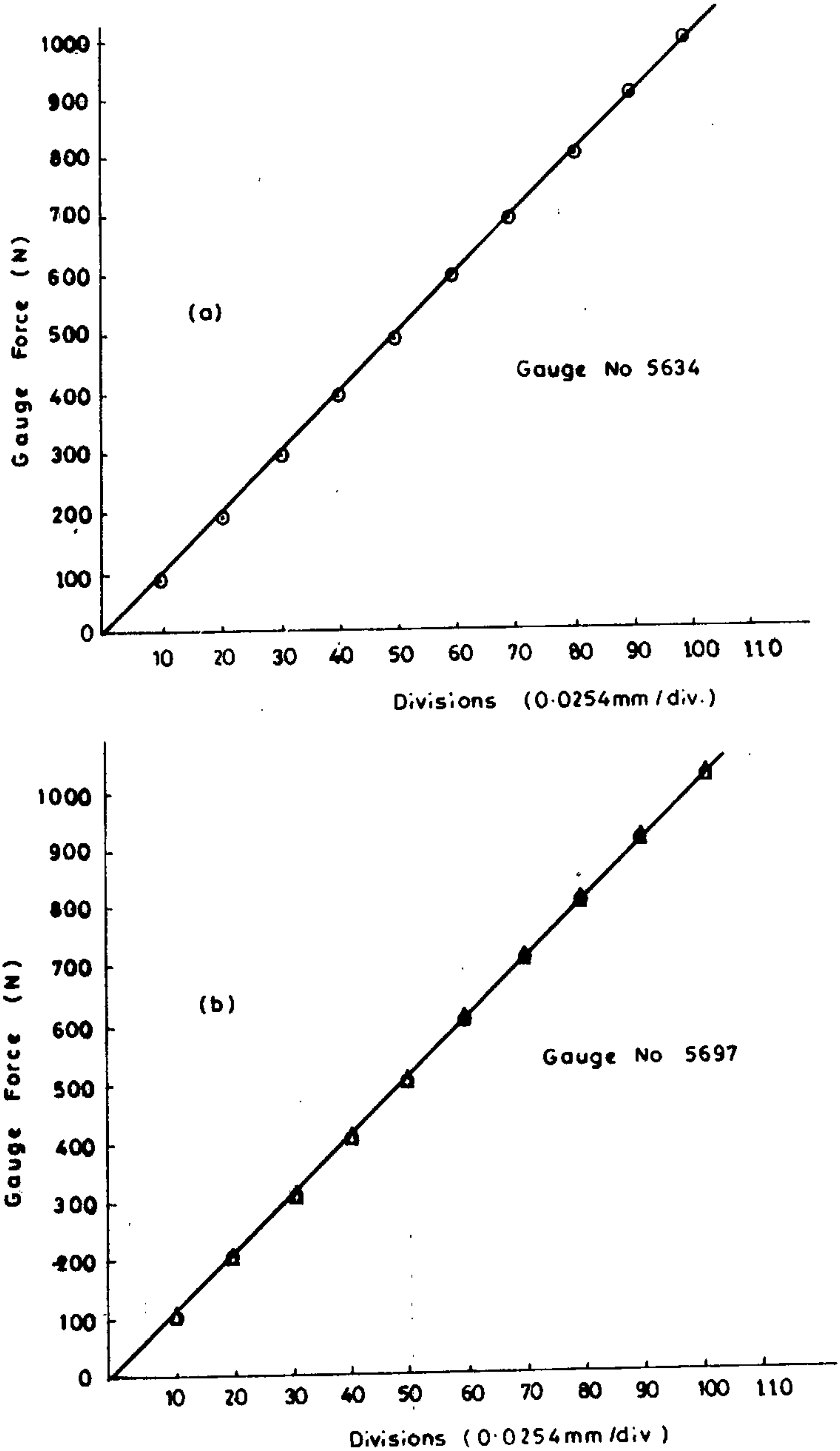

FIG 6:1 CALIBRATION OF GAUGES.

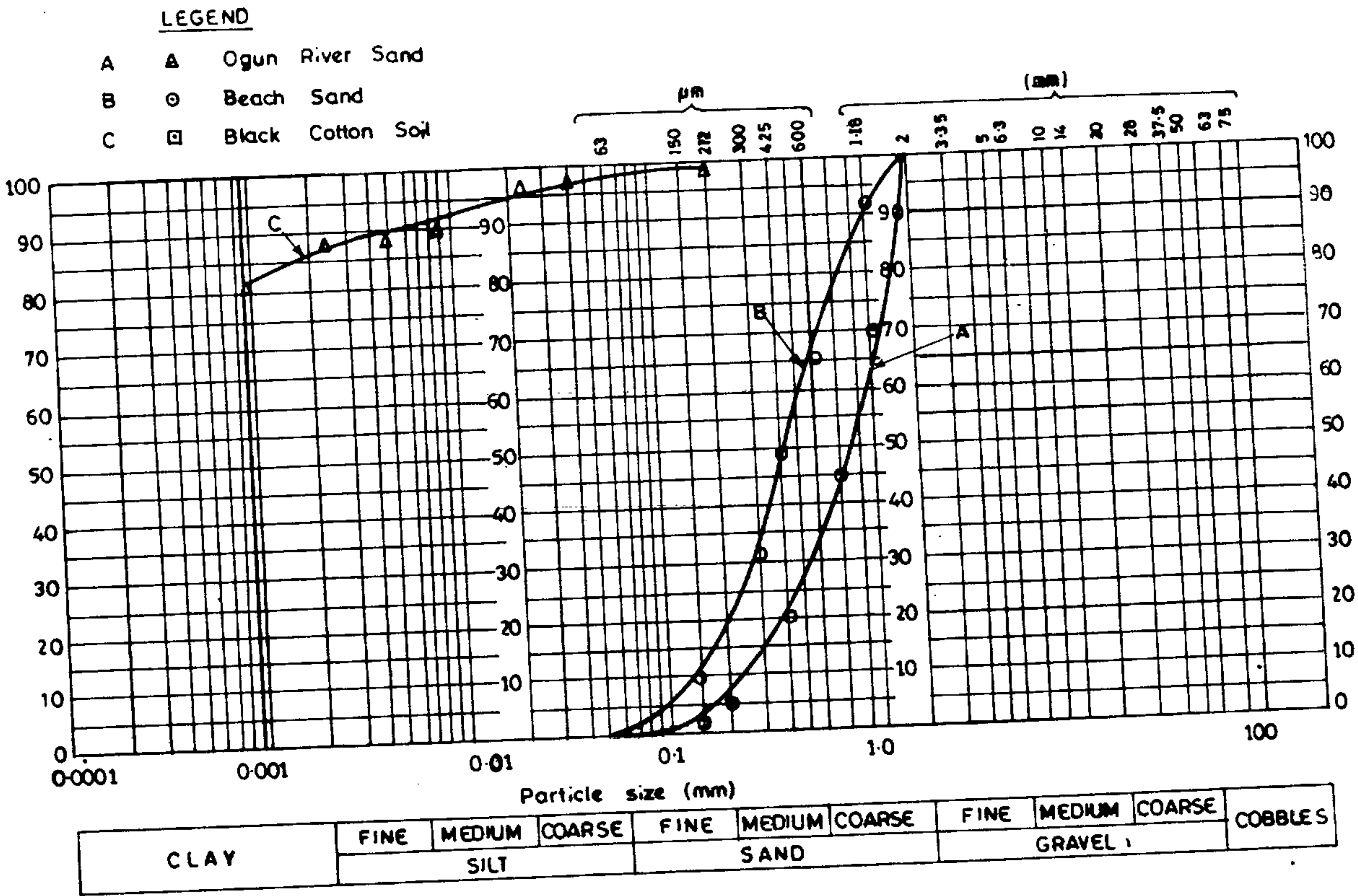

FIG 6·2 PARTICLE SIZE GRADING CURVES OF OGUN RIVER SAND, BEACH SAND AND BLACK COTTON SOIL.

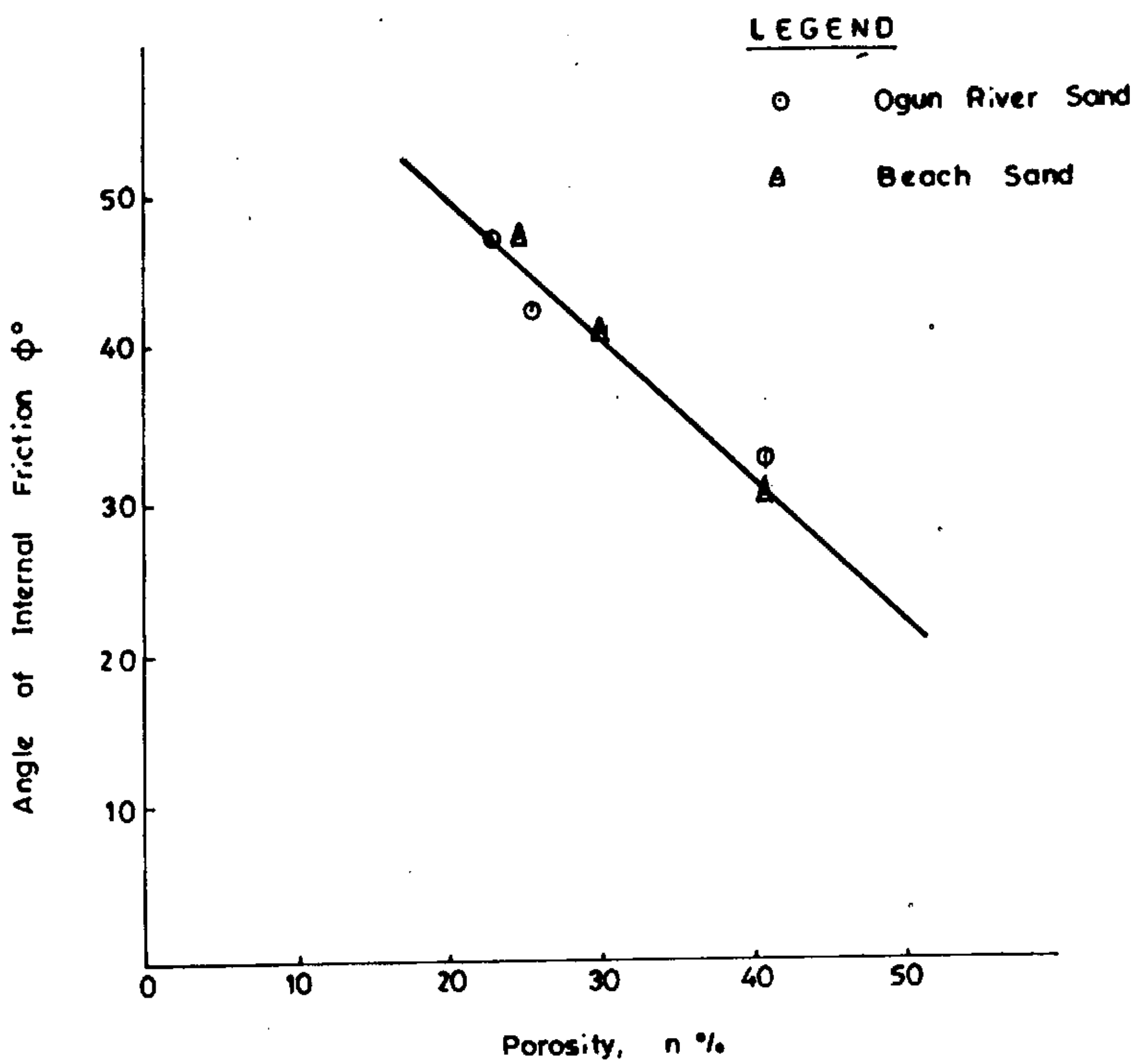

FIG 6·3 PLOTS OF ANGLE OF INTERNAL FRICTION φ VERSUS POROSITY n %

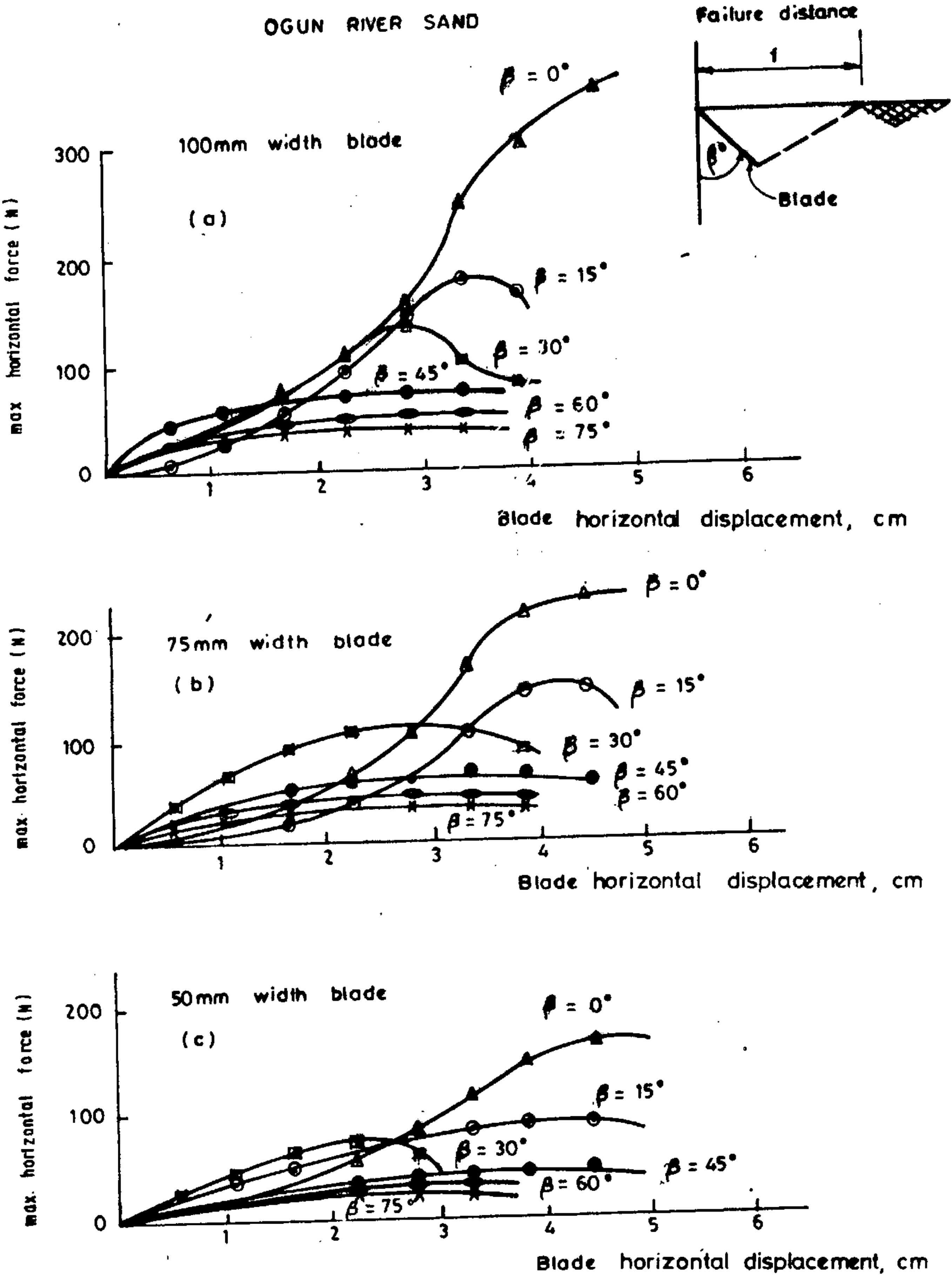

FIGURE 6.4. PLOTS OF HORIZONTAL FORCE Vs BLADE HORIZONTAL DISPLACEMENT

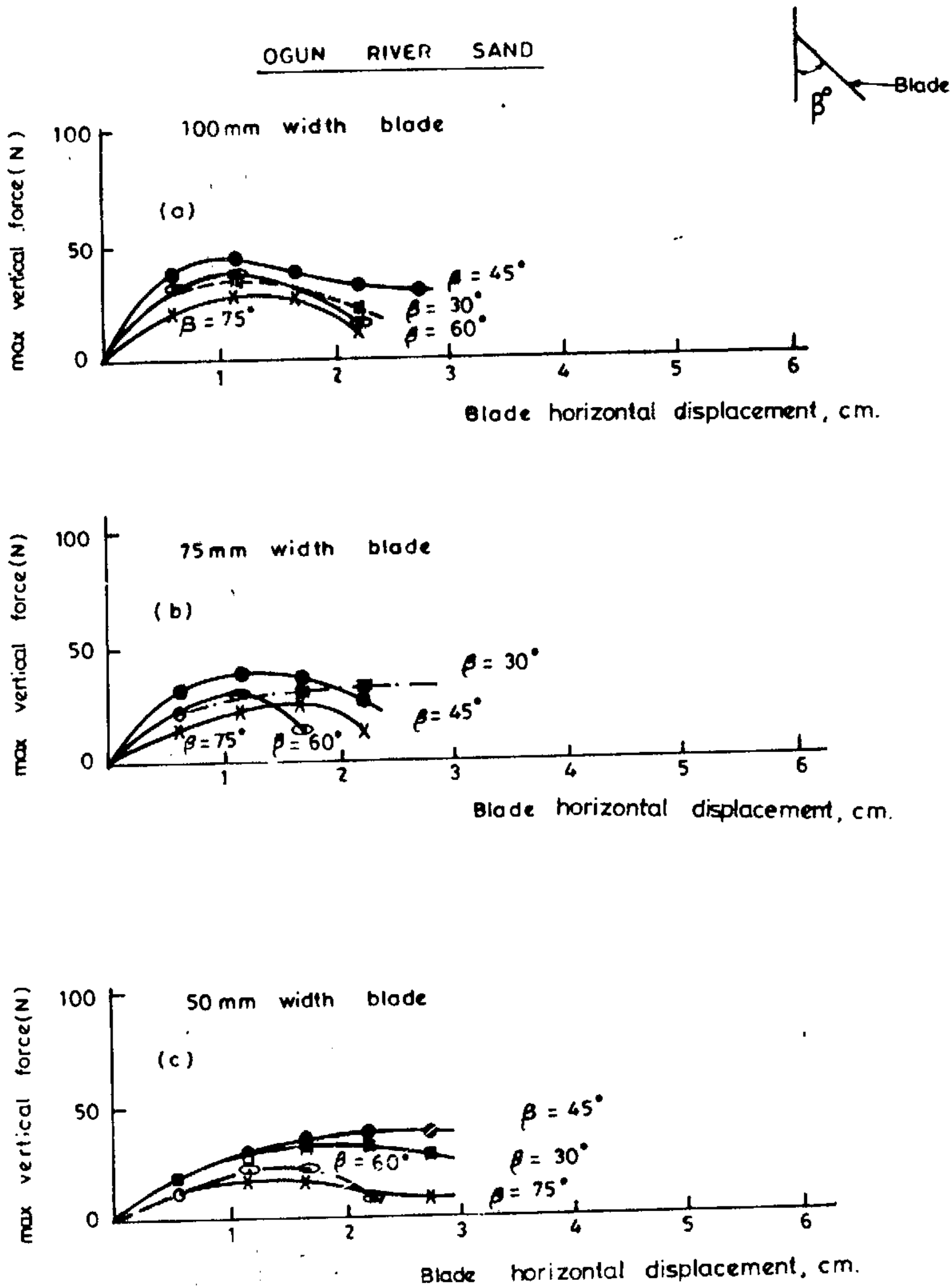

FIGURE 6.5. PLOTS OF VERTICAL FORCE Vs BLADE HORIZONTAL DISPLACEMENT.

BEACH SAND

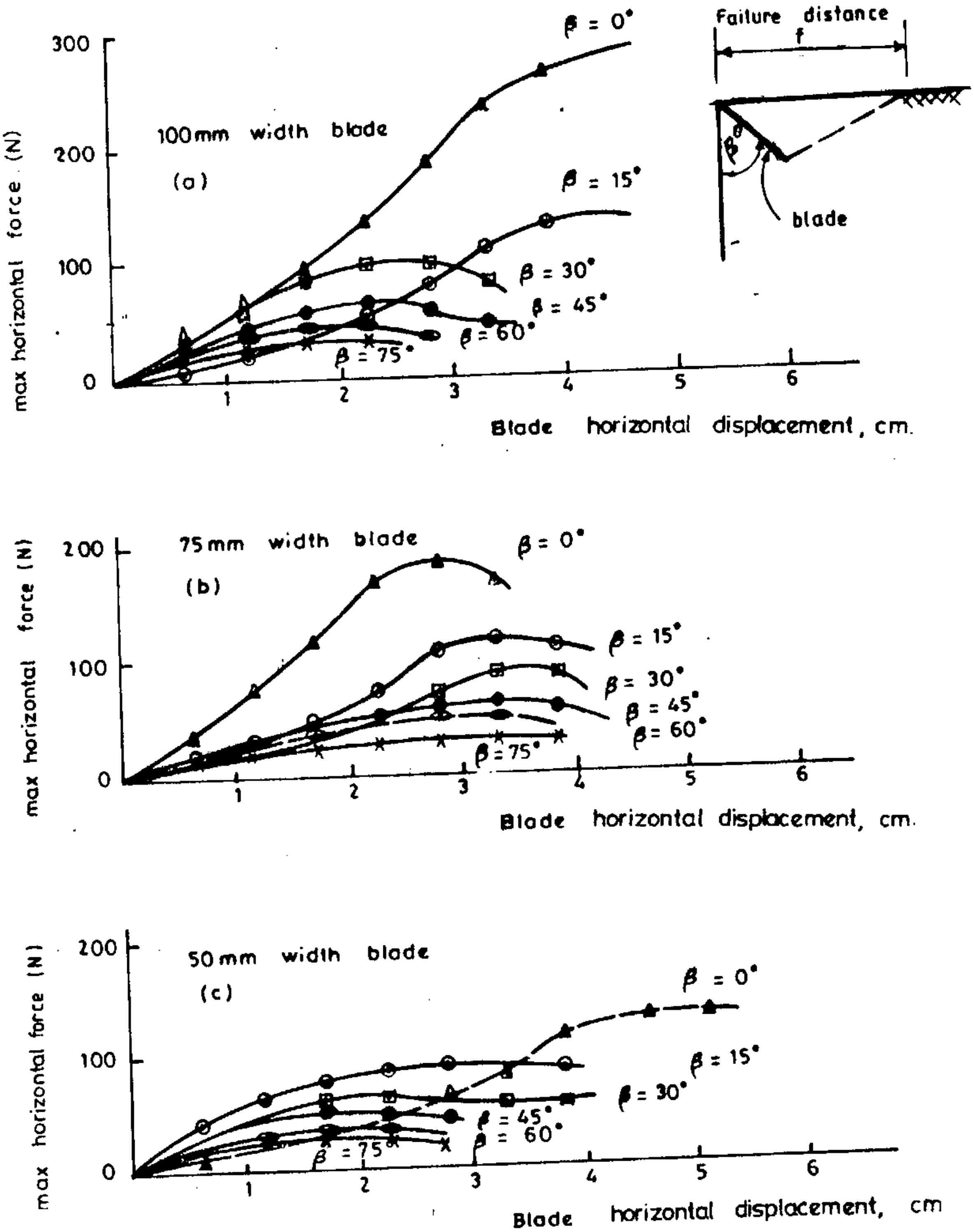

FIGURE 6.6. PLOTS OF HORIZONTAL FORCE Vs BLADE HORIZONTAL DISPLACEMENT.

BEACH SAND

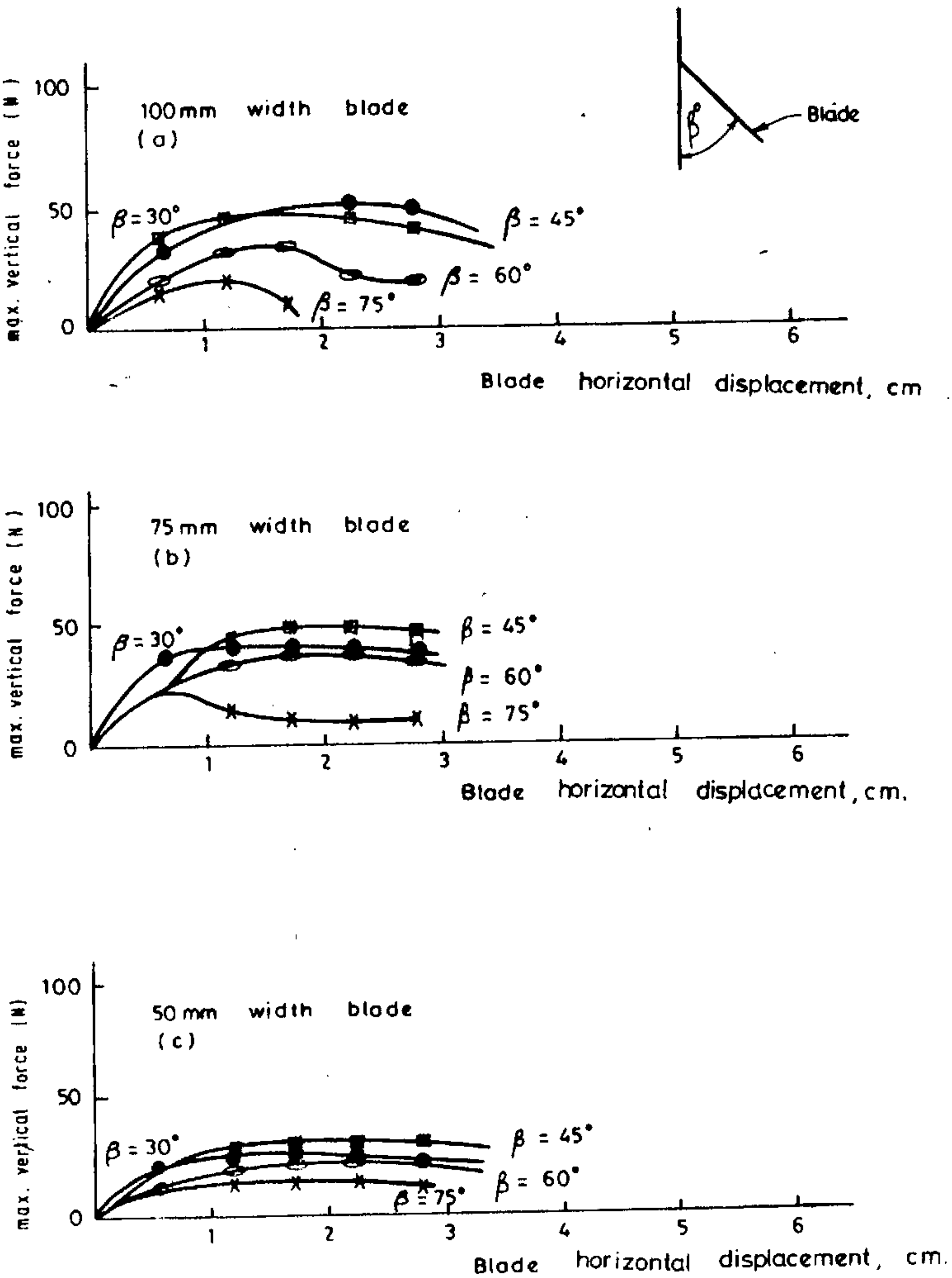

FIGURE 6.7. PLOTS OF VERTICAL FORCE Vs BLADE HORIZONTAL DISPLACEMENT.

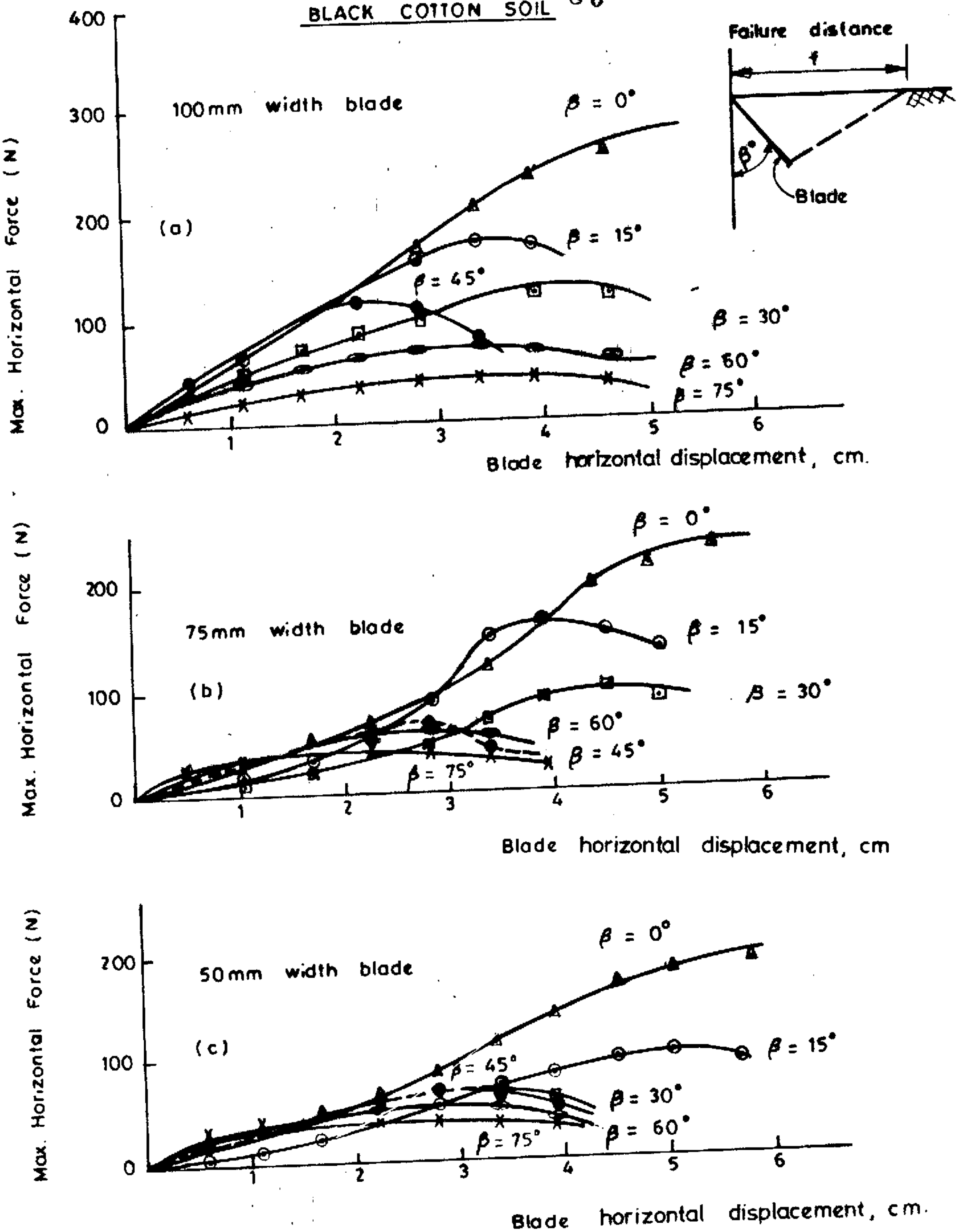

FIGURE 6.8. PLOTS OF HORIZONTAL FORCE Vs BLADE HORIZONTAL DISPLACEMENT.

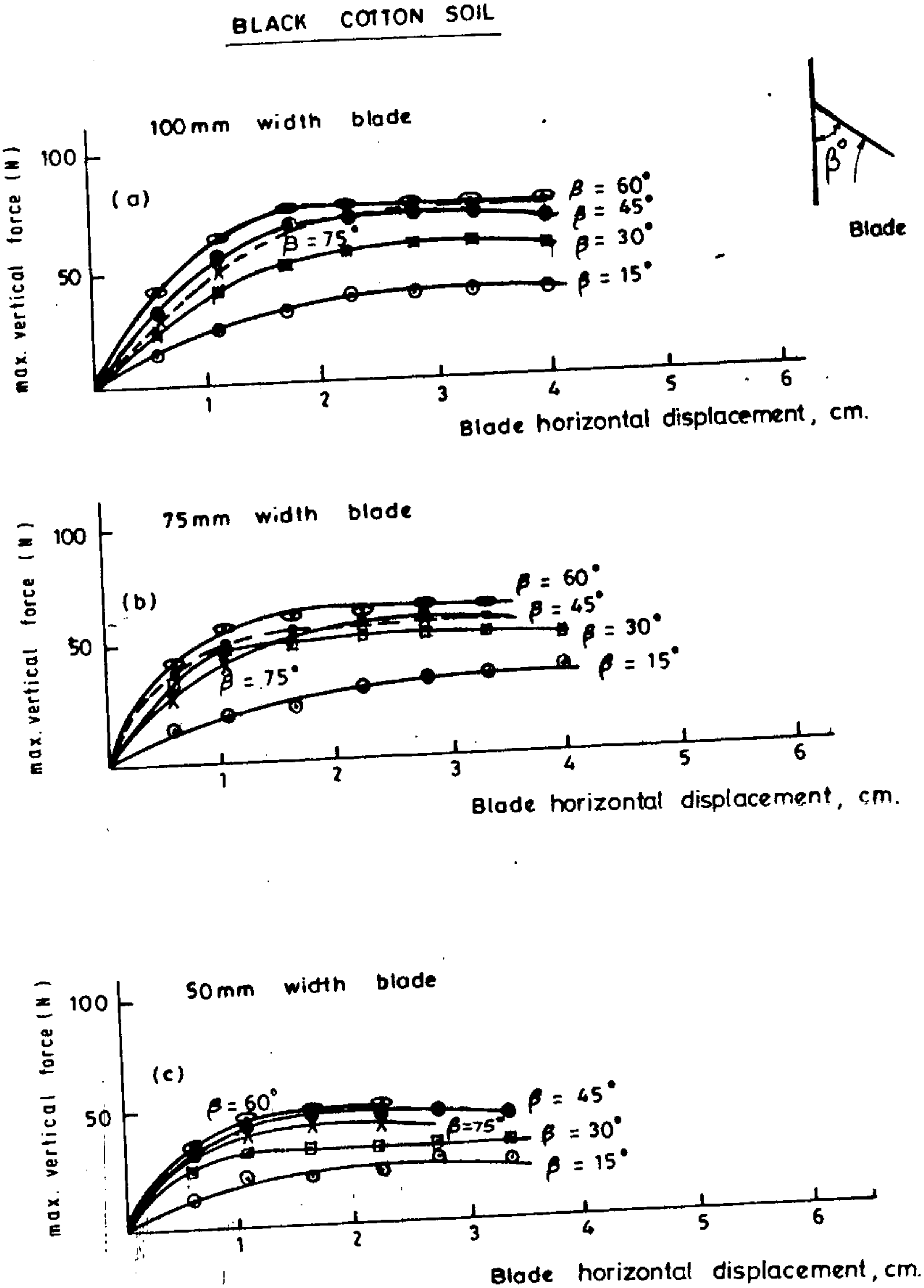

FIGURE 6.9 . PLOTS OF VERTICAL FORCE Vs BLADE HORIZONTAL DISPLACEMENT

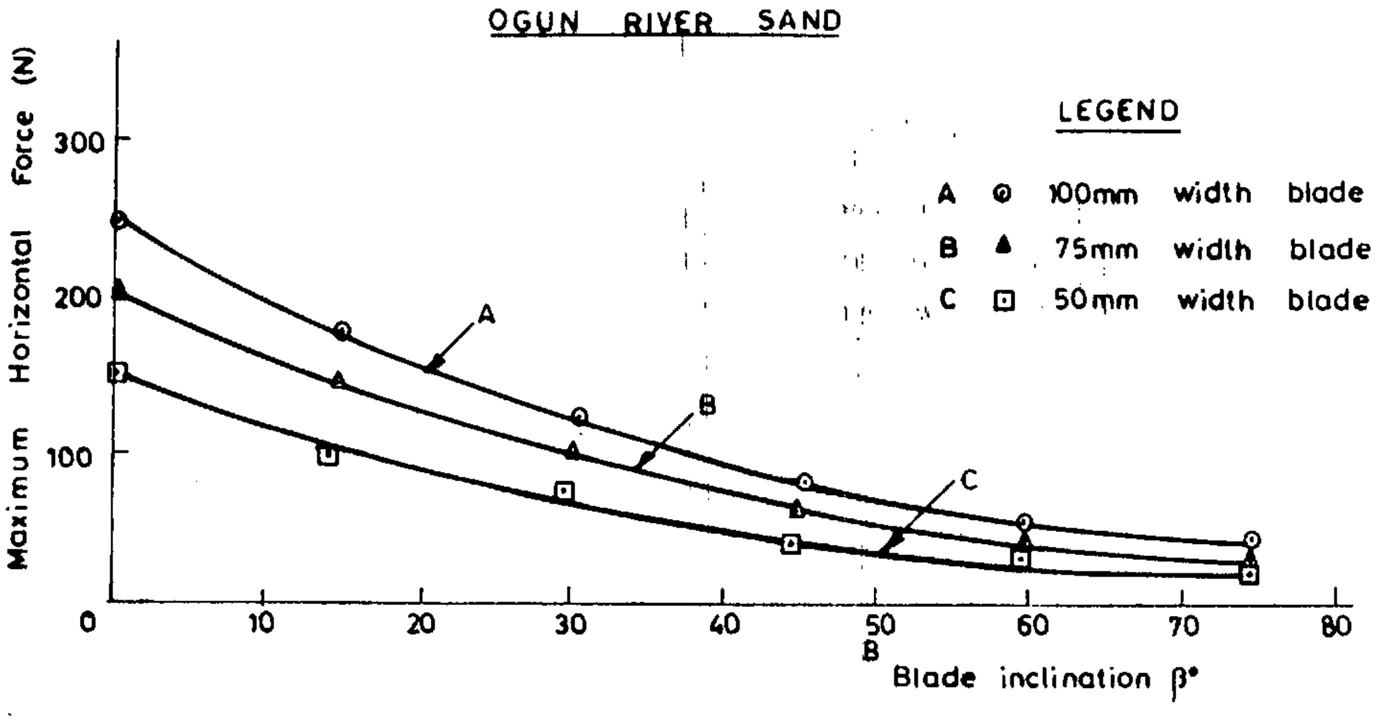

FIG. 6·10. GRAPH OF MAXIMUM HORIZONTAL FORCE VERSUS BLADE INCLINATION β° FOR VARIOUS BLADE WIDTHS

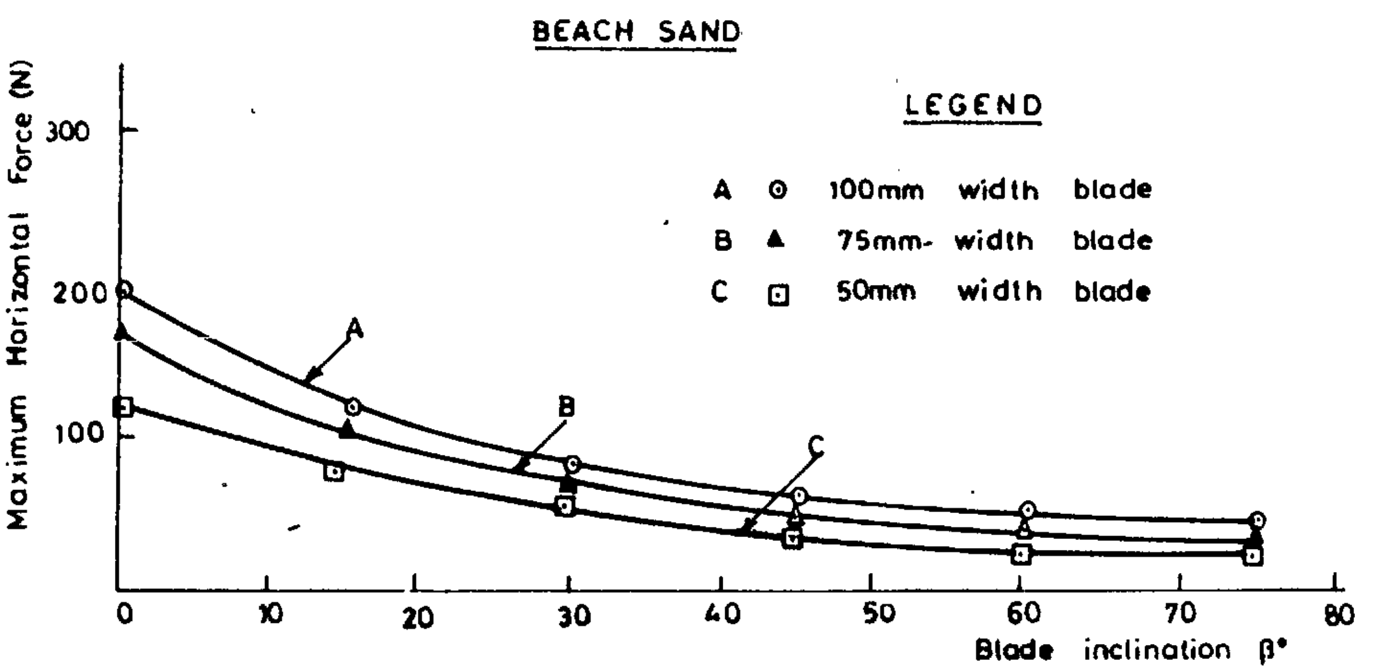

FIG. 6·11 GRAPH OF MAXIMUM HORIZONTAL FORCE VERSUS ANGLE OF BLADE INCLINATION β° FOR VARIOUS BLADE WIDTHS

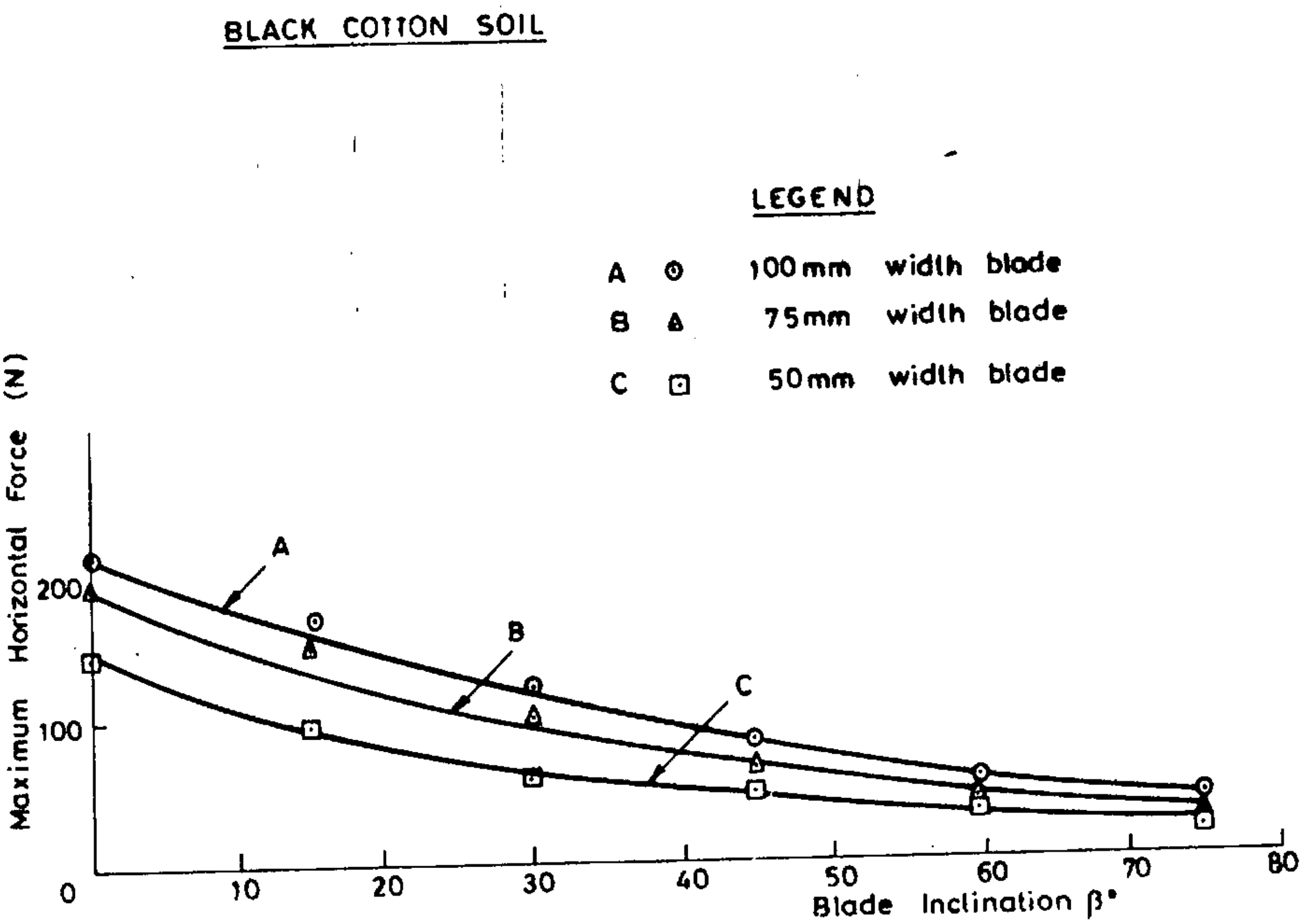

FIG. 6.12 GRAPH OF MAXIMUM HORIZONTAL FORCE VERSUS BLADE INCLINATION β° FOR VARIOUS BLADE WIDTHS.

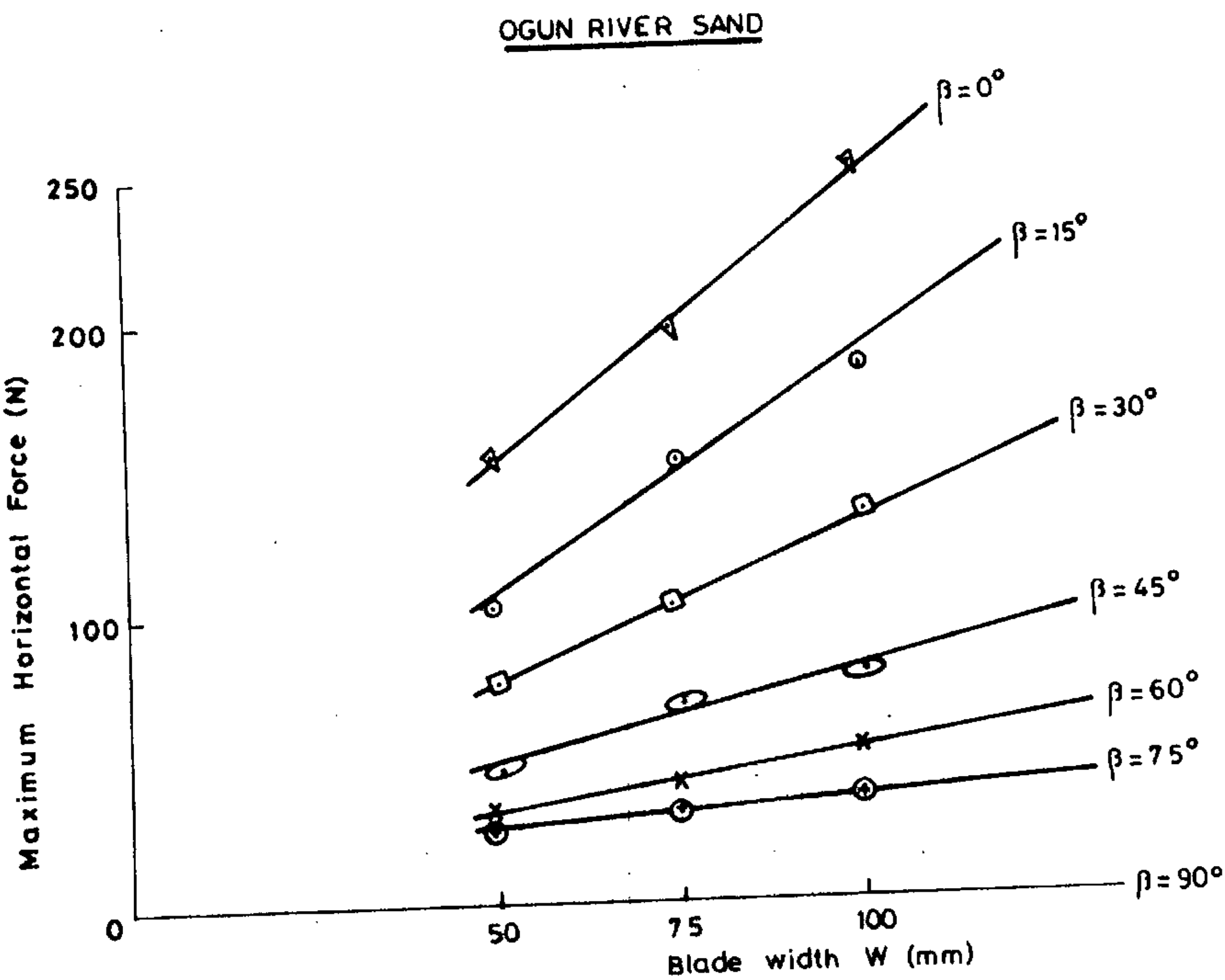

FIG. 6·13 :- GRAPH OF MAXIMUM HORIZONTAL FORCE VERSUS BLADE WIDTH FOR OGUN RIVER SAND.

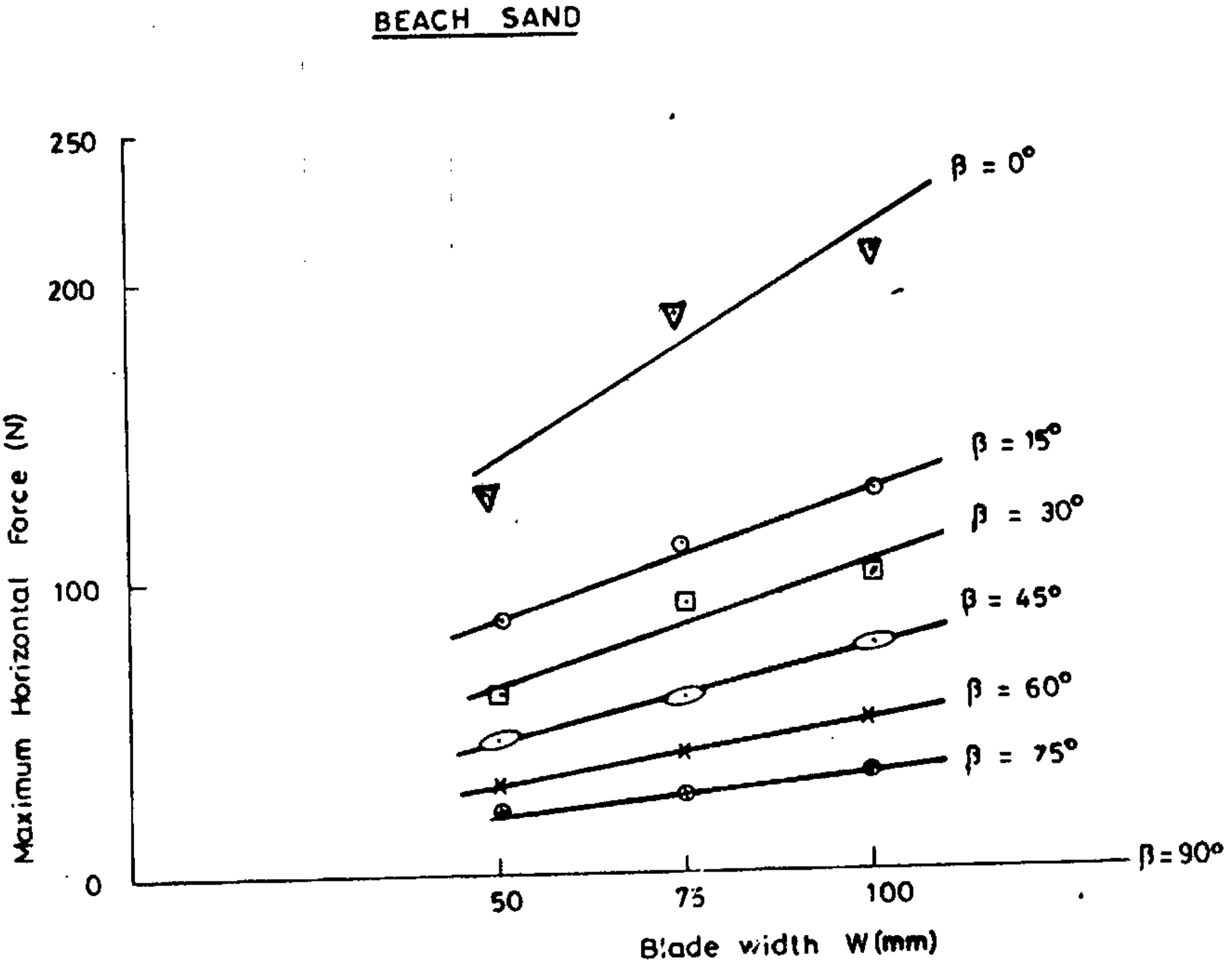

FIG. 6·14 GRAPH OF MAXIMUM HORIZONTAL FORCE VERSUS BLADE WIDTH FOR BEACH SAND.

BLACK COTTON SOIL

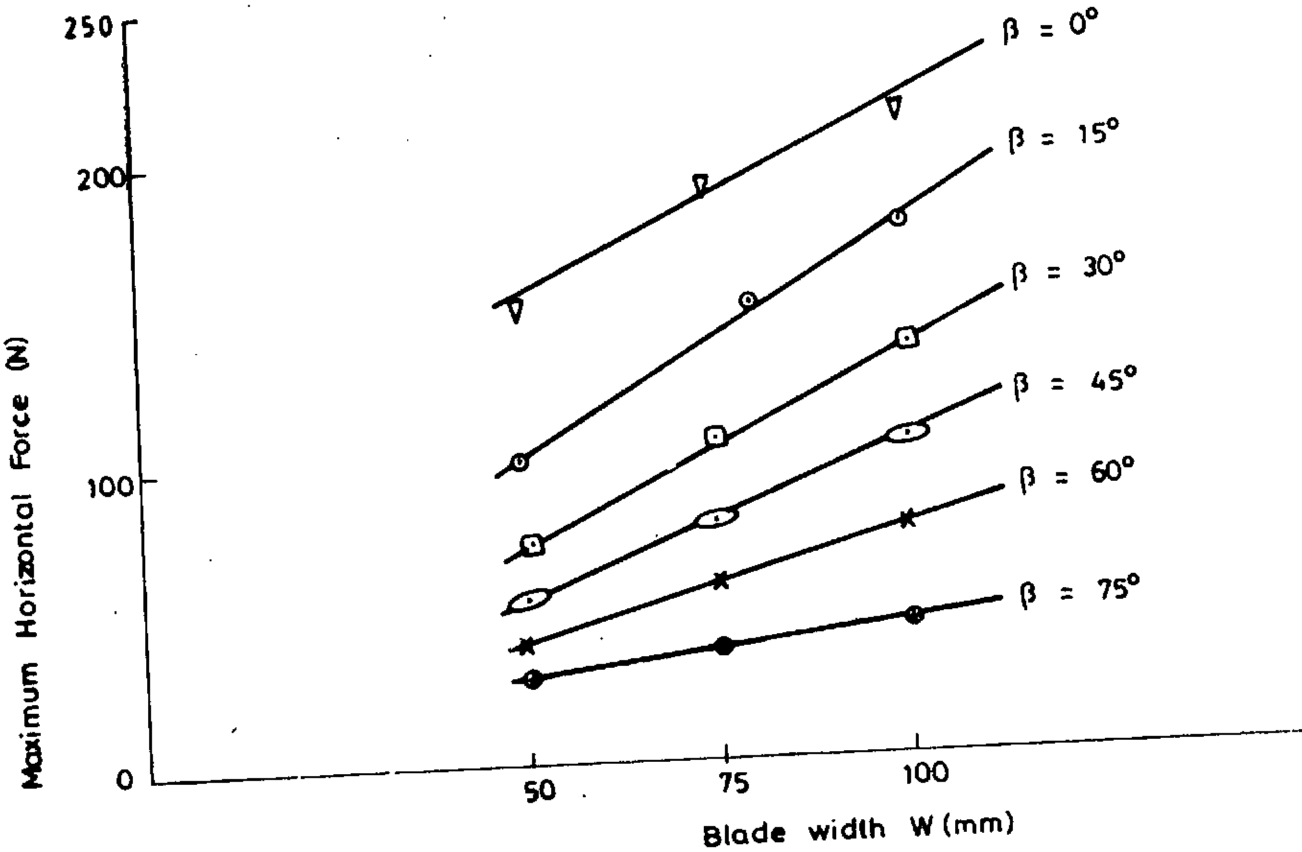

FIG. 6.15 GRAPH OF MAXIMUM HORIZONTAL FORCE VERSUS BLADE WIDTH FOR BLACK COTTON SOIL.

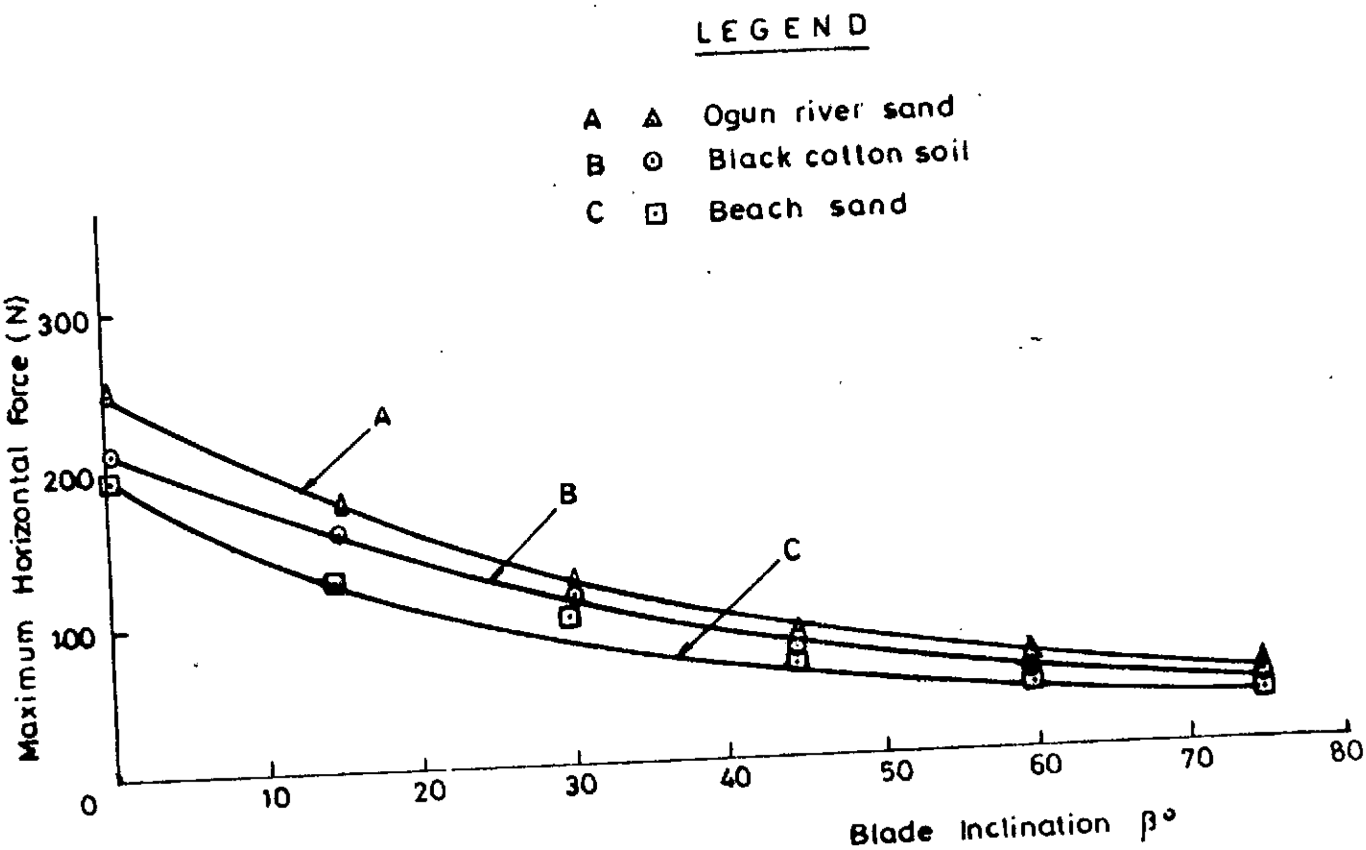

FIG. 6·16 GRAPH OF MAXIMUM HORIZONTAL FORCE VERSUS BLADE INCLINATION β° FOR OGUN RIVER SAND, BEACH SAND, AND BLACK COTTON SOIL FOR 100mm WIDTH BLADE.

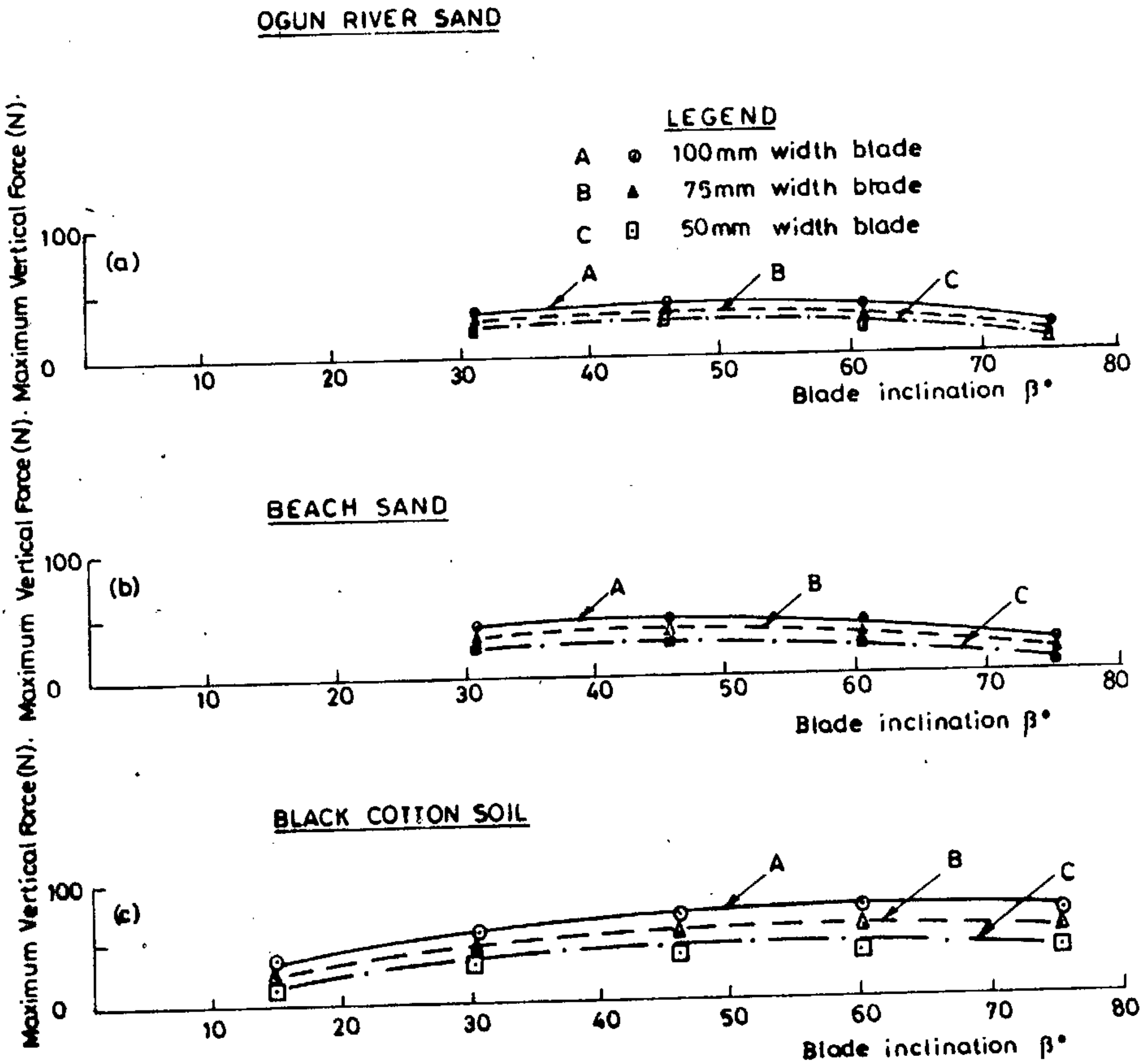

FIG. 6·17 GRAPH OF MAXIMUM VERTICAL FORCE VERSUS ANGLE OF BLADE INCLINATION β° FOR VARIOUS WIDTHS OF BLADE.

OGUN RIVER SAND

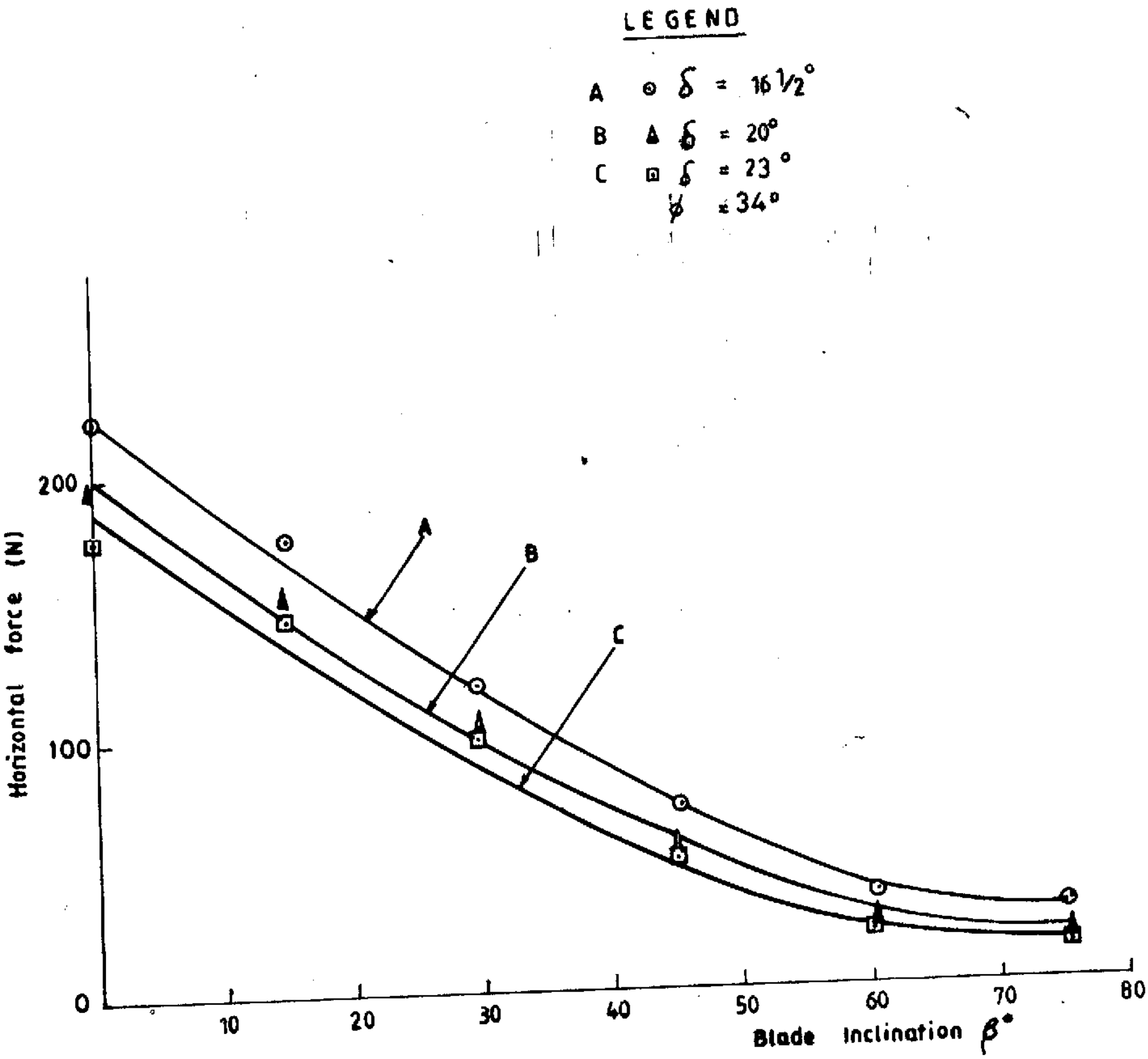

Figure 6·18 GRAPHS OF HORIZONTAL FORCE VERSUS BLADE INCLINATION β°, WITH VARYING SOIL-BLADE FRICTION δ°, FOR OGUN RIVER SAND.

BEACH SAND

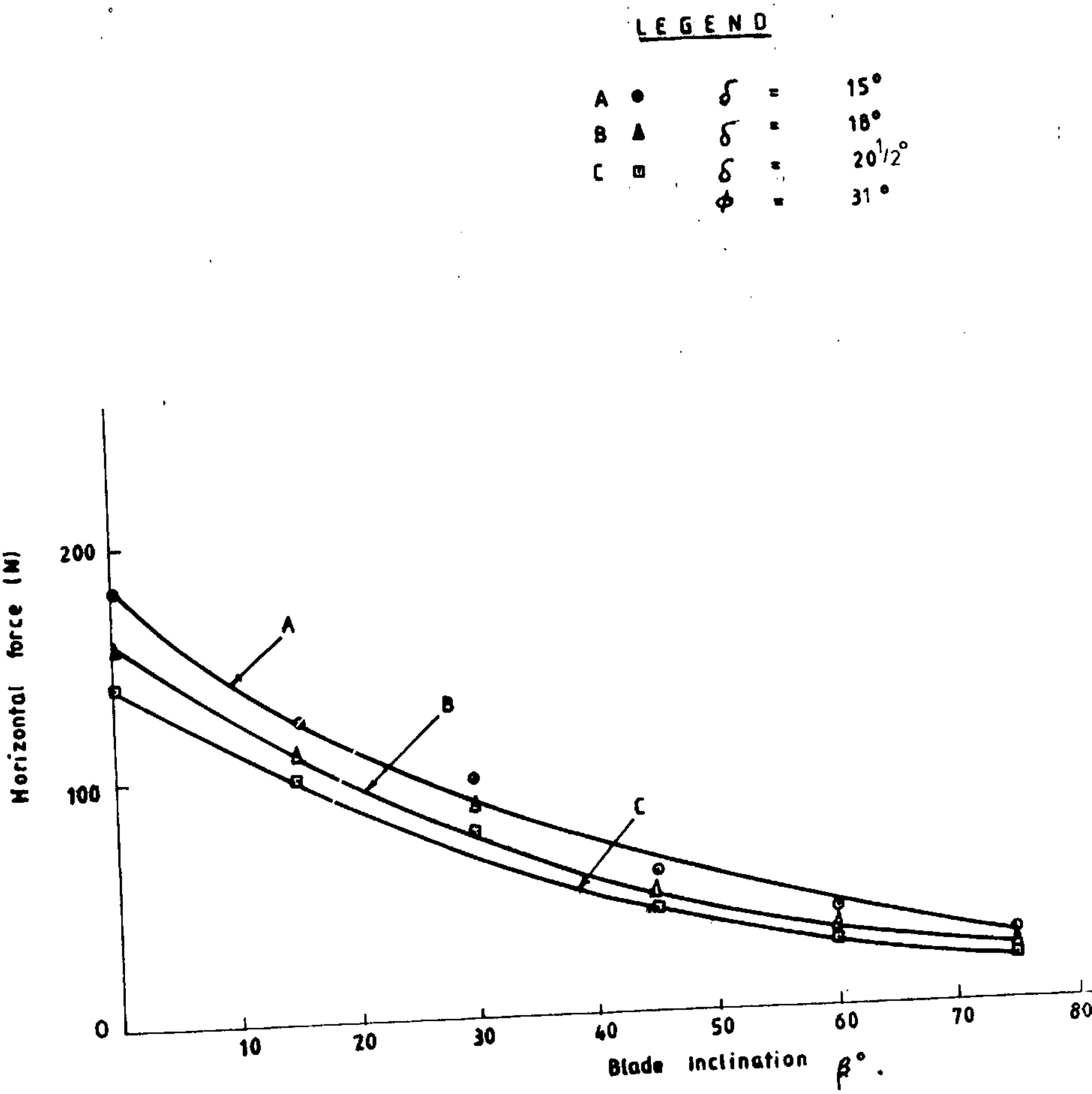

Figure 6·19 GRAPHS OF HORIZONTAL FORCE VERSUS BLADE INCLINATION β°, FOR VARYING SOIL - BLADE FRICTION δ°, FOR BEACH SAND.

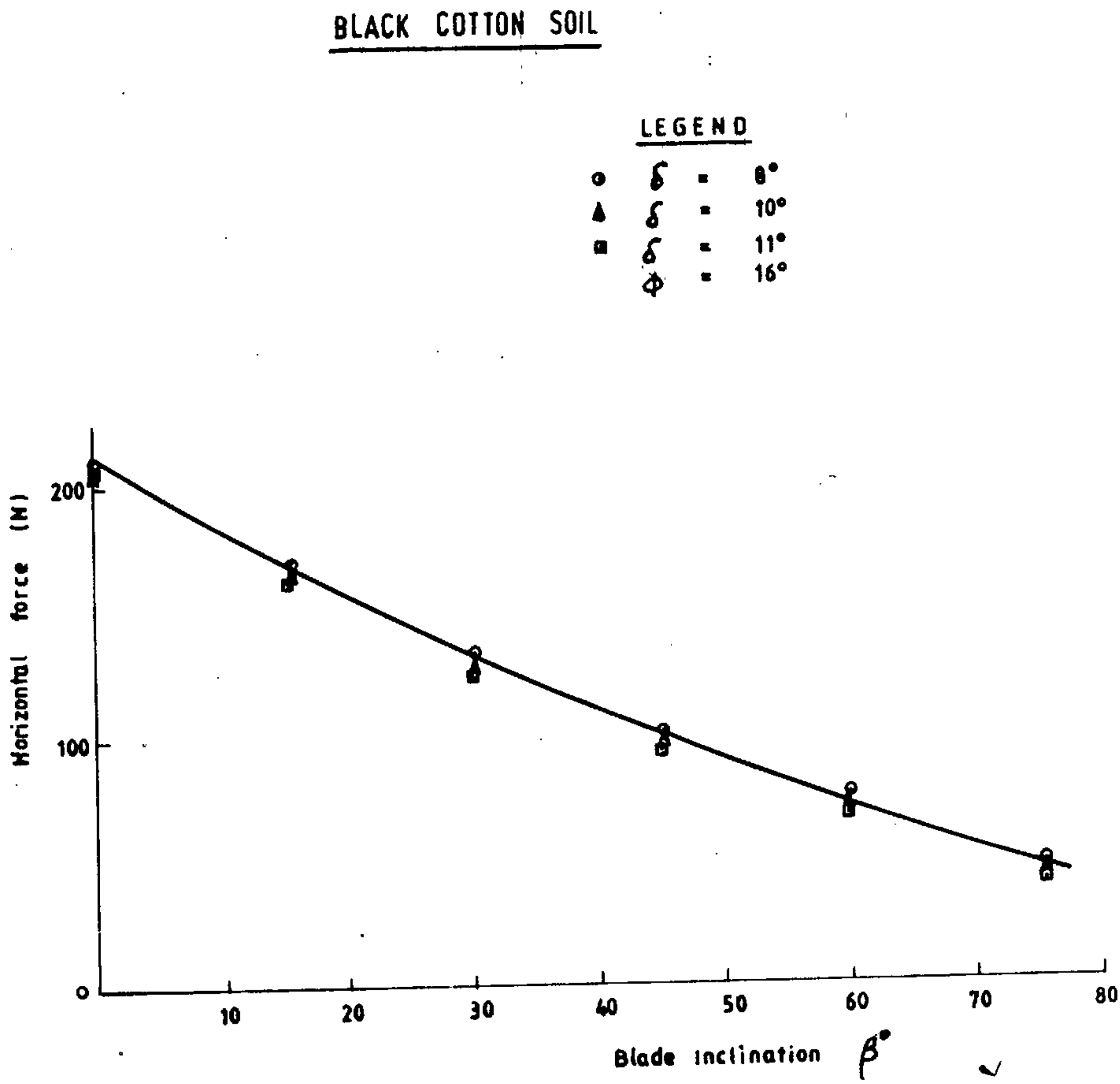

Figure 6·20 GRAPH OF HORIZONTAL FORCE VERSUS BLADE INCLINATION β°, FOR VARYING SOIL-BLADE FRICTION δ°, FOR BLACK COTTON SOIL

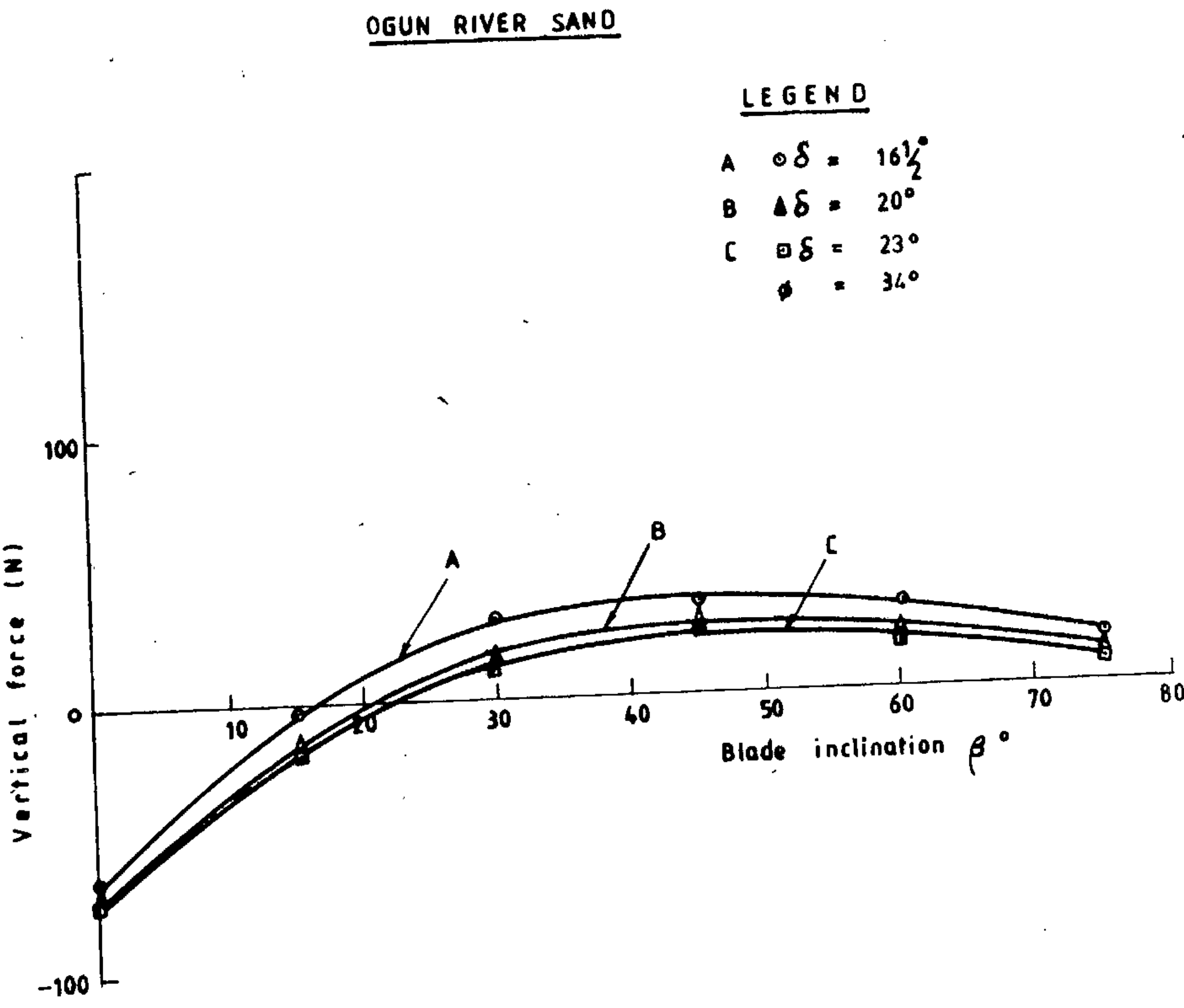

Figure 6·21 GRAPH OF VERTICAL FORCE VERSUS BLADE INCLINATION β°, FOR VARYING SOIL-BLADE FRICTION δ°, FOR OGUN RIVER SAND.

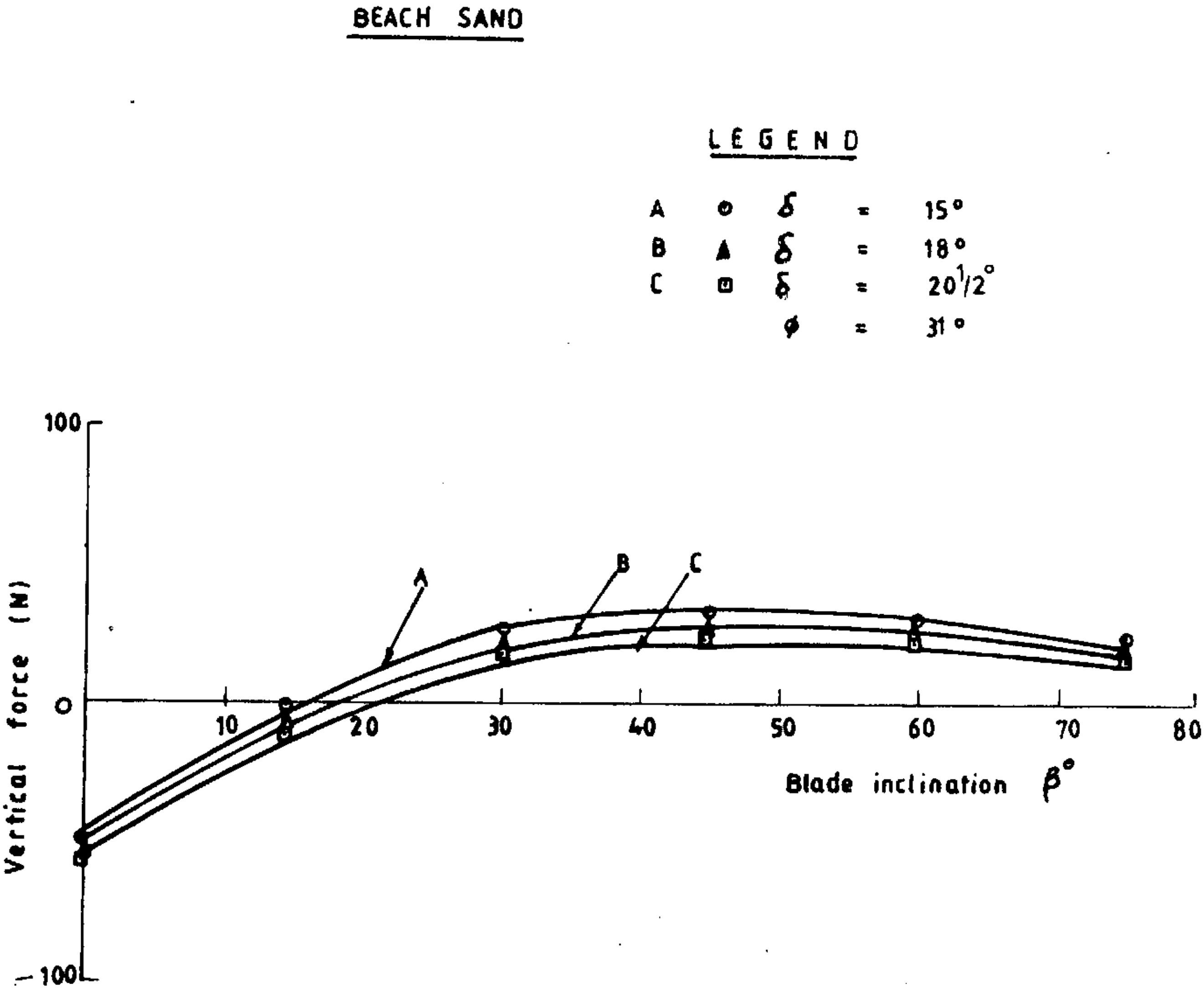

Figure 6·22 GRAPH OF VERTICAL FORCE VERSUS BLADE INCLINATION β^o, WITH VARYING SOIL – BLADE FRICTION δ^o, FOR BEACH SAND.

BLACK COTTON SOIL

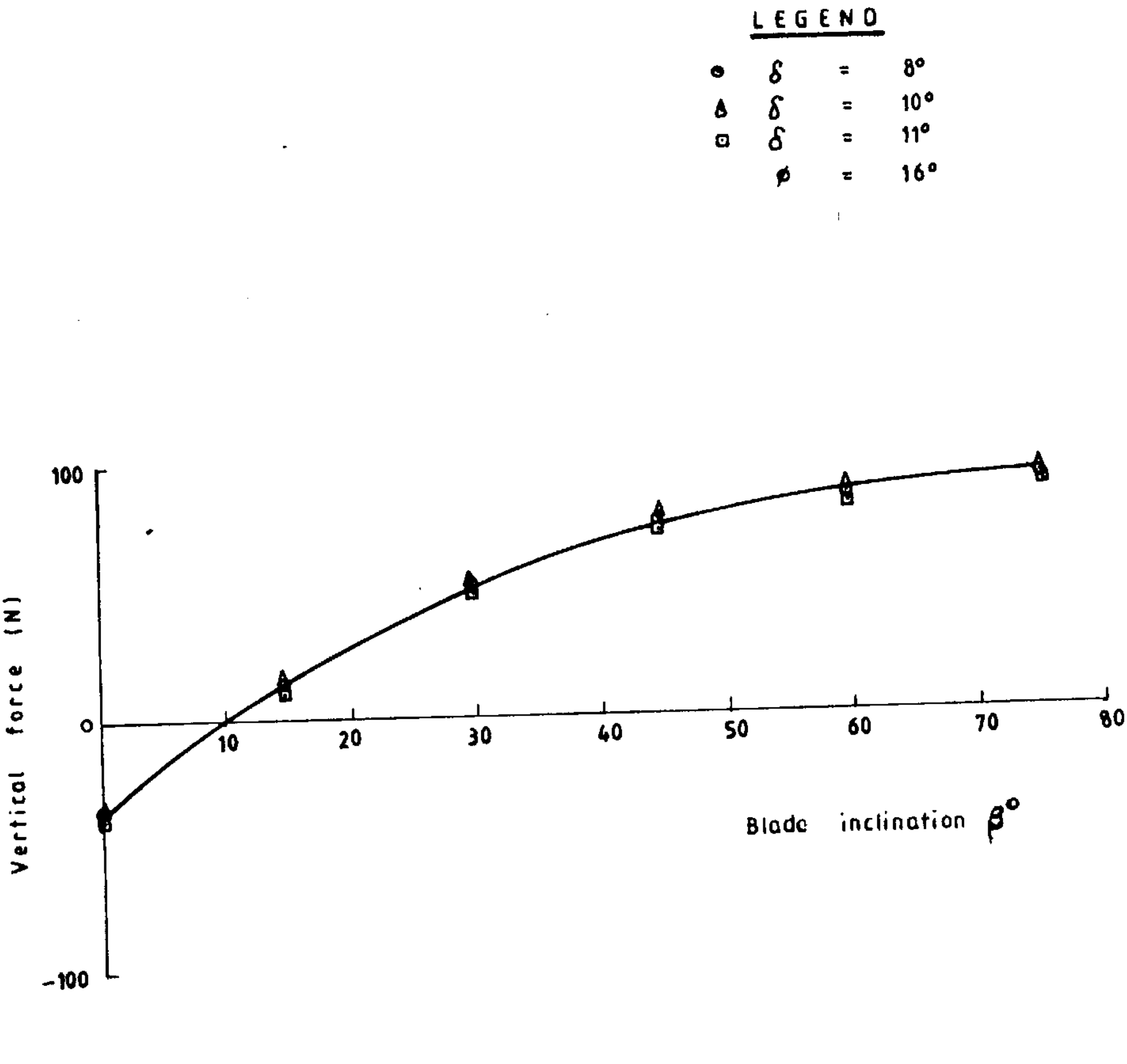

Figure 6.23 GRAPH OF VERTICAL FORCE VERSUS BLADE INCLINATION β°, FOR VARYING SOIL-BLADE FRICTION δ,° FOR BLACK COTTON SOIL.

OGUN RIVER SAND

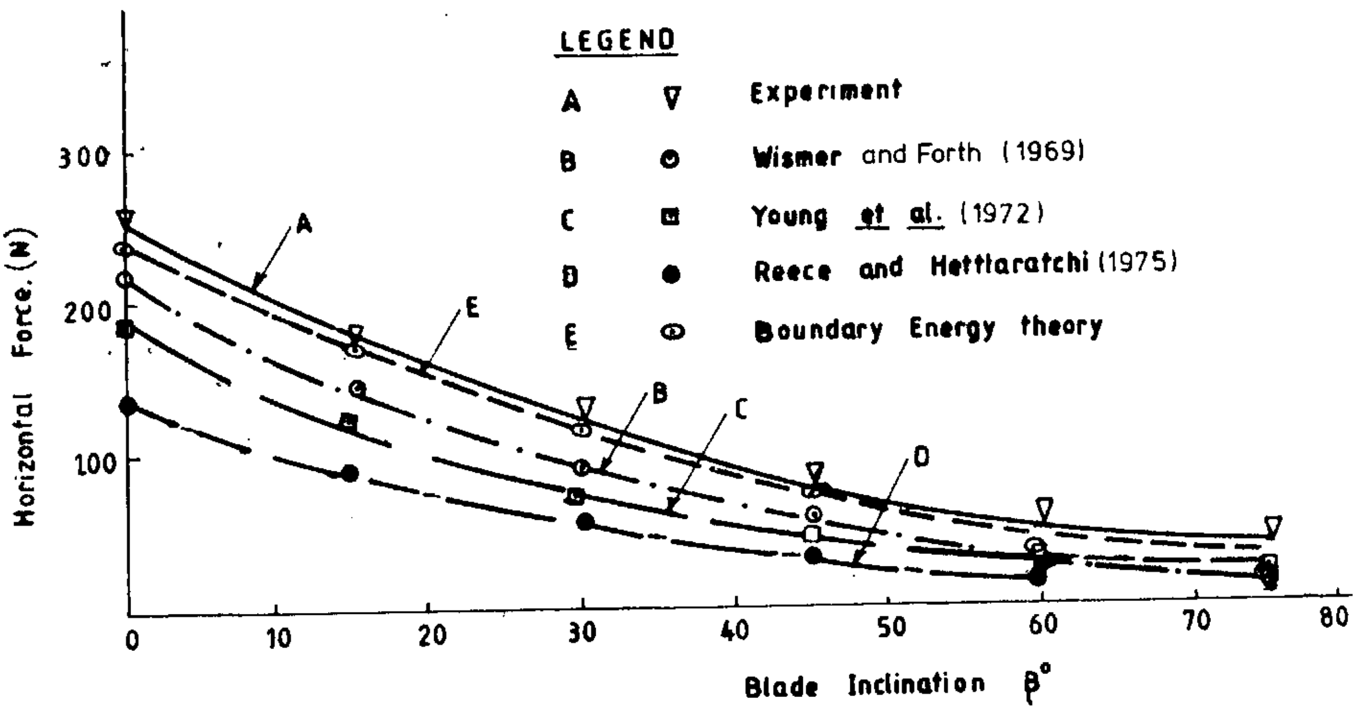

FIG 6.24 GRAPH OF EXPERIMENTAL AND THEORETICAL HORIZONTAL FORCES VERSUS ANGLE OF BLADE INCLINATION β°, FOR OGUN RIVER SAND.

BEACH SAND

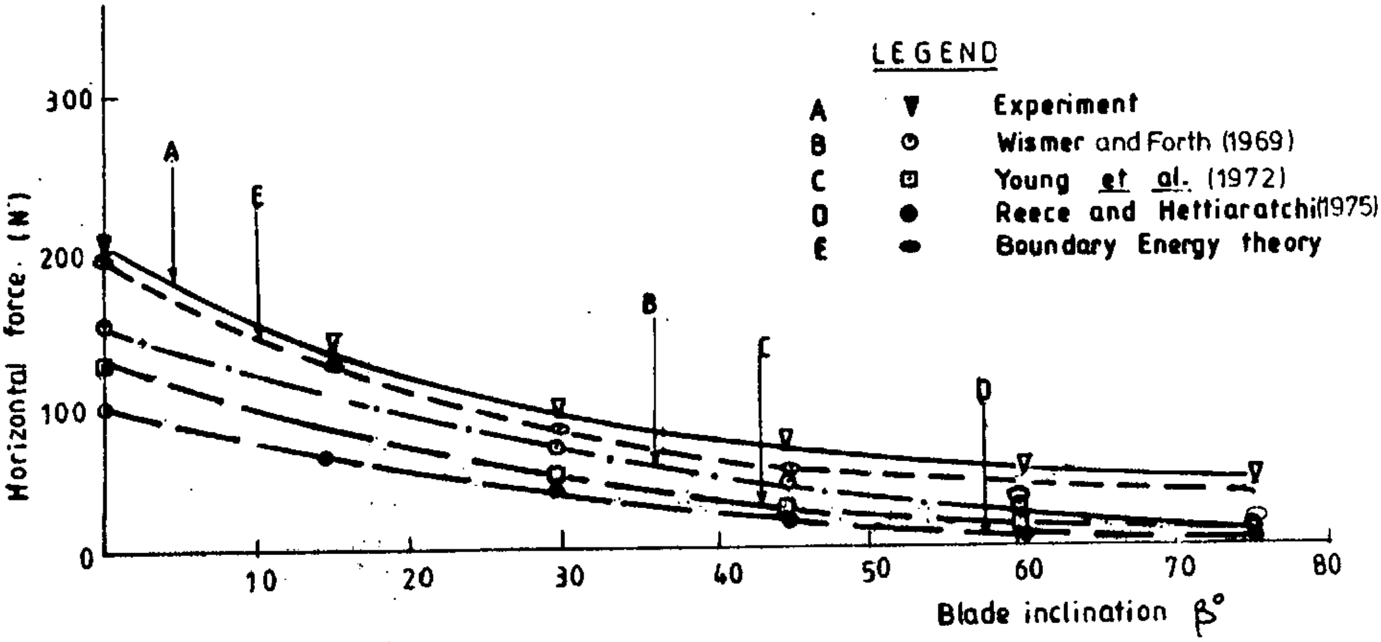

Figure 6.25. GRAPH OF EXPERIMENTAL AND THEORETICAL HORIZONTAL FORCES VERSUS ANGLE OF BLADE INCLINATION β° FOR BEACH SAND.

BLACK COTTON SOIL

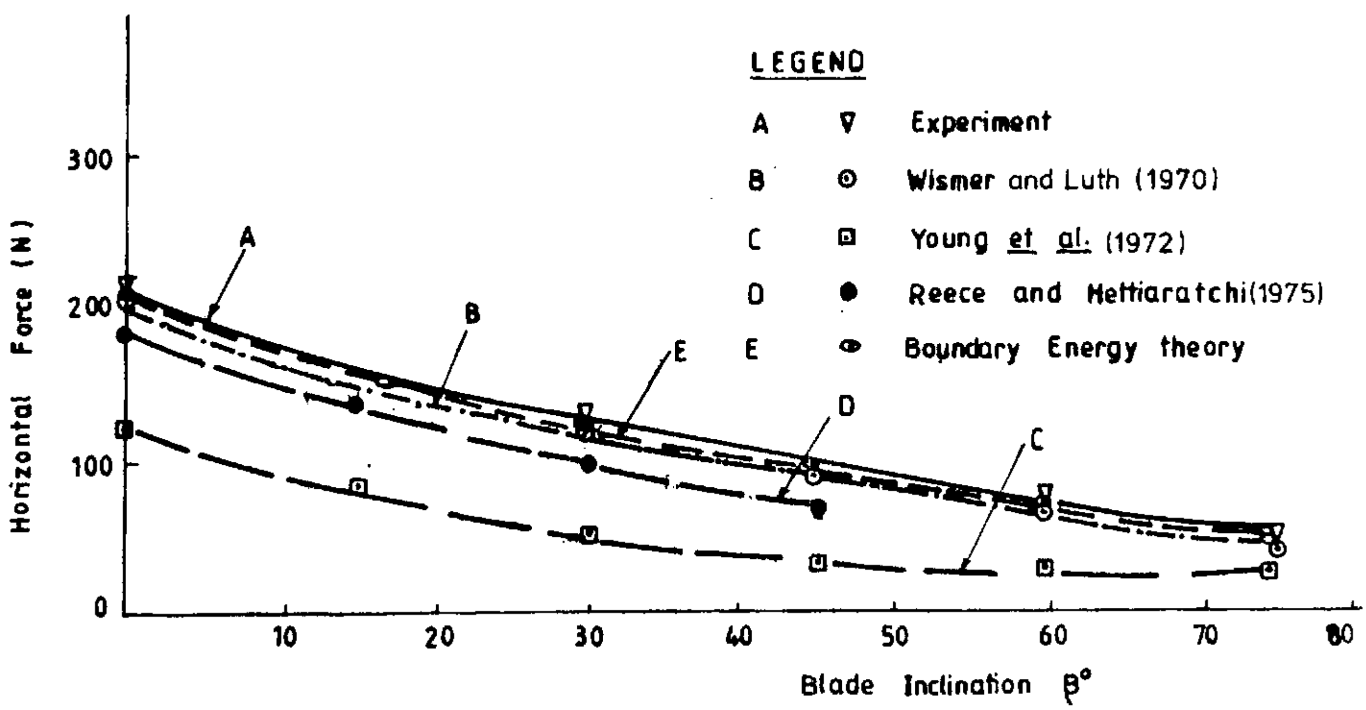

FIG 6·26 GRAPH OF EXPERIMENTAL AND THEORETICAL HORIZONTAL FORCES VERSUS ANGLE OF BLADE INCLINATION β° FOR BLACK COTTON SOIL.

OGUN RIVER SAND

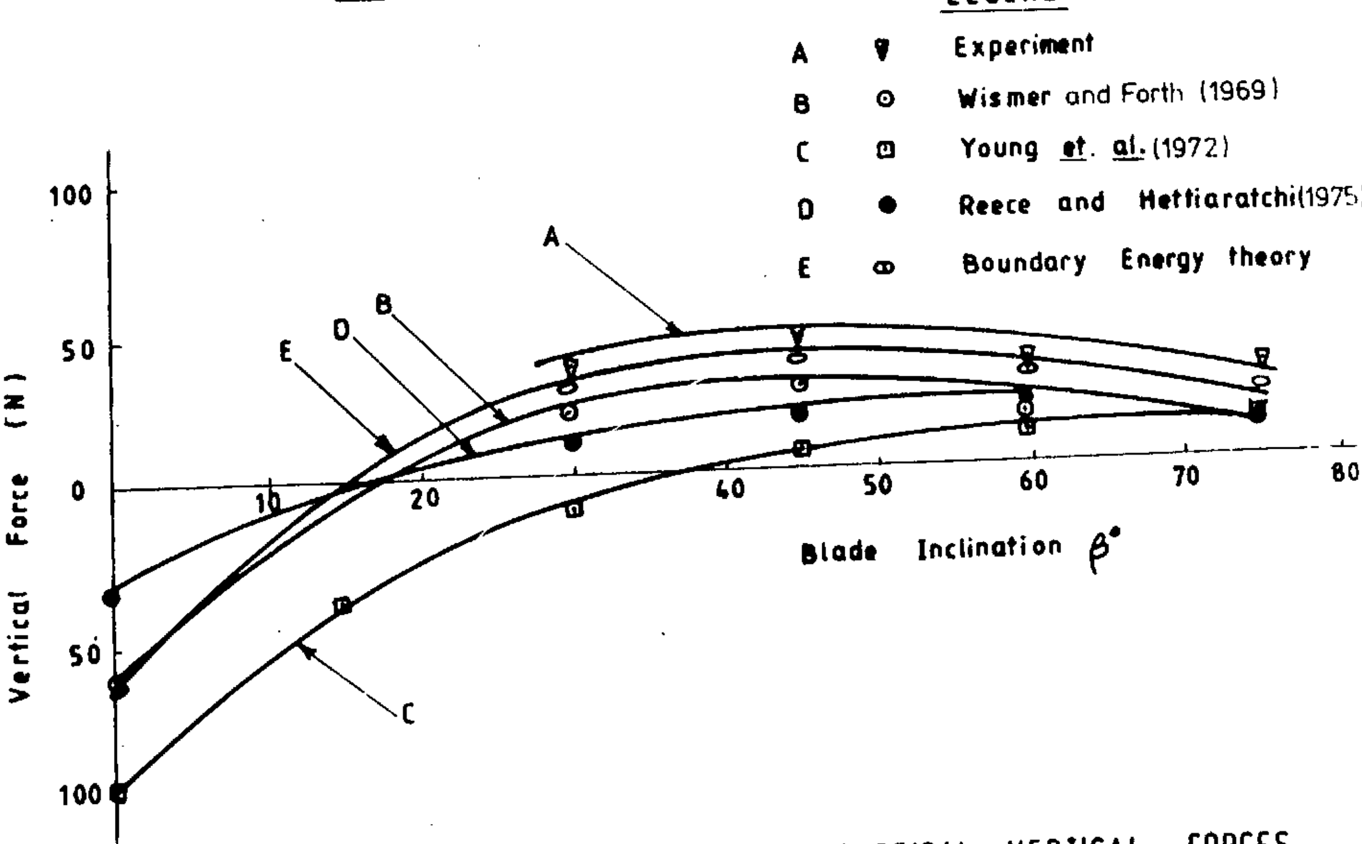

FIG 6.27 GRAPH OF EXPERIMENTAL AND THEORETICAL VERTICAL FORCES VERSUS ANGLE OF BLADE INCLINATION β° FOR OGUN RIVER SAND

BEACH SAND

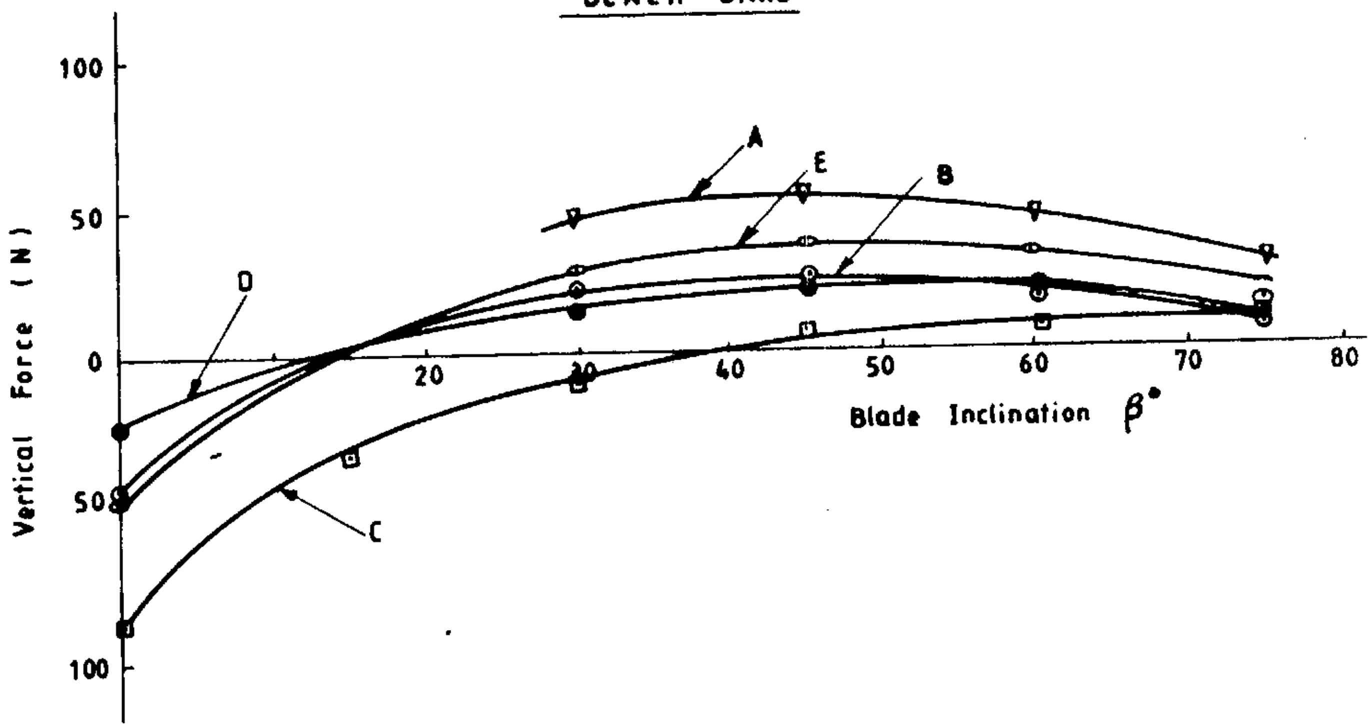

FIG 6.28 GRAPH OF EXPERIMENTAL AND THEORETICAL VERTICAL FORCES VERSUS ANGLE OF BLADE INCLINATION β° FOR BEACH SAND

BLACK COTTON SOIL

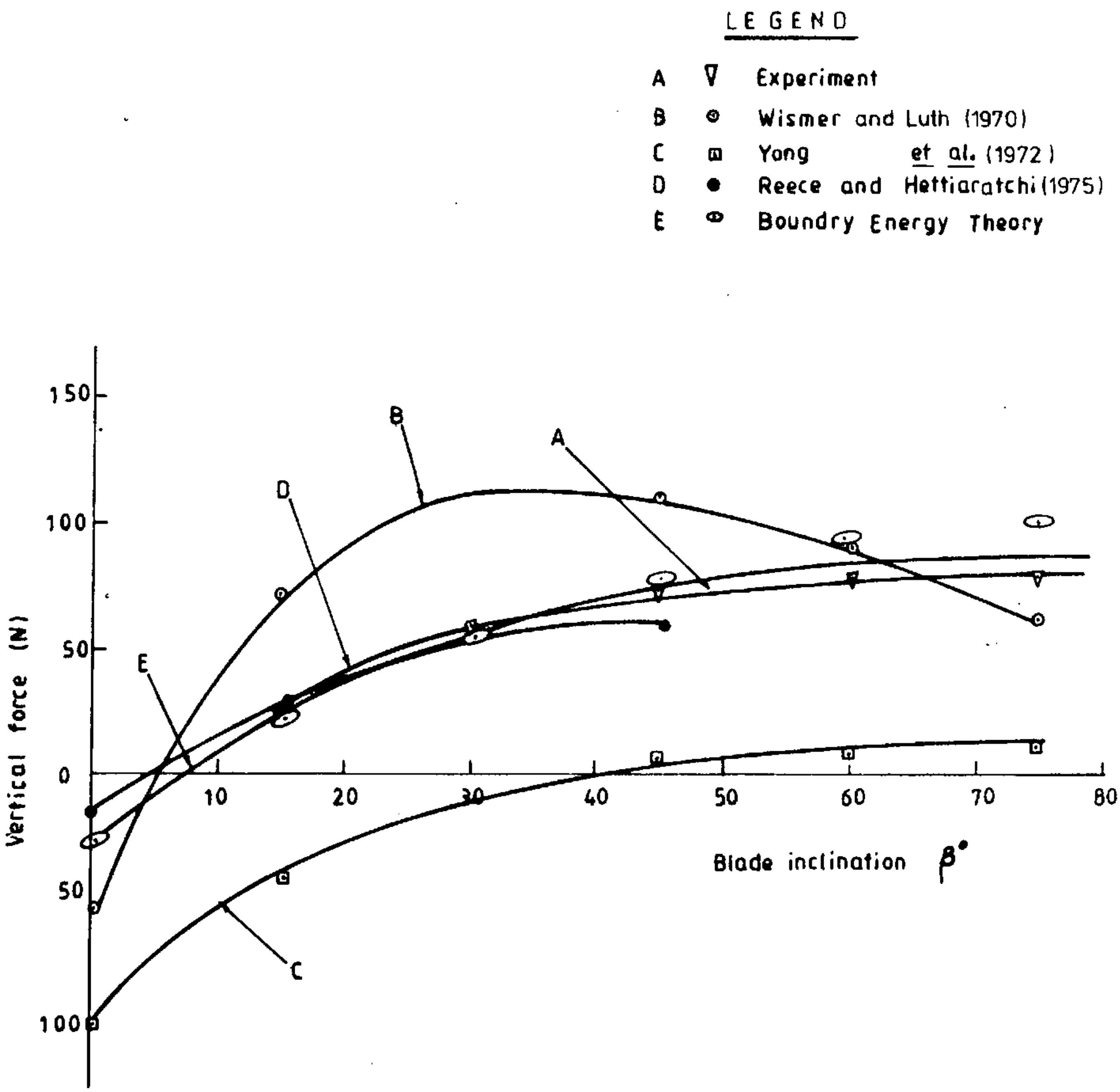

Figure 6·29 GRAPH OF EXPERIMENTAL AND THEORETICAL VERTICAL FORCES VERSUS ANGLE OF BLADE INCLINATION β° FOR BLACK COTTON SOIL.

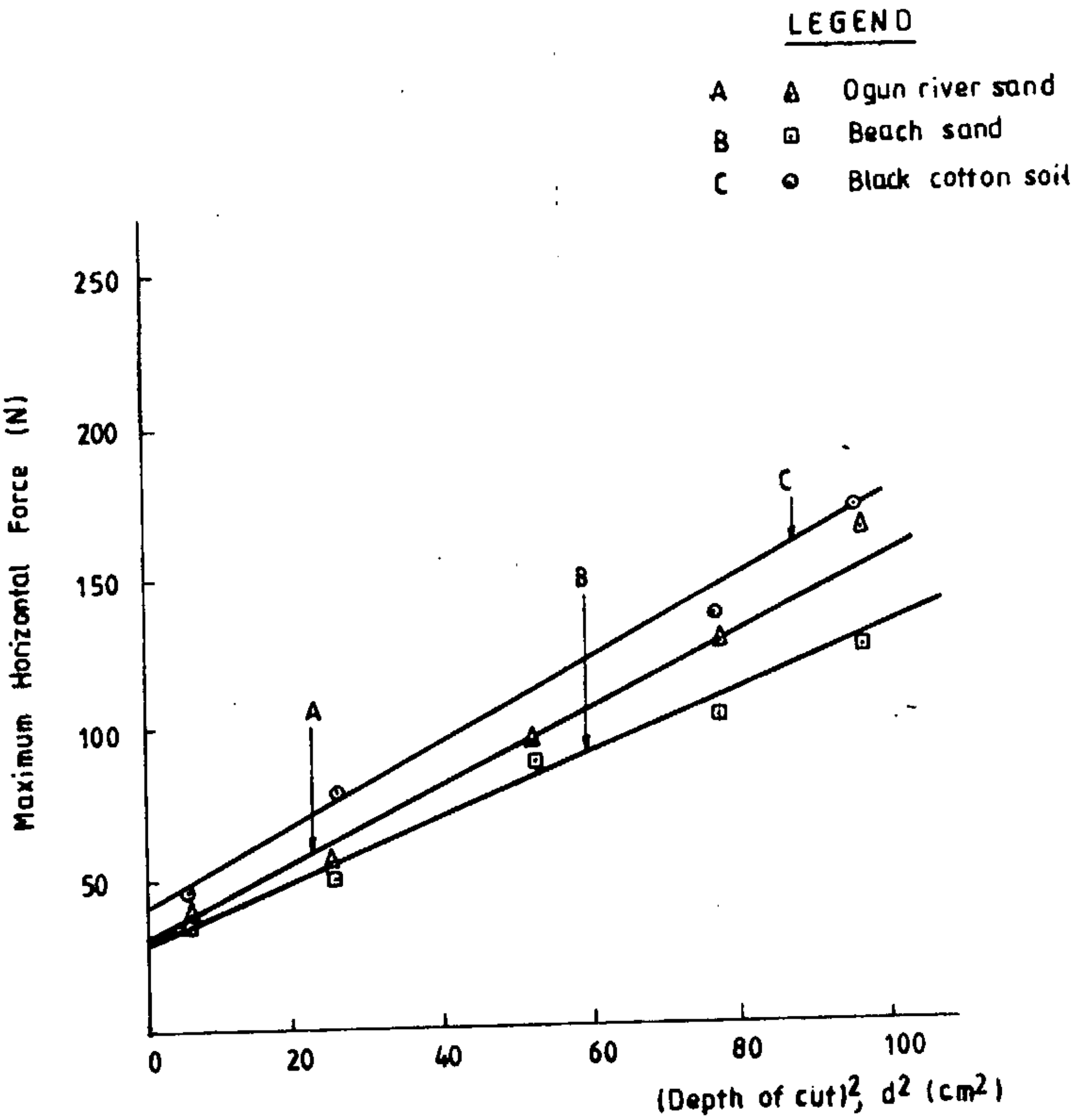

FIGURE 6·30 GRAPH OF HORIZONTAL FORCE VERSUS SQUARE OF DEPTH OF CUT.

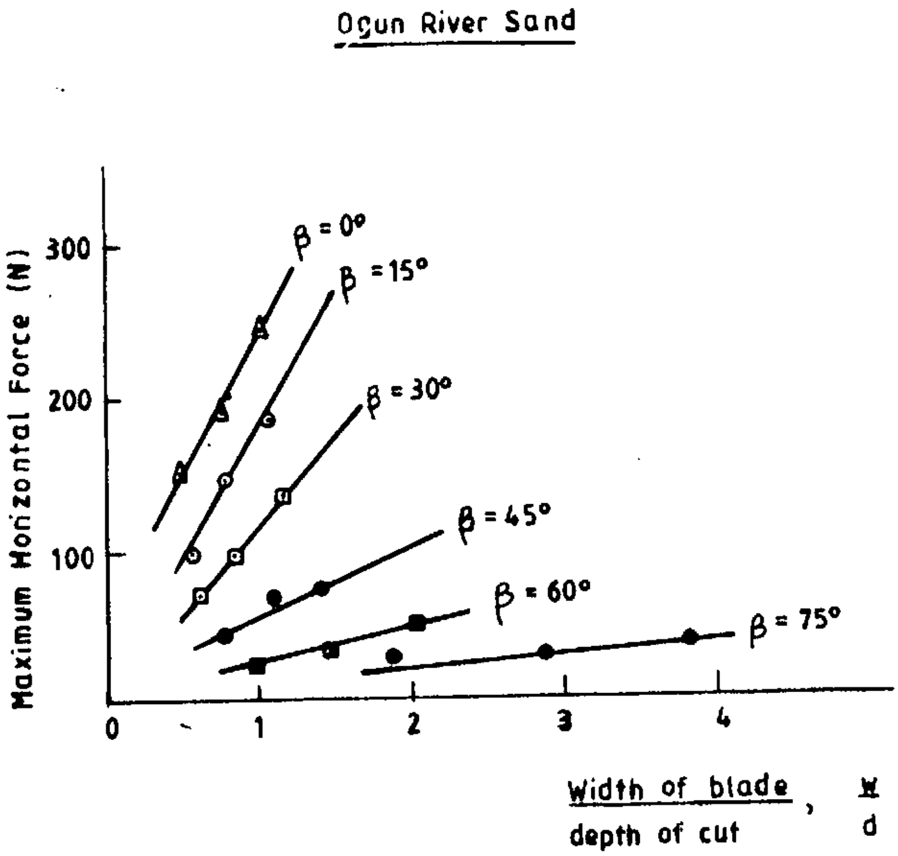

FIGURE 6·31 GRAPH OF MAXIMUM HORIZONTAL FORCE VERSUS RATIO OF BLADE WIDTH AND DEPTH OF CUT.

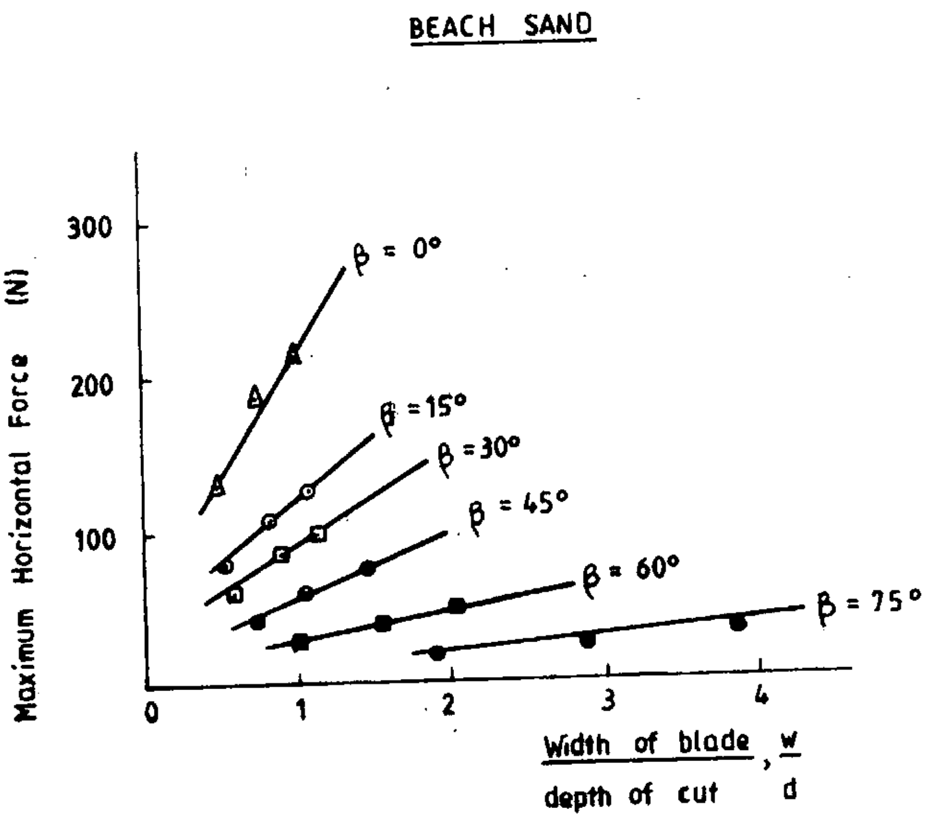

FIGURE 6·32 GRAPH OF MAXIMUM HORIZONTAL FORCE VERSUS RATIO OF BLADE WIDTH AND DEPTH OF CUT.

Black Cotton Soil

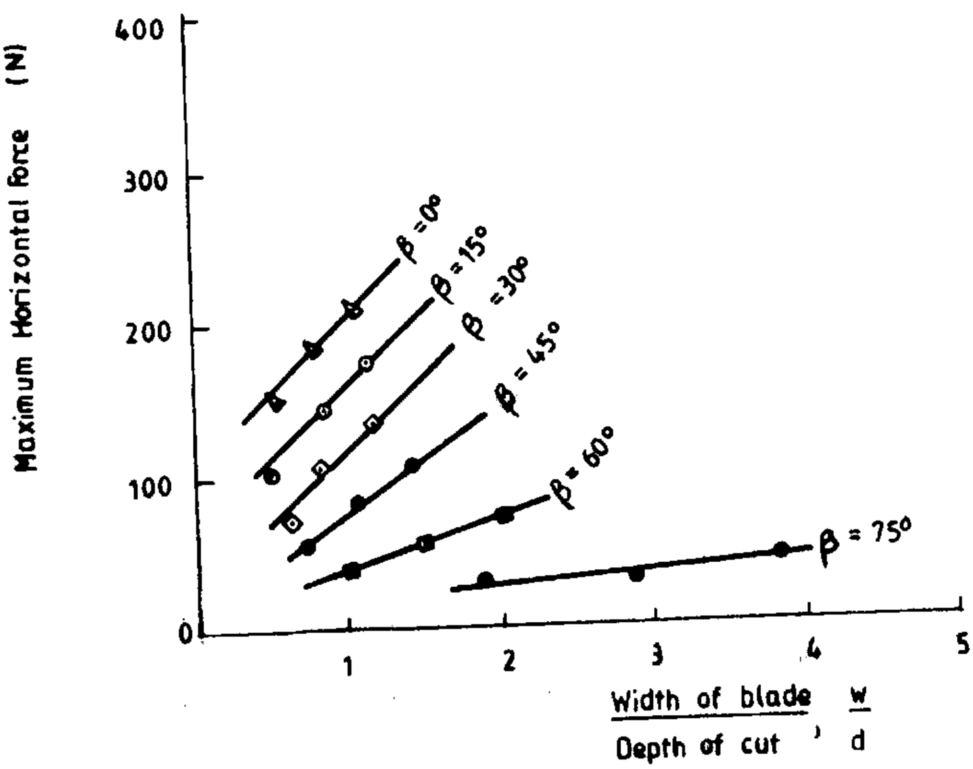

Figure 6·33 GRAPH OF MAXIMUM HORIZONTAL FORCE VERSUS RATIO OF BLADE WIDTH AND DEPTH OF CUT.

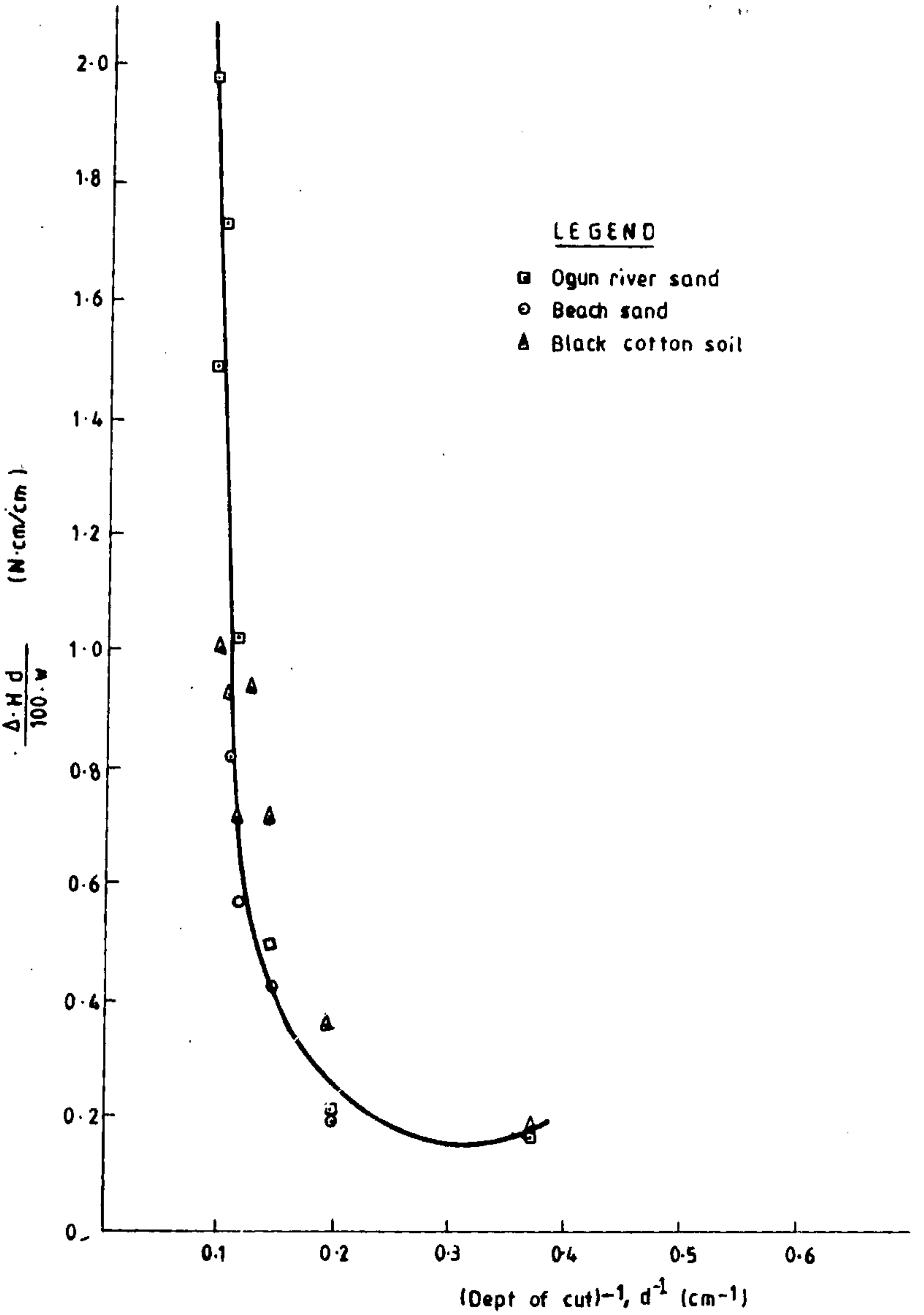

Figure 6.34 GRAPH OF HORIZONTAL FORCE INCREMENT PER BLADE WIDTH TO DEPTH OF CUT RATIO, VERSUS INVERSE OF DEPTH OF CUT.

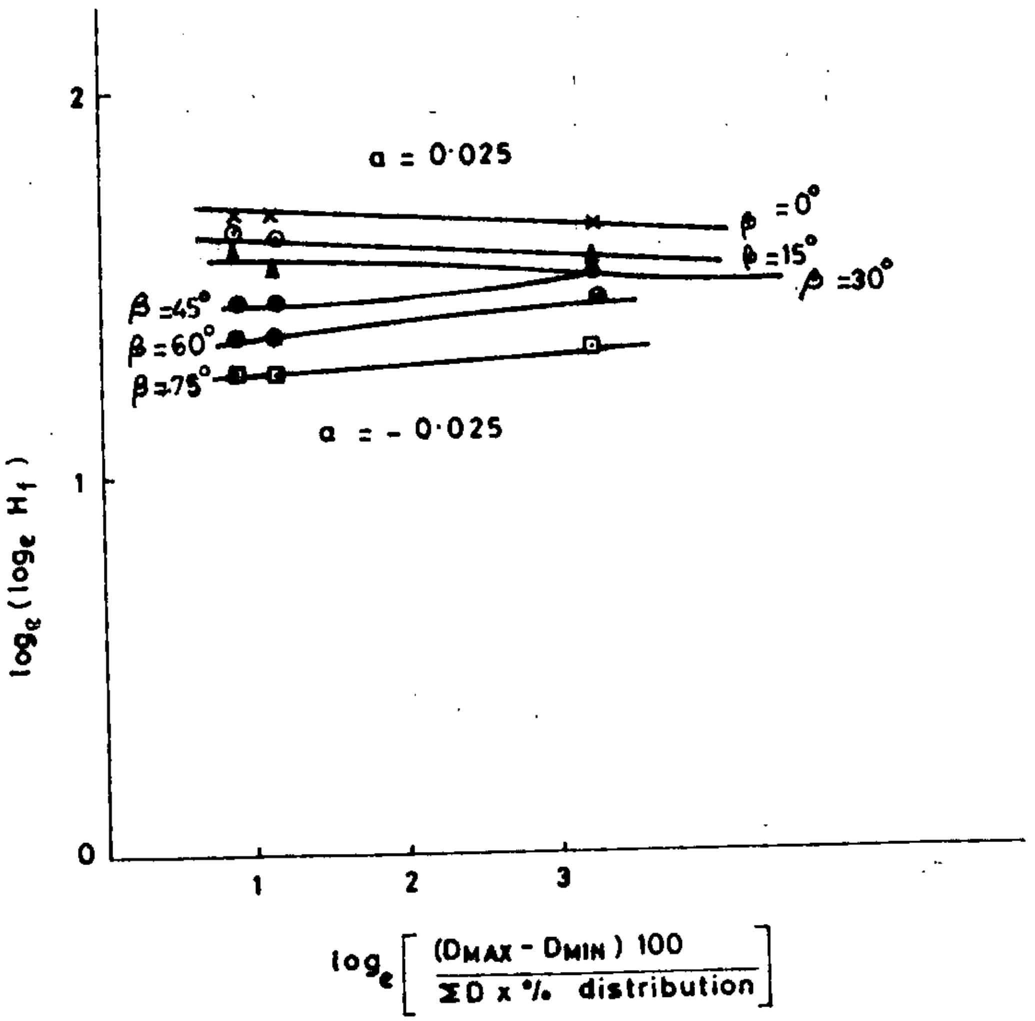

FIG 6·35 GRAPH OF $\log_e(\log_e H_f)$ VERSUS $\log_e\left[\frac{(D_{MAX} - D_{MIN})\,100}{\Sigma D \times \%\ \text{distribution}}\right]$, IN NEWTONS.

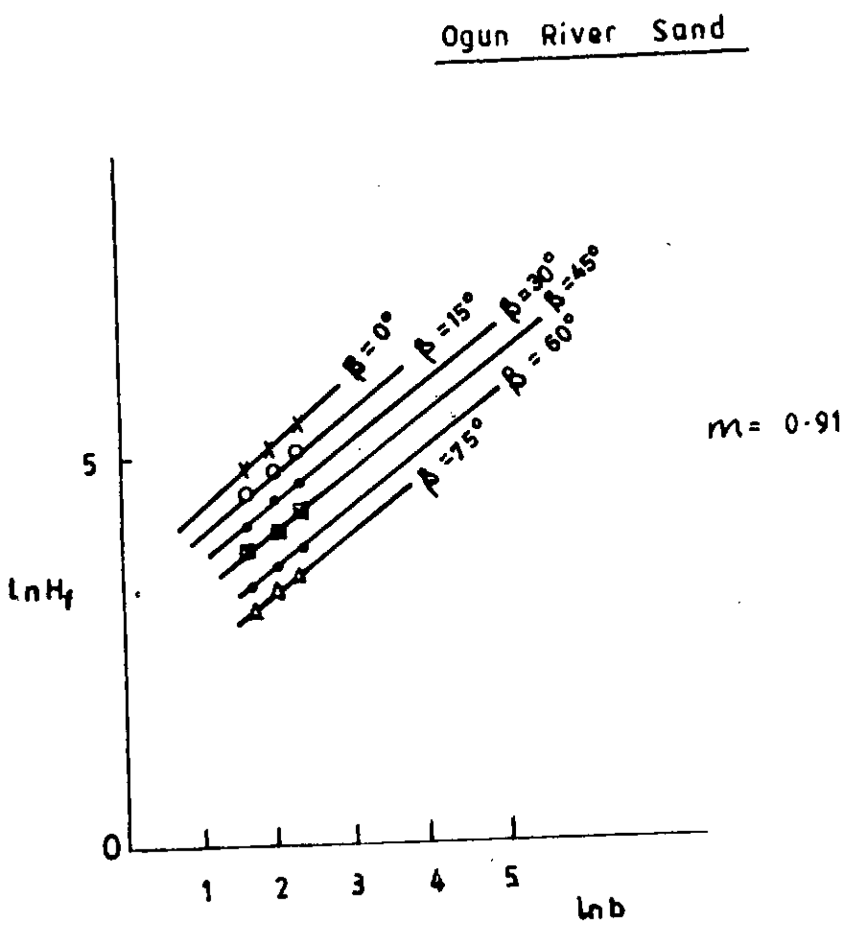

Figure 6·36 GRAPH OF Ln H_f VERSUS Ln b FOR OGUN RIVER SAND.

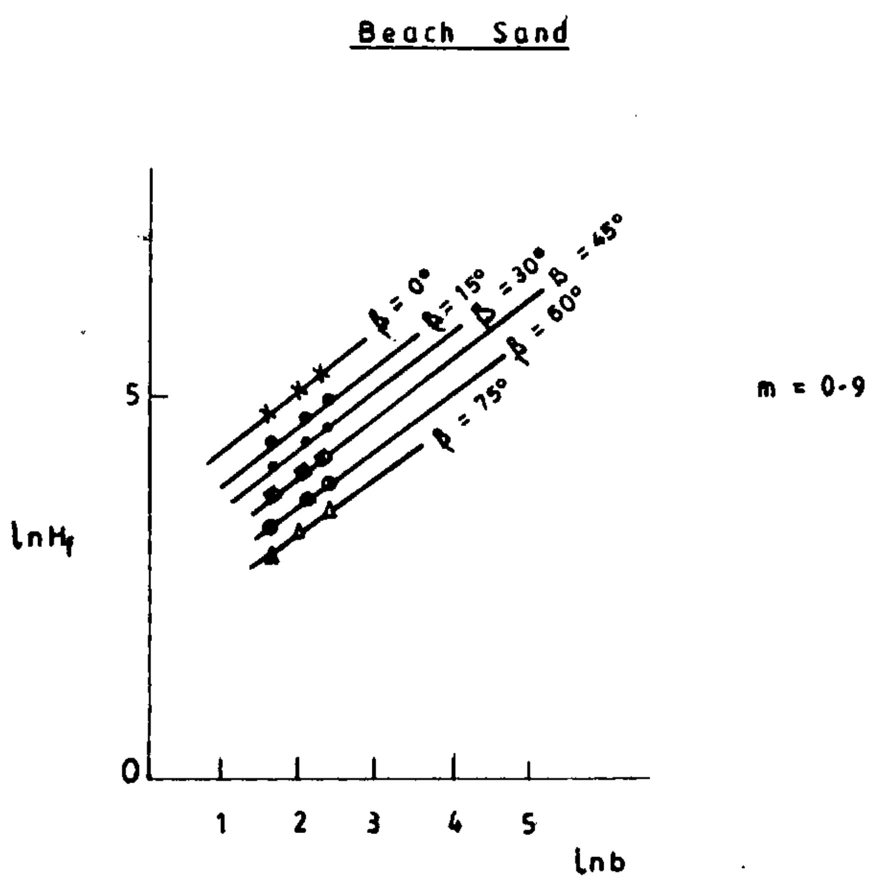

Figure 6·37 GRAPH OF $\ln H_f$ VERSUS $\ln b$ FOR BEACH SAND.

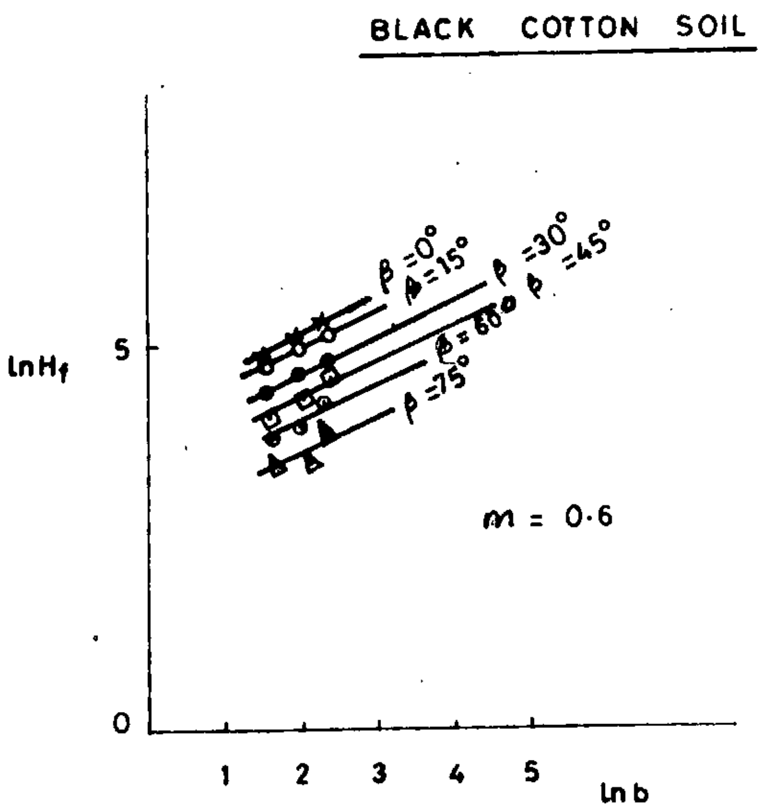

FIG 6.38 GRAPH OF ln H_f VERSUS ln b FOR BLACK COTTON SOIL

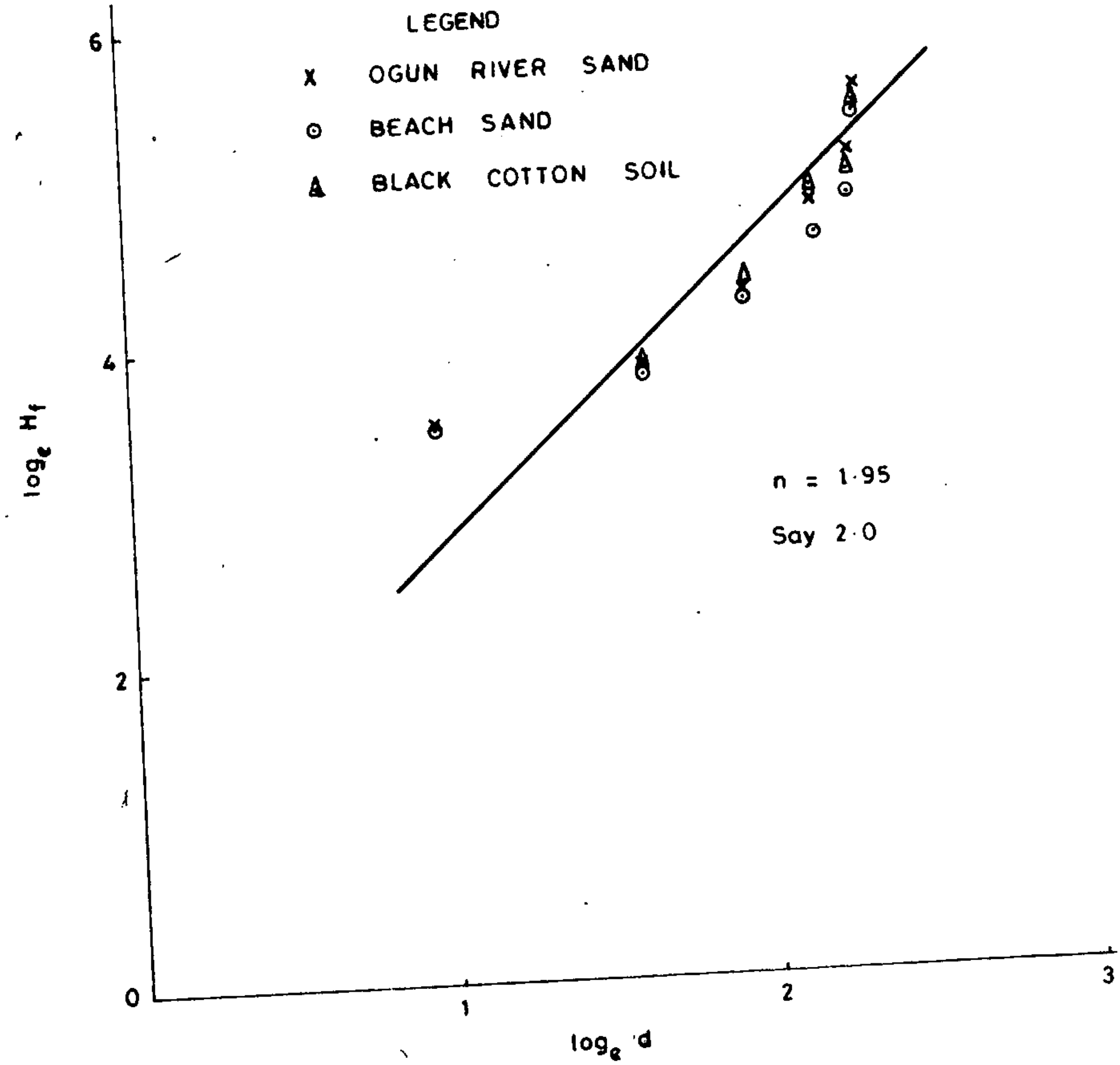

FIG 6.39 GRAPH OF $\log_e H_f$ VERSUS $\log_e d$ FOR DIFFERENT SOIL TYPES.

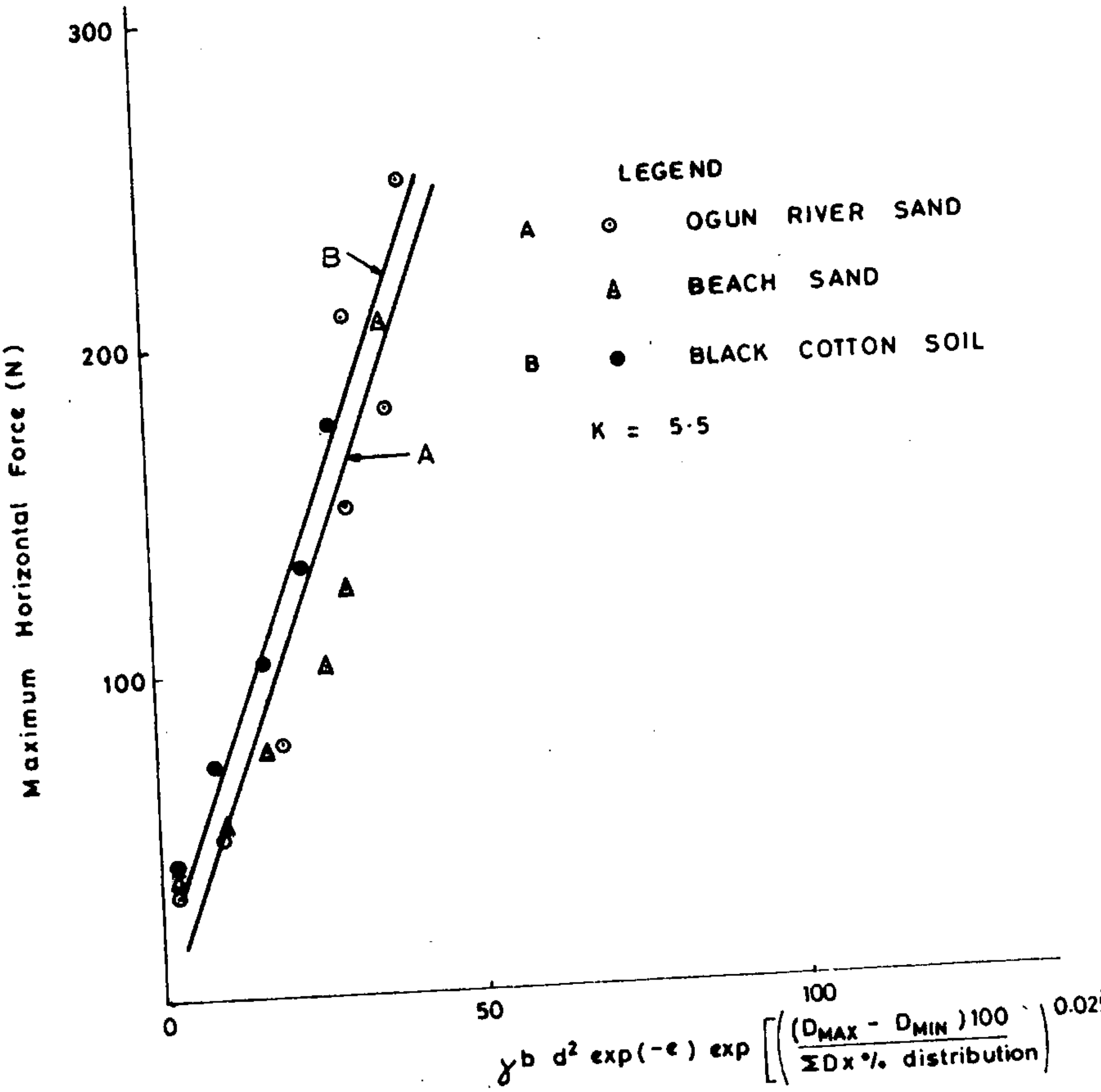

FIG 6.40 GRAPH OF MAXIMUM HORIZONTAL FORCE VERSUS $\gamma b\, d^2 \exp(-e) \exp\left[\left(\frac{(D_{MAX} - D_{MIN})100}{\Sigma Dx\ \%\ distribution}\right)^{0.025}\right]$ IN NEWTONS.

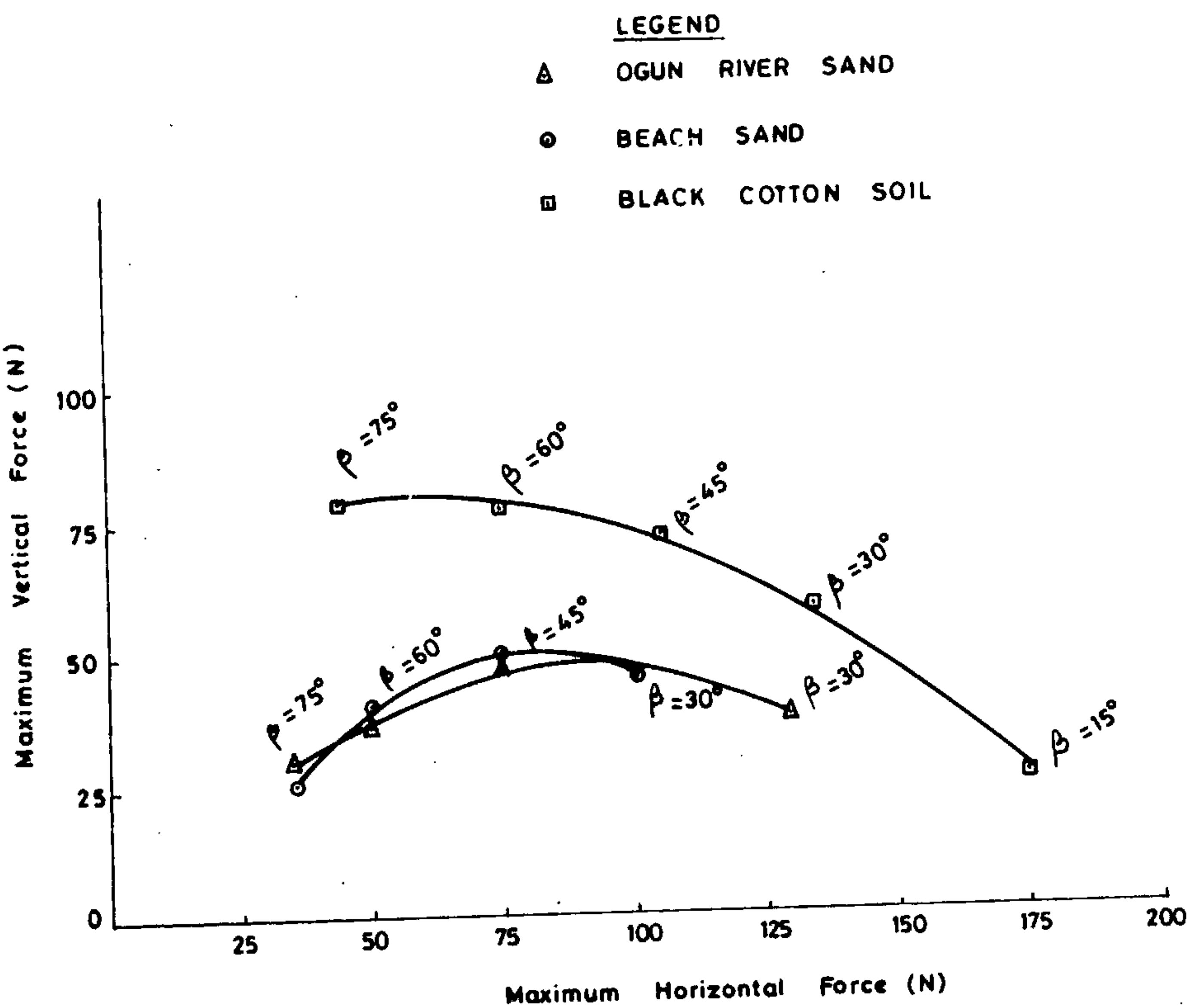

FIG 6·41 GRAPH OF MAXIMUM VERTICAL FORCE VERSUS MAXIMUM HORIZONTAL FORCE FOR 100mm WIDTH BLADE.

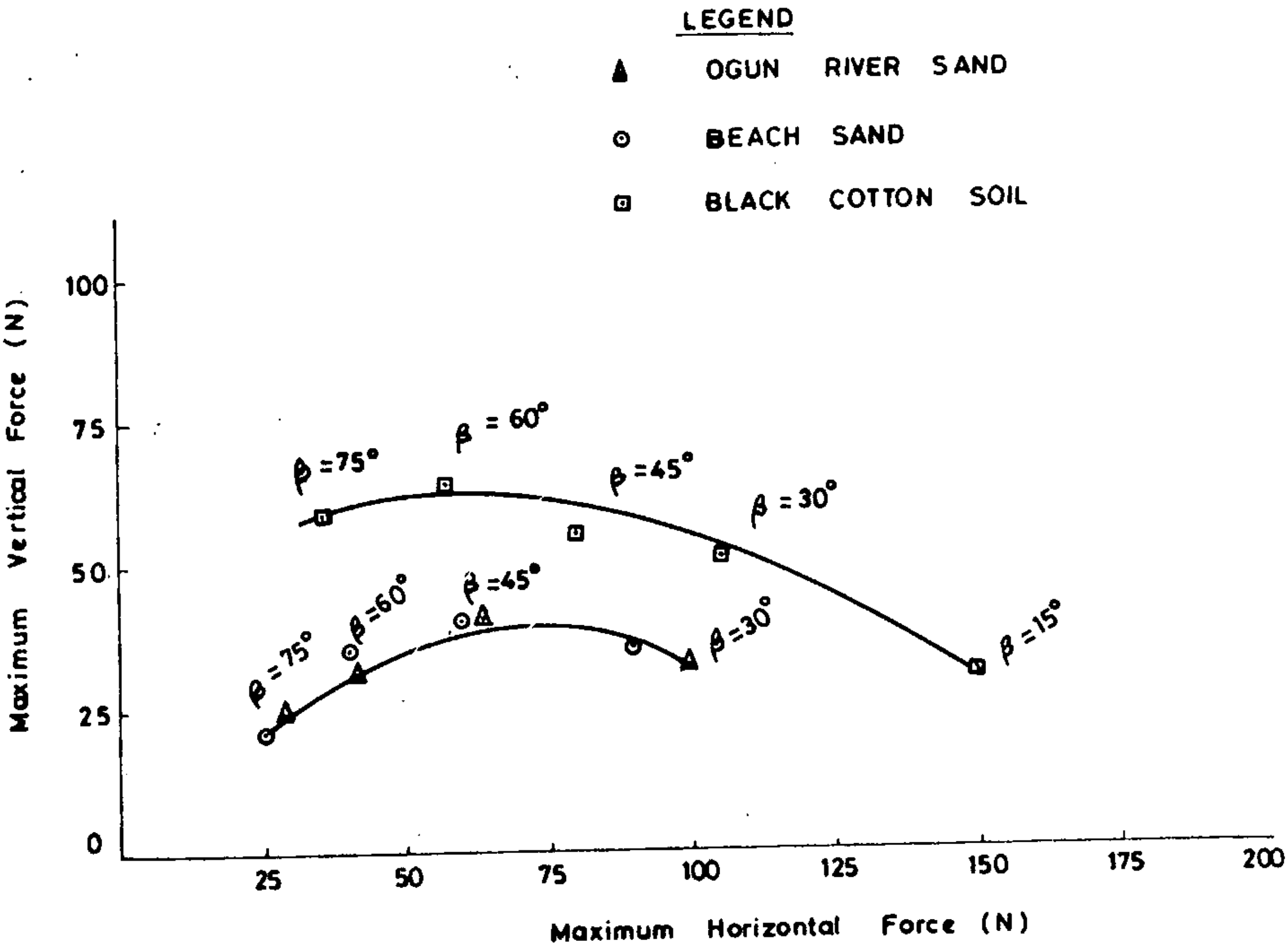

FIG 6.42 GRAPH OF MAXIMUM VERTICAL FORCE VERSUS MAXIMUM HORIZONTAL FORCE FOR 75mm WIDTH BLADE.

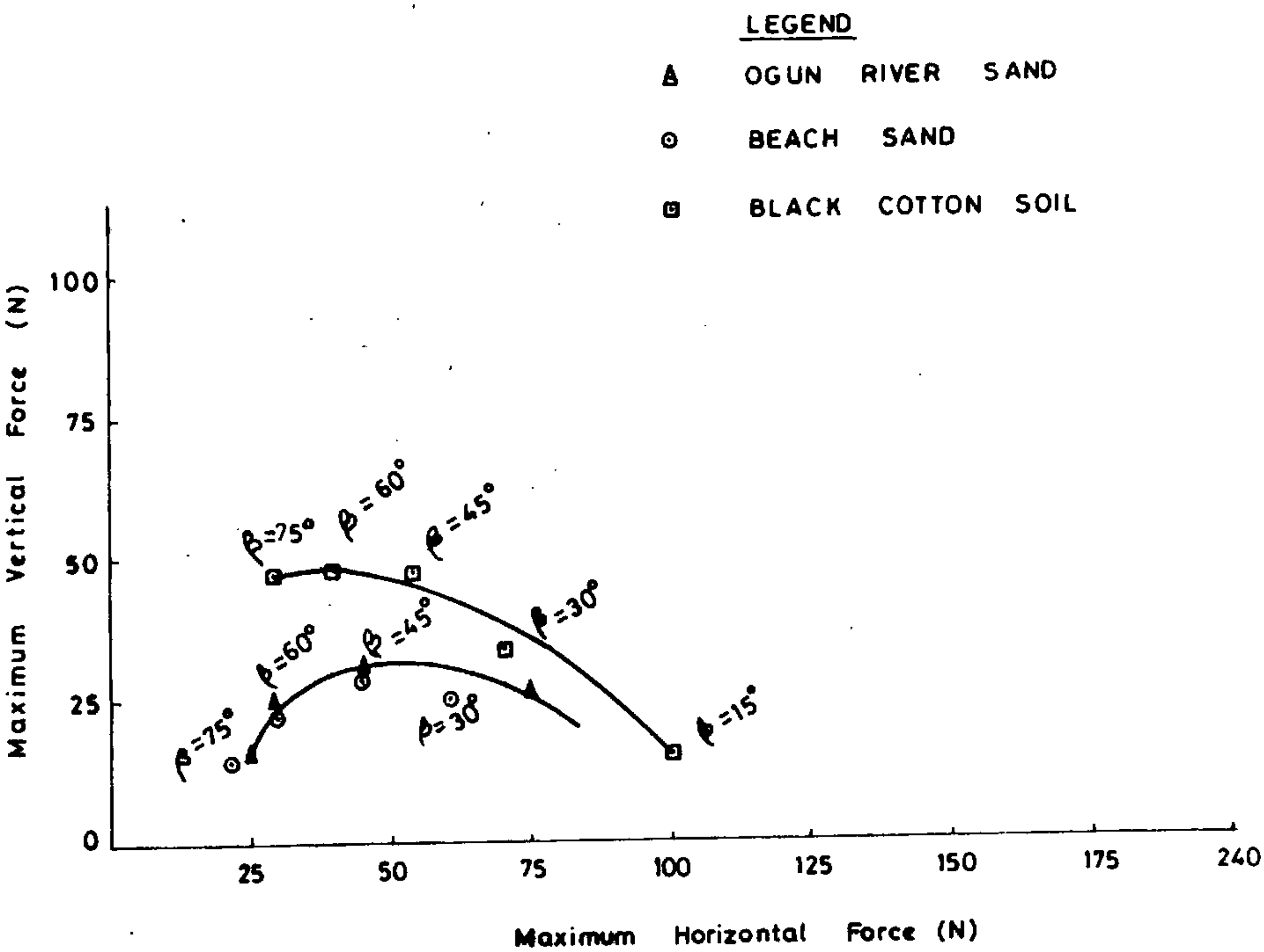

FIG 6.43 GRAPH OF MAXIMUM VERTICAL FORCE VERSUS MAXIMUM HORIZONTAL FORCE FOR 50mm WIDTH BLADE.

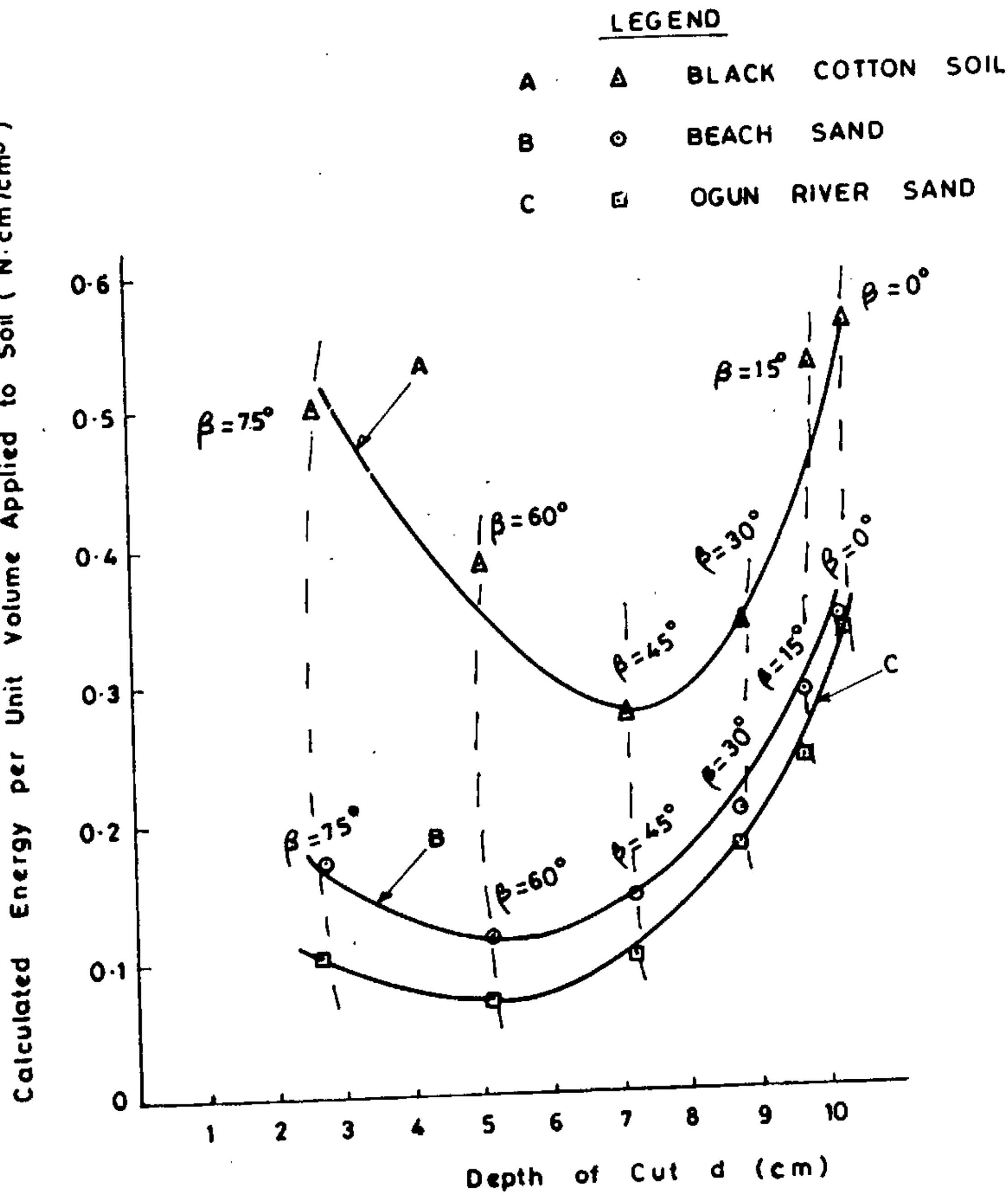

FIG 6·44 GRAPH OF ENERGY PER UNIT VOLUME APPLIED TO CUT SOIL VERSUS DEPTH OF CUT OF 100mm WIDTH BLADE.

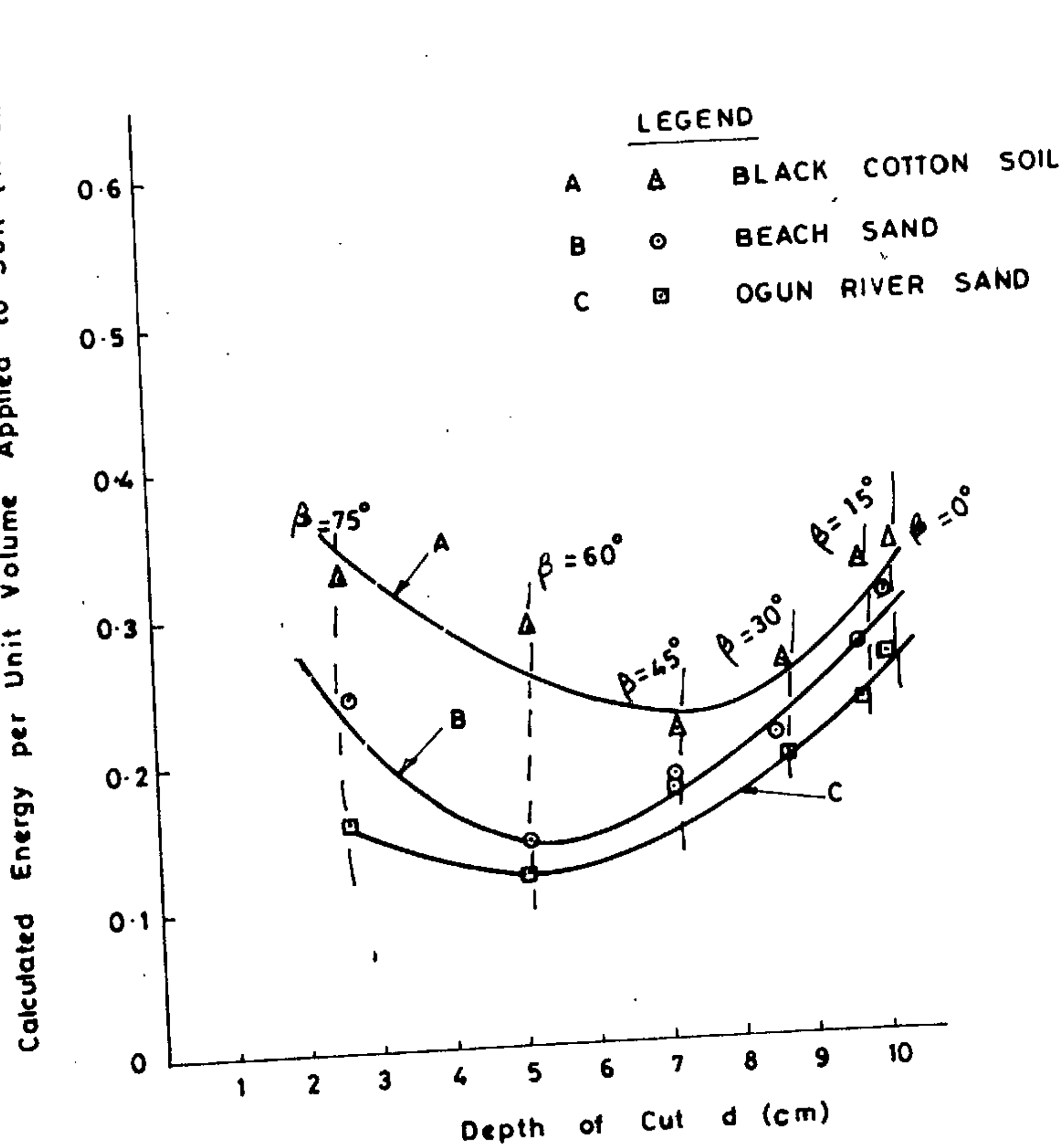

FIG 6.45 GRAPH OF ENERGY PER UNIT VOLUME APPLIED TO CUT SOIL VERSUS DEPTH OF CUT OF 75mm WIDTH BLADE.

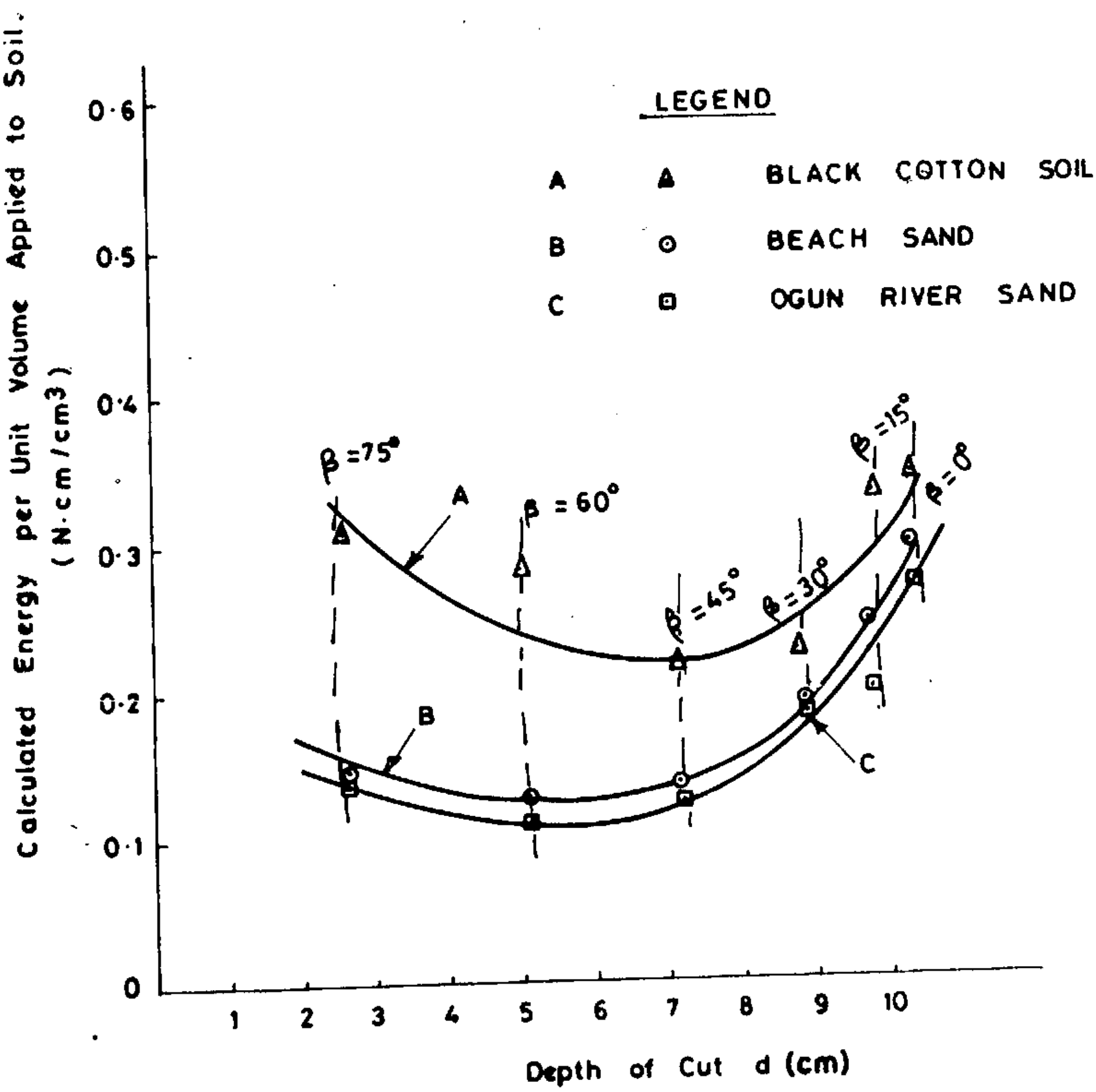

FIG 6·46 GRAPH OF ENERGY PER UNIT VOLUME APPLIED TO CUT SOIL VERSUS DEPTH OF CUT OF 50mm WIDTH BLADE.

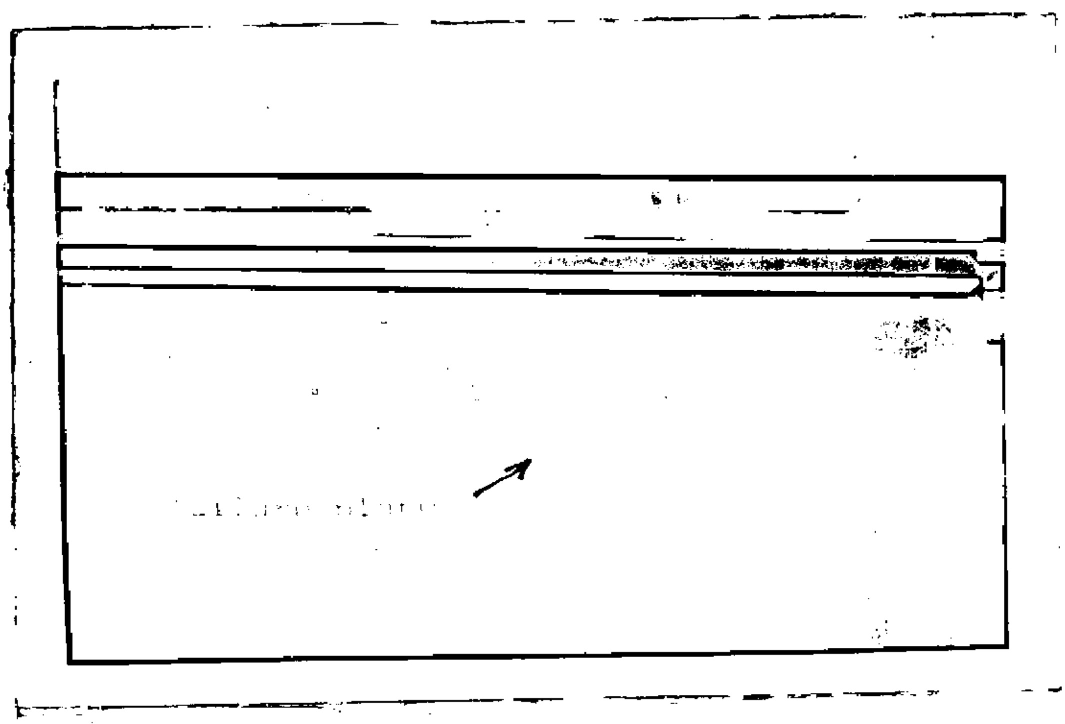

FIGURE 6.47: Ruptured boundary for vertical 100mm width blade in Ogun river sand.

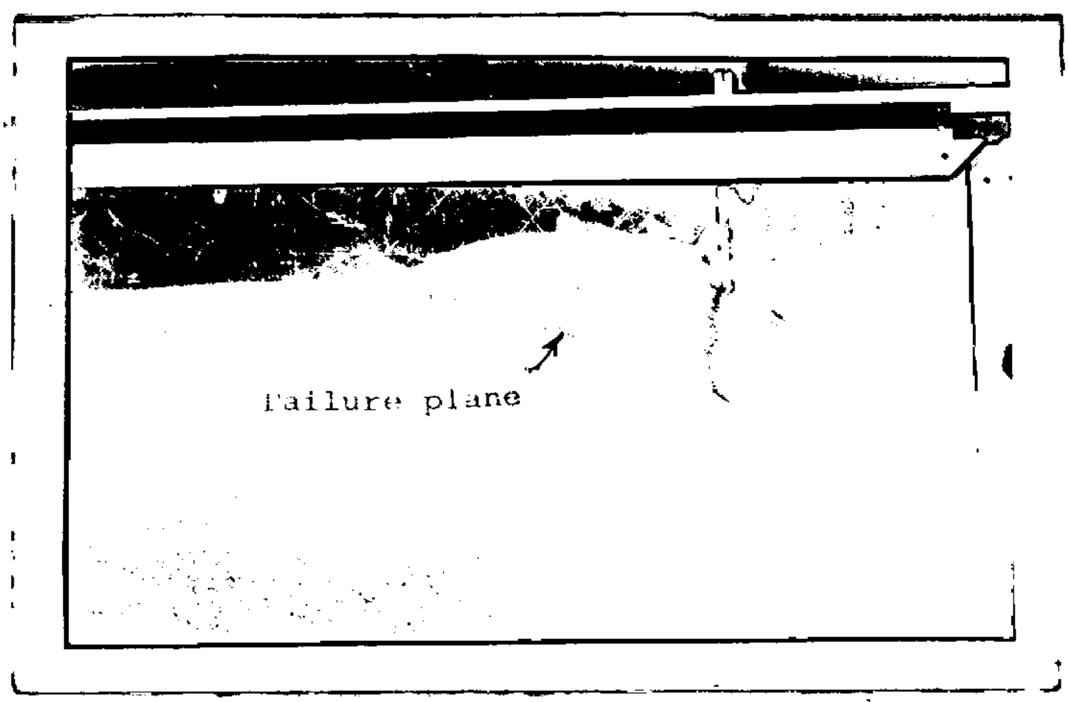

FIGURE 6.48: Ruptured boundary for vertical 100mm width blade in beach sand.

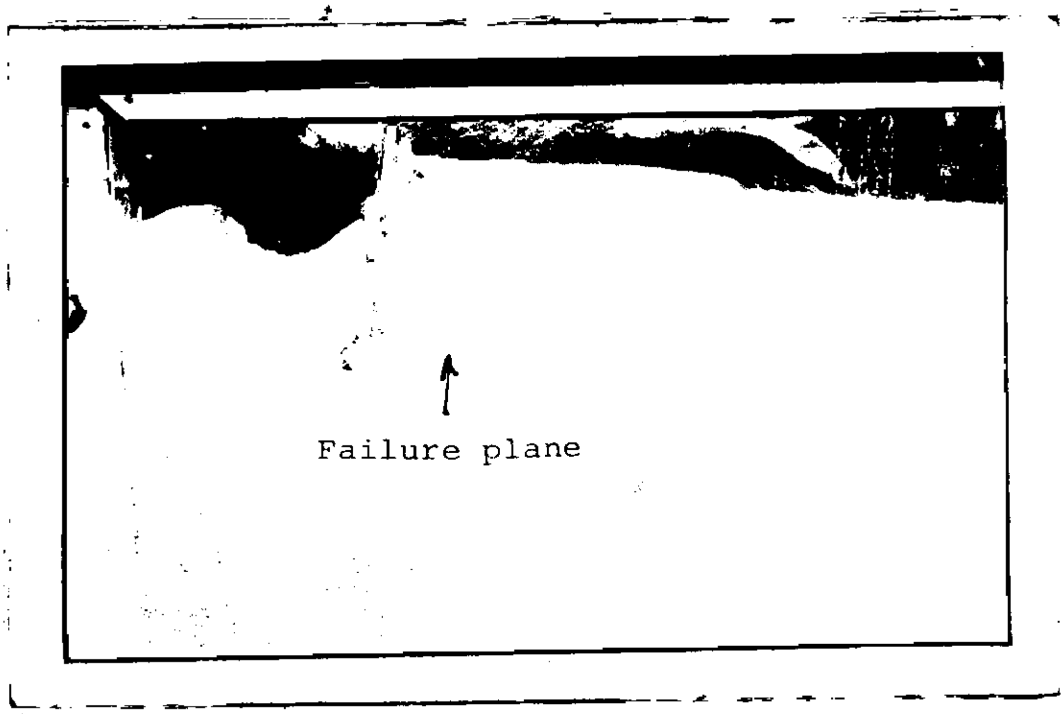

FIGURE 6.49: Ruptured boundary for vertical 100mm, width blade in black cotton soil (air dried).

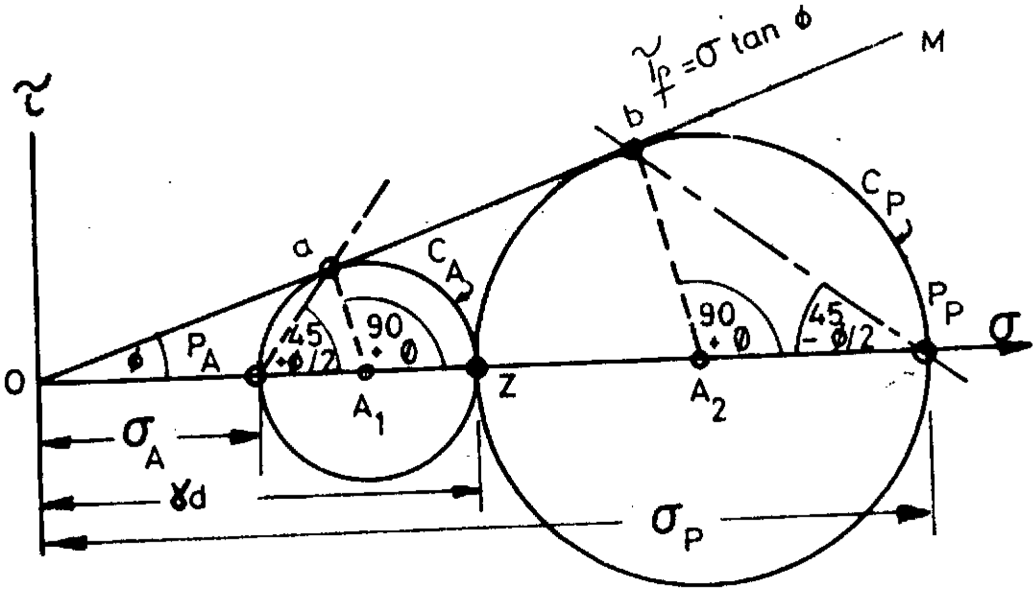

FIGURE: 6·50:- MOHR DIAGRAM OF ACTIVE AND PASSIVE PRESSURES FOR COHESIONLESS SOILS.

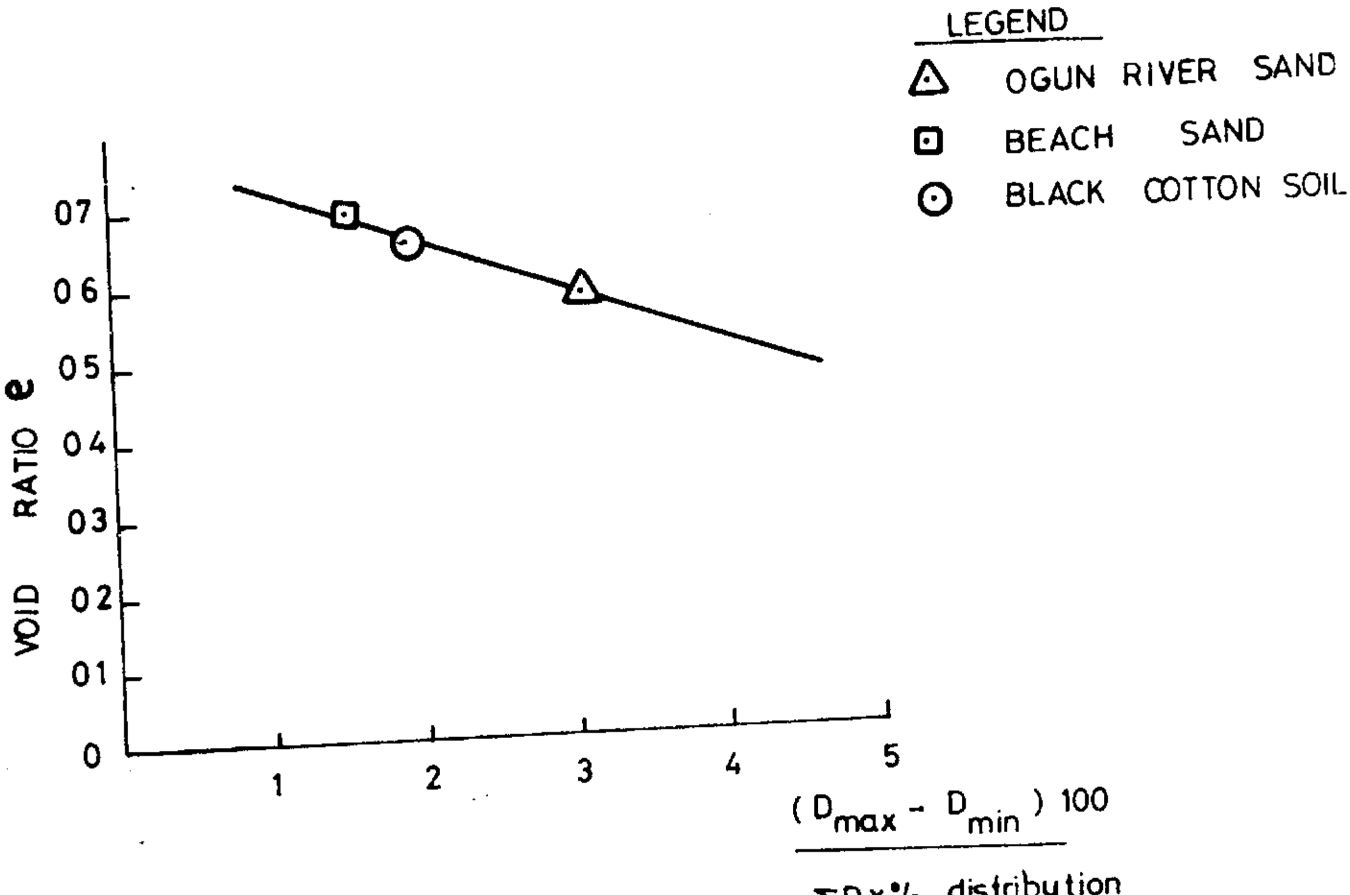

FIG. 6·51: GRAPH OF VOID RATIO, e VERSUS $\frac{(D_{max}-D_{min})\,100}{\Sigma D \times \%\ \text{distribution}}$

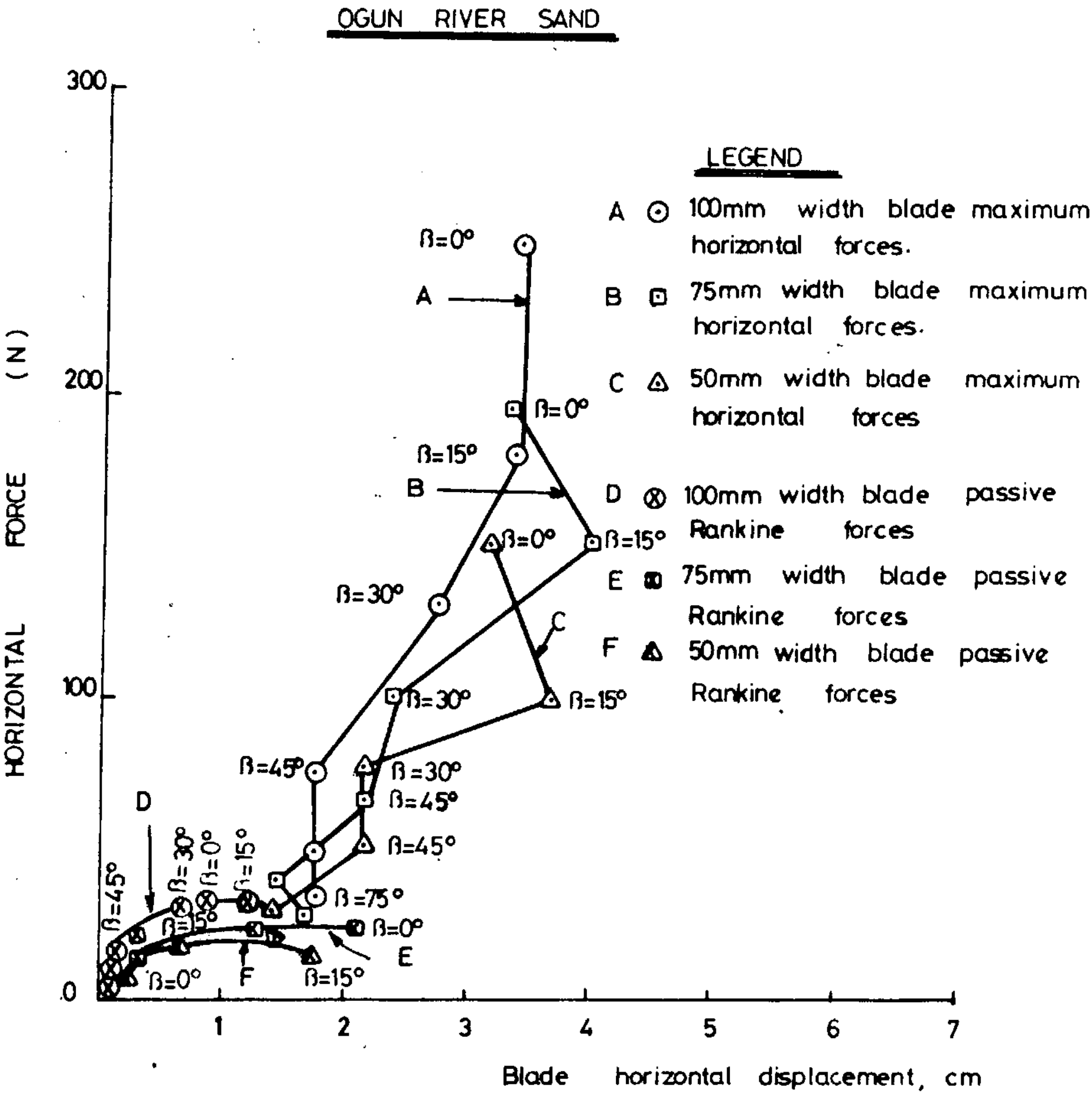

FIGURE. 6·52 : GRAPHS OF PASSIVE RANKINE FORCES AND MAXIMUM HORIZONTAL FORCES VERSUS BLADE HORIZONTAL DISPLACEMENT.

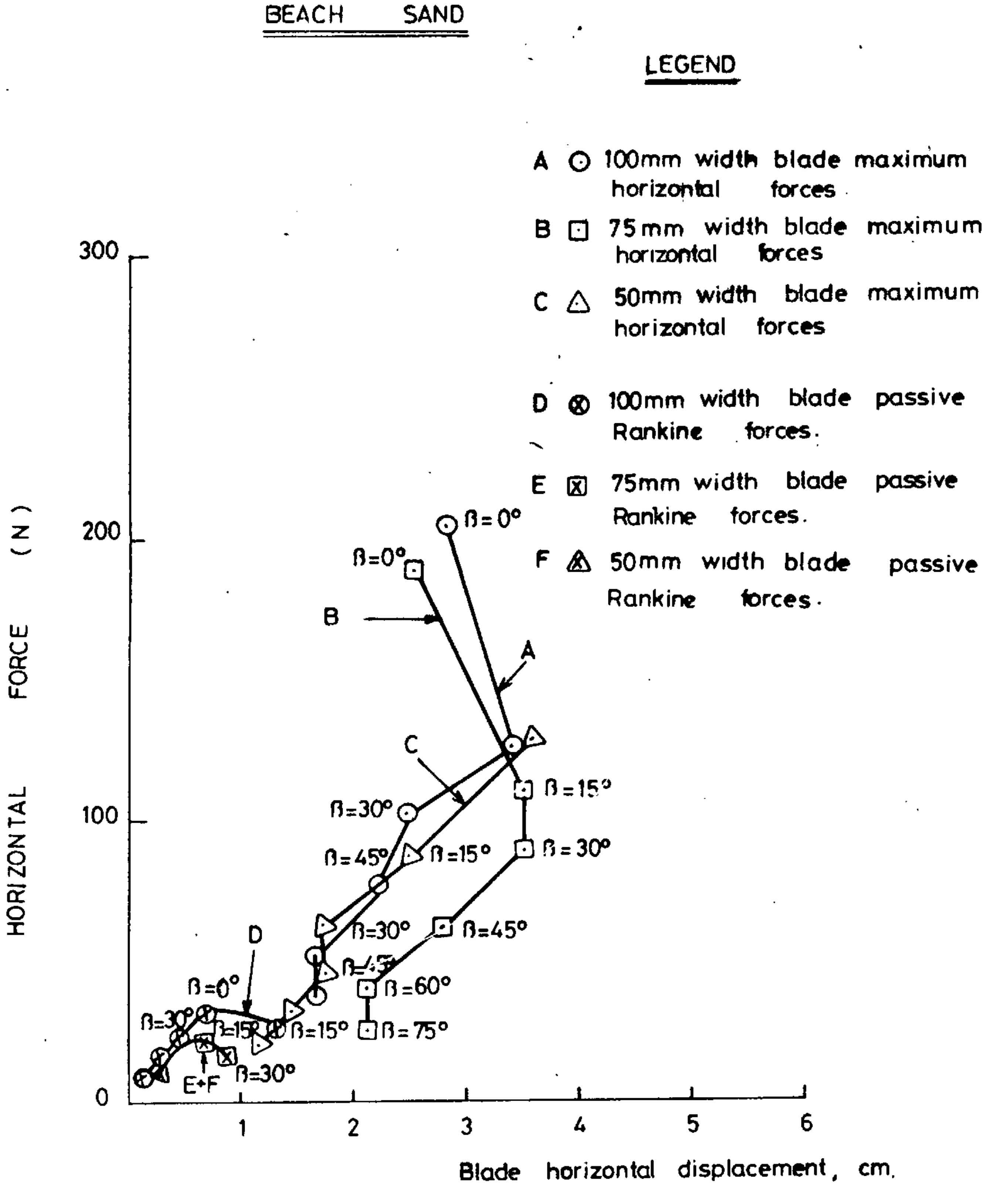

FIGURE. 6·53 :- GRAPHS OF PASSIVE RANKINE FORCES AND MAXIMUM HORIZONTAL FORCES VERSUS BLADE HORIZONTAL DISPLACEMENT.

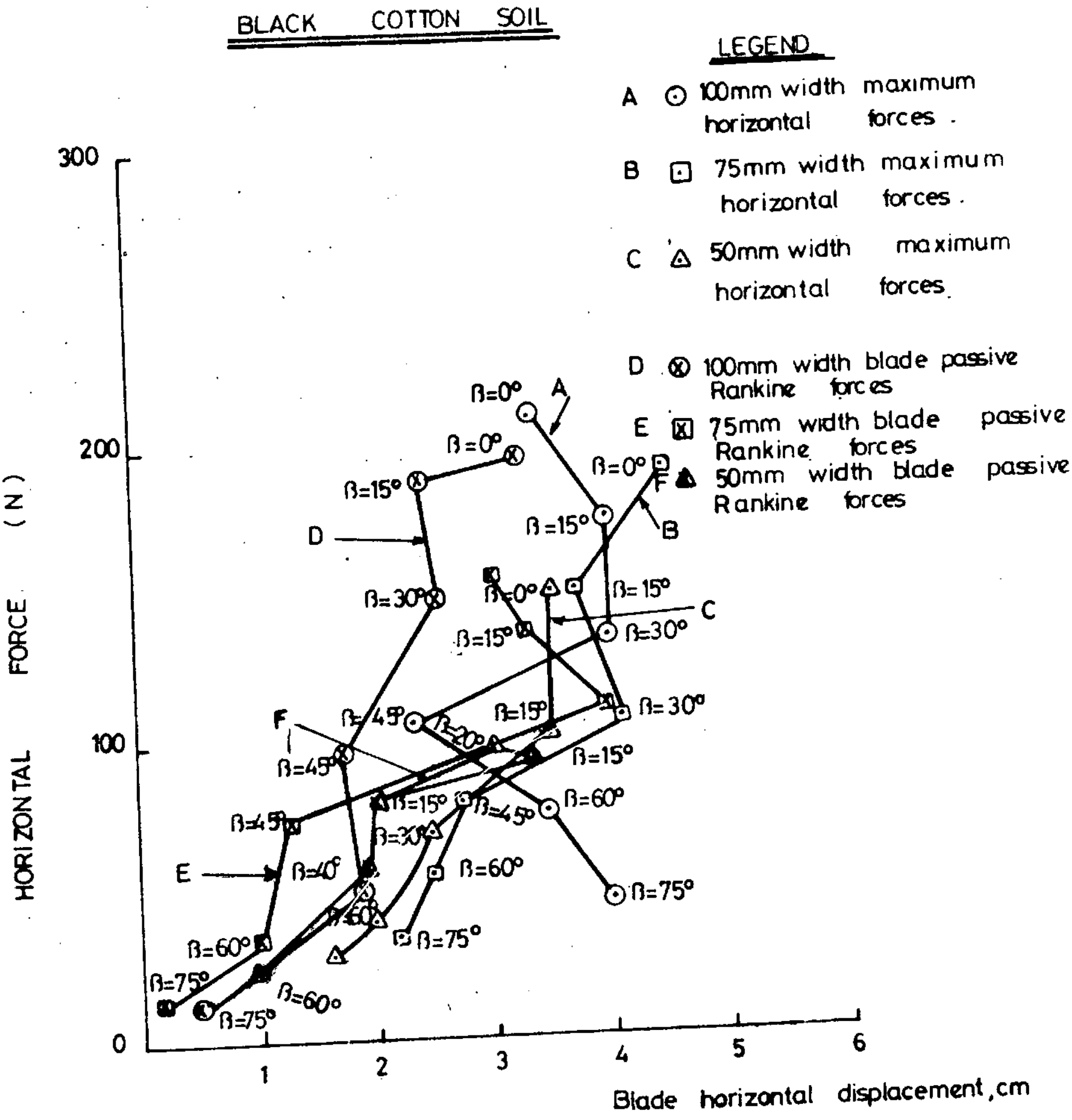

FIGURE. 6.54: GRAPHS OF PASSIVE RANKINE FORCES AND MAXIMUM HORIZONTAL FORCES VERSUS BLADE HORIZONTAL DISPLACEMENT.

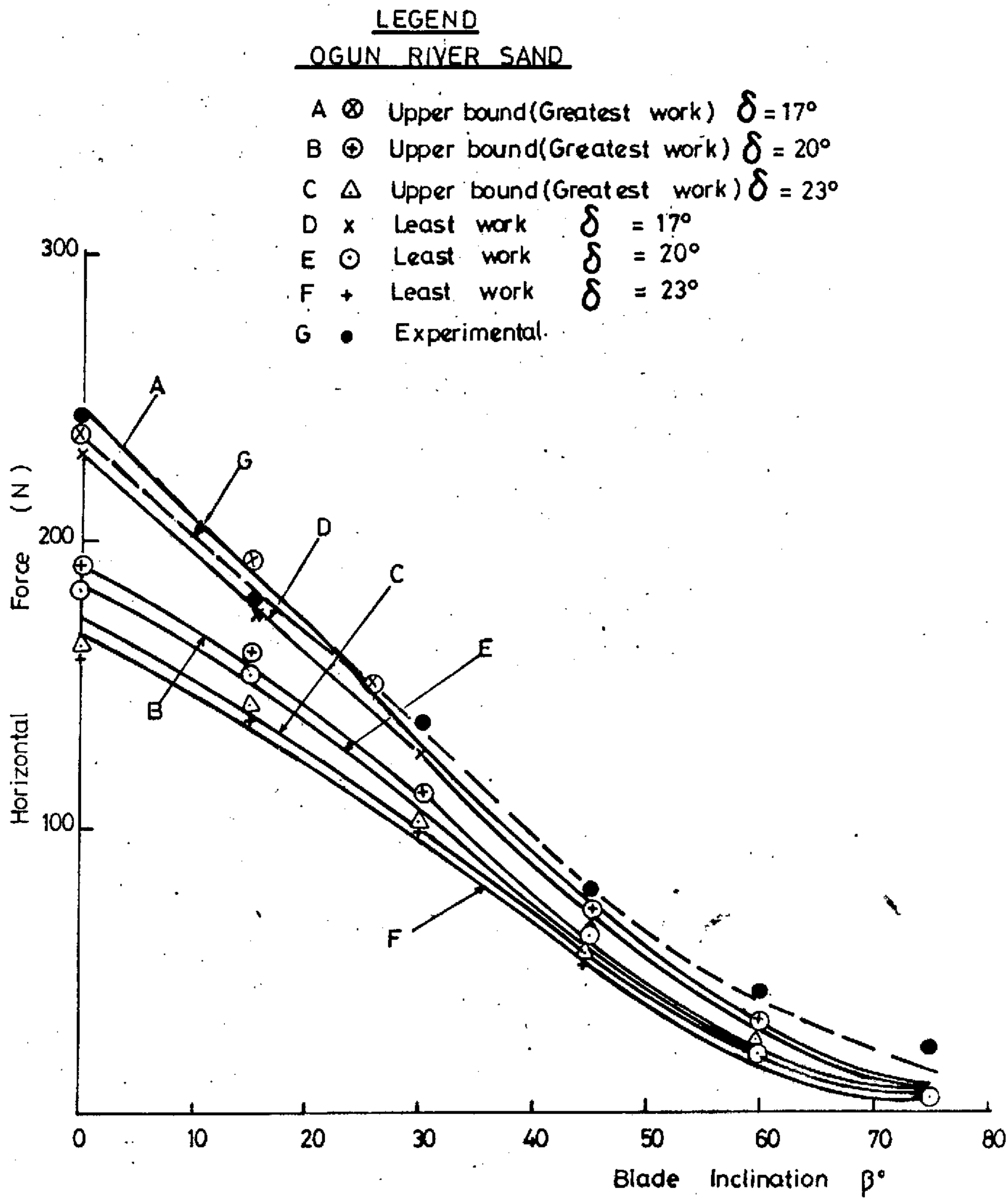

FIGURE. 6.55 :- GRAPH OF HORIZONTAL FORCE VERSUS BLADE INCLINATION β° WITH VARYING SOIL-BLADE FRICTION δ° FOR OGUN RIVER SAND (BOUNDARY ENERGY THEORY)

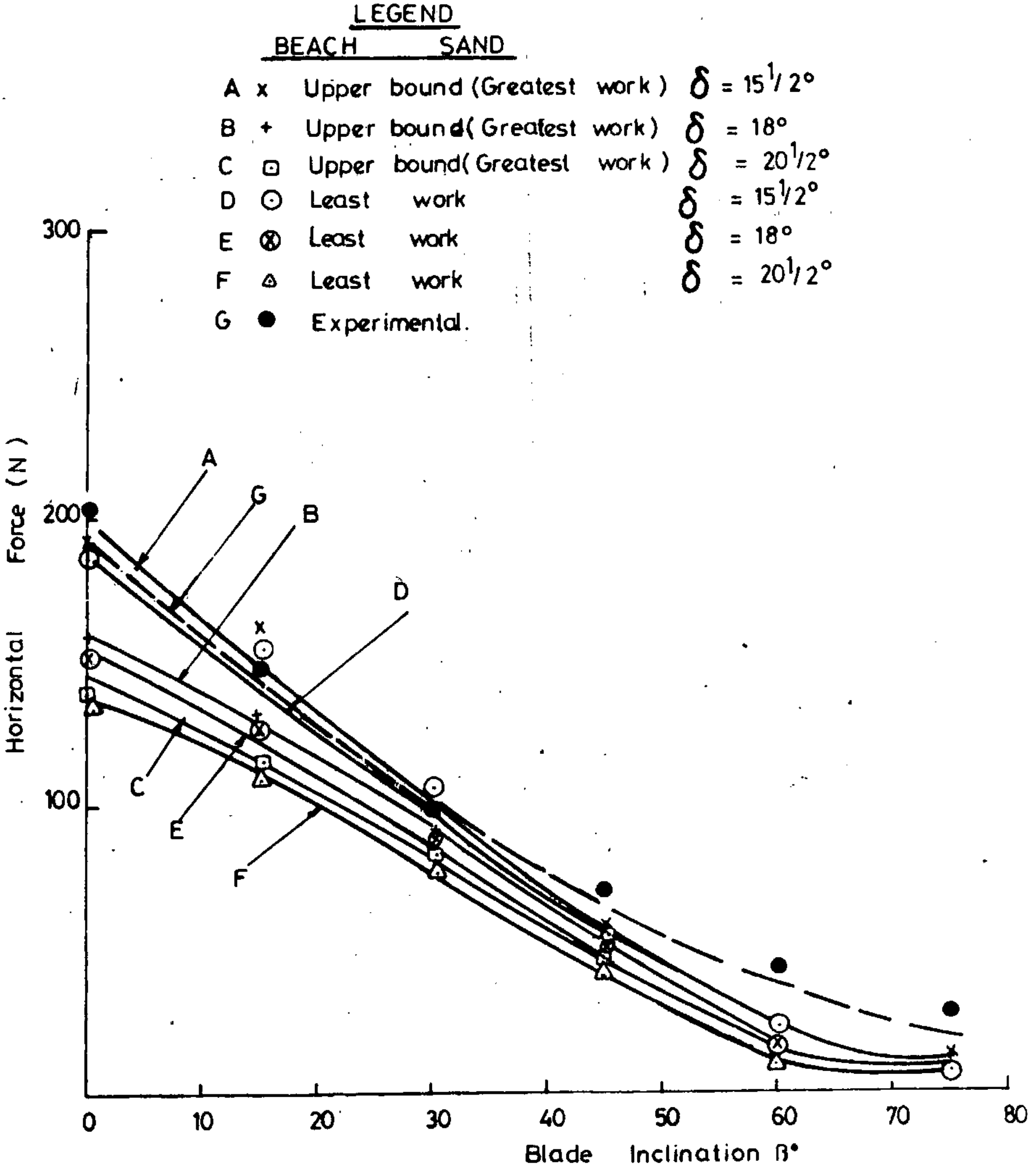

FIGURE 6·56 : GRAPHS OF HORIZONTAL FORCE VERSUS BLADE INCLINATION β° WITH VARYING SOIL-BLADE FRICTION δ° FOR BEACH SAND (BOUNDARY ENERGY THEORY)

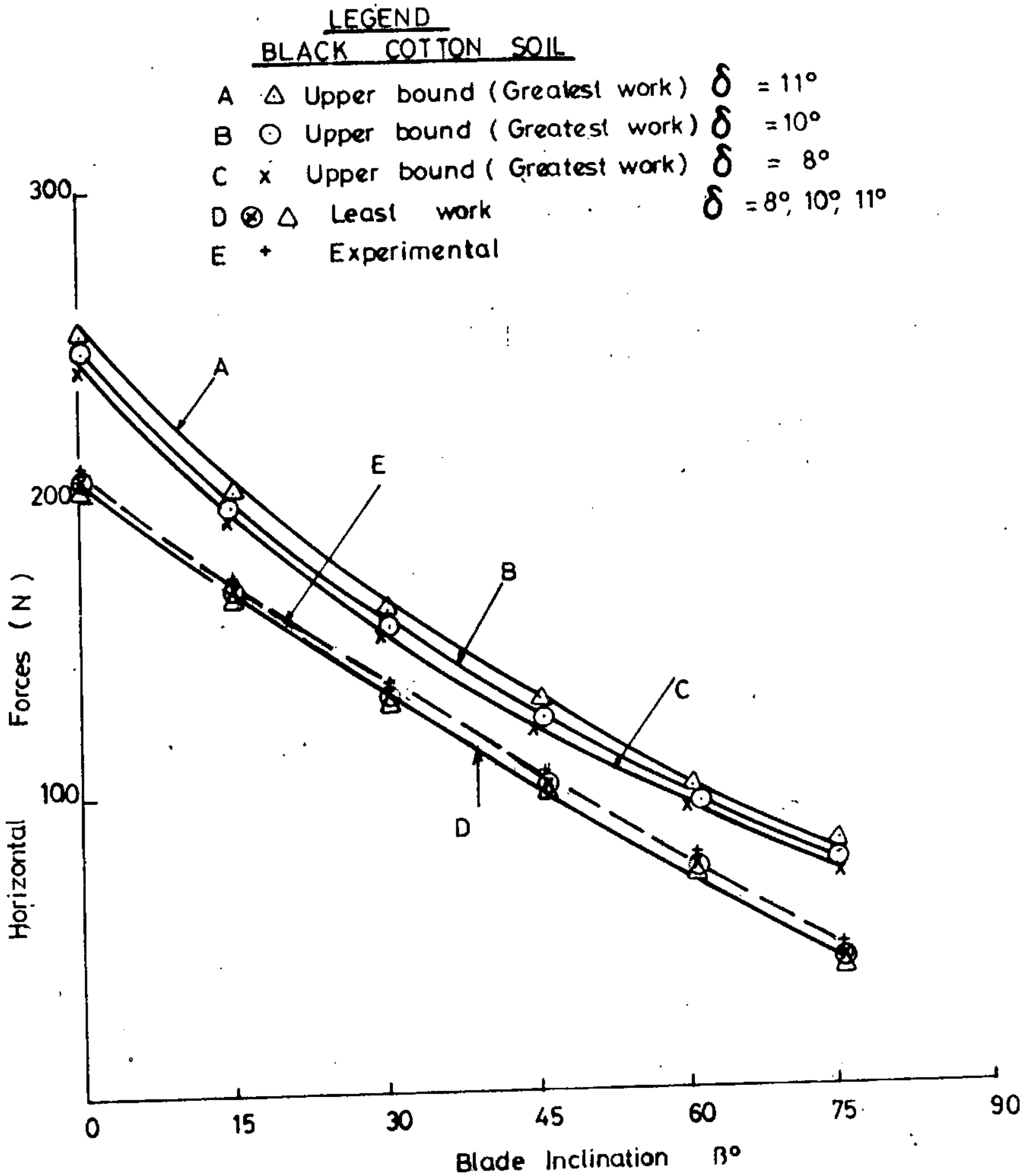

FIGURE 6.57 - GRAPH OF HORIZONTAL FORCE VERSUS BLADE INCLINATION β° WITH VARYING SOIL-BLADE FRICTION δ°, FOR BLACK COTTON SOIL (BOUNDARY ENERGY THEORY)

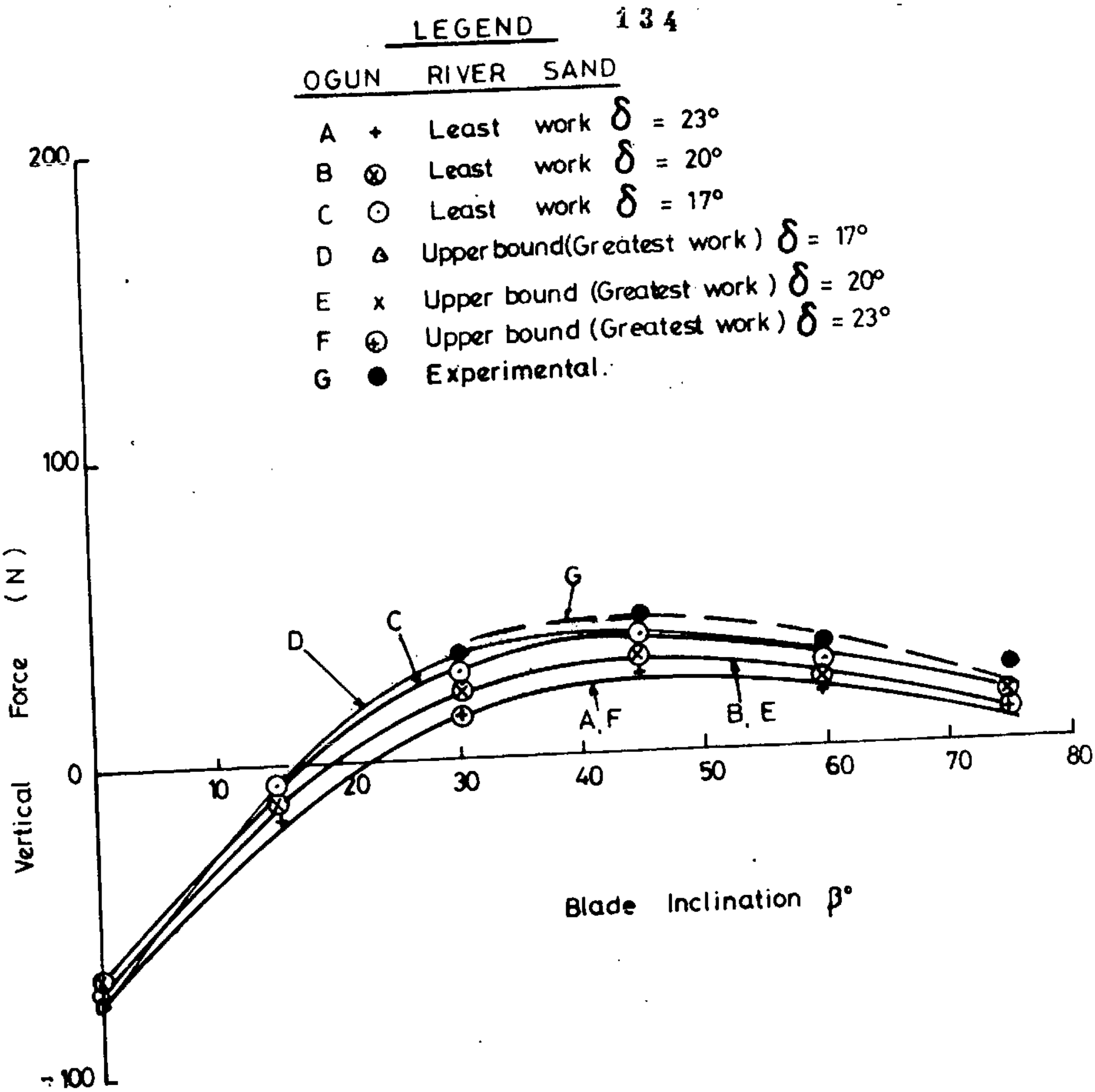

FIG. 6·58: GRAPH OF VERTICAL FORCE VERSUS BLADE INCLINATION β° WITH VARYING SOIL-BLADE FRICTION δ° FOR OGUN RIVER SAND (BOUNDARY ENERGY THEORY)

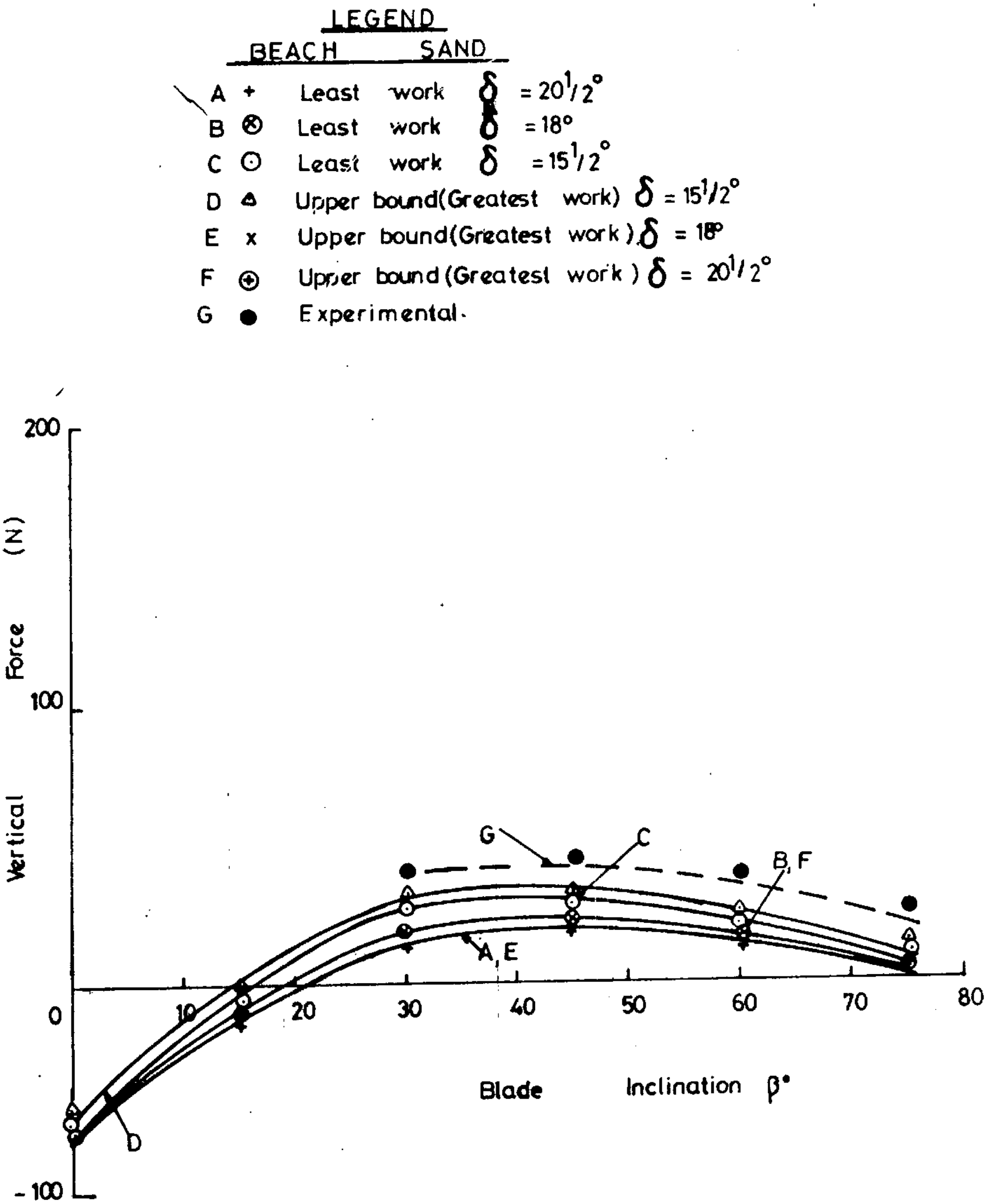

FIG. 6·59 : GRAPH OF VERTICAL FORCE VERSUS BLADE INCLINATION β° WITH VARYING SOIL-BLADE FRICTION δ° FOR BEACH SAND (BOUNDARY ENERGY THEORY)

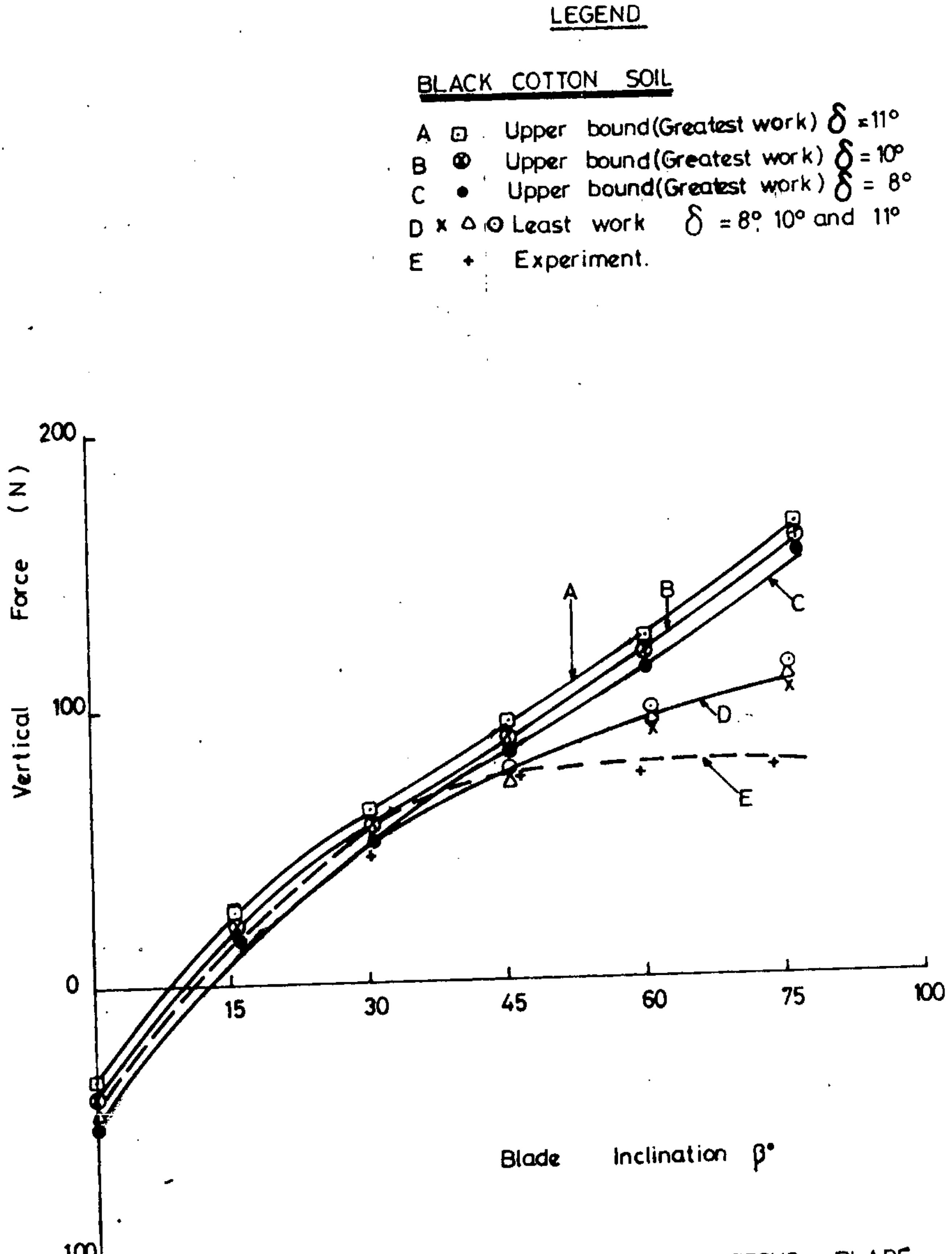

FIG. 6.60 : GRAPH OF VERTICAL FORCE VERSUS BLADE INCLINATION β° WITH VARYING SOIL BLADE FRICTION δ°, FOR BLACK COTTON SOIL (BOUNDARY ENERGY THEORY)

CHAPTER 7

7. Discussion of Results

In order to predict accurately the horizontal and vertical components of the operative forces in soil cutting, it is essential that some specific properties of the soil be known. The shear parameters cohesion C, and mobilised angle of friction ϕ, were substituted into equations derived by all the theories, and the resulting equations were numerically solved. The boundary energy theory is the most accurate of all the theories in predicting the horizontal and vertical components of forces in soil cutting. At a blade inclination of $\beta = 30^{o}$, the theoretical and experimental horizontal components of forces taken in pairs for Ogun river sand were (126 N, 130 N). Whilst for beach sand and black cotton soil, at the same blade inclination, the values were (101 N, 100 N) and (135 N, 135 N) respectively. The theoretical and experimental vertical components of forces taken in pairs at blade inclination $\beta = 30^{o}$, for Ogun river sand were (29 N, 37 N). Whilst for beach sand and blach cotton soil, at the same blade inclination, these values were (27 N, 40 N) and (55 N, 58 N) respectively. (See Tables 6.7 - 6.12). After some practice and timing it was able to achieve the rate of application of 0.11 cm/sec, with smooth movement of the hydraulic jack plunger. This movement gave consistent results. Edge effects were neglected, since the corners of the soil bin are not within the area of influence of the failure plane and are therefore neglected by other researchers and in this work.

A simple practicability of the test, is its usefulness in the design of hoes, for farmers, with blade inclinations $\beta = 57^o$ and 45^o to give optimal performance in cohesionless and cohesive soils respectively. The result of the tests will also help in the design of soil cutting implements like ploughs, harrows and cultivating equipments to cope with cohesioness soils and cohesive soils. It will also help in the design of the shape and type of material used for the soil engaging implements. The soil properties like cohesion C and angle of internal friction ϕ, and void ratio e, affect the design of soil implements, by resisting more force. Knowing the range of resistance, the implements can be designed to cope with the induced bending moments. This work can also be applied to design of shear studs for heavy duty tyres of tractors, graders, and bulldozers by reducing slips and hence increase the performance of these vehicles. A military application of this work is in the design of grouser tracks for armoured vehicles and military tanks, for greater mobility of these vehicles in difficult terrain.

7.1- Vertical Blade Movement into Soil

The stress of soil with cohesion and angle of internal friction, in a state of incipient failure according to Coulomb's criterion gives

$$\sigma_1' = 2c \tan(45^\circ + \frac{\phi}{2}) + \sigma_3' \tan^2(45 + \frac{\phi}{2})$$

$$= 2c \sqrt{N_\phi} + \sigma_3' N_\phi \qquad (7.1)$$

From the Mohr diagram in Figure 6.49, the passive Rankine stress is therefore expressed as follows:

$$\sigma_p' = 2c \sqrt{N_\phi} + \gamma d N_\phi \qquad (7.2)$$

The passive force H_p is written as follows:

$$H_p = \tfrac{1}{2}\gamma b d^2 [\tan(45^\circ + \frac{\phi-\beta}{2}) + \tan\beta]^2 \cos\beta + \frac{cbd \cos\phi}{\cos^2(45+\frac{\phi-\beta}{2})}$$

(Tsytovich, 1987) (7.3)

For blade at inclination $\beta = 0^\circ$, the maximum horizontal force in soil cutting is expressed in terms of the product of K factors and passive force acting on the blade as follows:

$$H = Kb(\tfrac{1}{2}\gamma d^2 \tan^2(45^\circ + \frac{\phi}{2}) + 2cd\tan(45^\circ + \frac{\phi}{2})) \qquad (7.4)$$

For Ogun river sand, for a blade width of 100mm, blade inclination $\beta = 0^\circ$, angle of internal friction $\phi = 34^\circ$, and maximum horizontal force of 250 N, the value of K was found to 7.5. Similarly the value of K for beach sand and black cotton soil, at same blade width and blade inclination were found to be 7.0 and 1.06 respectively. There was no appreciable difference between the K values for the cohesionless soils. The significance of K is that a design engineer can quickly estimate the maximum horizontal component of force acting on a vertical blade during soil cutting, by multiplying the passive Rankine force by the K value of the soil. The K factors at various blade inclinations β^0, are as shown in Tables 6.14 - 6.16. The K factors at blade inclination $\beta = 75^o$, for Ogun river sand, beach sand and black cotton soil, were higher than those at blade inclinations $\beta < 75^o$. This was due to friction in the vertical carriage at blade inclination $\beta = 75^o$. The vertical carriage was greased by silicon grease.

7.1.1 Inclined Blade Movement into Soil

There is an almost a linear relationship between maximum horizontal force and the aquare of depth of cut (see Figure 6.30). The maximum horizontal force acting on the blade can then be written as follows:

$$H - H_o = S\gamma d^2 \qquad (7.5)$$

The coefficient of force transmission S can be derived from the maximum horizontal force versus square of depth of cut relationship of the particular soil as follows:

$$S = \frac{\text{Grad}\left(\frac{H}{d^2}\right)}{\gamma} \qquad (7.6)$$

The coefficient of force transmission S for Ogun river sand, beach sand and black cotton soil were 65.68cm, 55.42cm, and 86.26cm respectively. The horizontal component of force during soil cutting is therefore derived by substituting the appropriate value of S in equation (7.5).

7.1.2 Effect of keeping Blade Width Constant and Varying the Blade Inclination β^0, on Tool Performance

The maximum horizontal forces decreased rapidly from $\beta = 0^o$ to 40^o, and that the rate of decrease reduced considerably such that at about $\beta = 75^o$ the curve tends to flatten out (see Figure 6.16). This indicates that at large blade inclination $\beta = 75^o$ the cutting performance of the blade is low. This trend was observed by Yong and Hanna (70, 1977). The passive force in equation (7.3) varies with blade inclination β^0. This shows that the passive force decreases with increase in blade inclination β^0.

7.1.3 Effect of Constant Tool Angle β^0, and Variable Tool Width, on Tool Performance

The maximum horizontal force for the same blade inclination β^0 varies with the blade width, that is, the greater the blade width, the higher the horizontal force (see Figures 6.10 - 6.12). For example at a blade inclination of $\beta = 45^o$, the ratio of the maximum horizontal force of a blade width of 75mm to the maximum horizontal force of a blade width of 100mm was 86.6% for Ogun river sand. The ratio of maximum horizontal force of the blade width of 50mm to maximum horizontal force for a blade width of 100mm for same material and blade inclination was 60%. Similarly the force ratios of 75mm and 50mm width blades for beach sand and black cotton soil, taken in pairs were (80%, 60%) and (75.1%, 52.3%) respectively.

The graphs as shown in Figures 6.31 to 6.33 did not pass through the origin due to edge effect.

At a constant blade inclination β^0, the maximum horizontal force varied almost linearly with the ratio of blade width and depth of cut (see Figures 6.31 - 6.33). At a blade inclination $\beta = 0^o$, the slope was maximum. As the blade inclination increased, the slope decreased until at $\beta = 75^o$ the slope became small. For example the slope at a blade inclination of $\beta = 0^o$ was 61^o, and at a blade inclination $\beta = 75^o$, was 5^o for Ogun river sand. Similarly for beach sand and black cotton soil the slopes taken in pairs for $\beta = 0^o$ and $\beta = 75^o$ were (60^o, 5^o) and (44^o, 5^o) respectively (see Table 6.13). The significance of these results is that for small blade inclinations, the ratio of width of blade to depth of cut influences appreciably the maximum horizontal force acting on the cutting blade. The influence of the ratio of width of blade to depth of cut decreases as the blade inclination β^0 increases. A design engineer can choose the slope of the width of blade to depth of cut ratio, and estimate the blade inclination to suit the maximum horizontal component force required to be developed.

The graphical relationshp of $\frac{\Delta\ Hd}{100W}$ versus $\frac{1}{d}$ (see Figure 6.34), is valid for both cohesionless soils and cohesive soils, used in this study. At $\frac{1}{d} < 0.1$ the curve was almost linear with an obtuse slope. It was closer to the ordinate axis as $\frac{1}{d}$ decreased. At $\frac{1}{d} > 0.1$ the curve decreased rapidly with increase in $\frac{1}{d}$, and at $\frac{1}{d}$ equal to aboout 2.9cm the curve reached a minimum. At this depth of cut, the inclination of the blade β^0 was about 73^O. This angle can be regarded as the maximum inclination of the blade to produce a cutting effect since the blade is within the passive Rankine zone. The passive Rankine zone inclination $(45^O + \phi/2)$ to the vertical for Ogun river sand was 62^O. The passive Rankine zone inclinations to the vertical, for beach sand and black cotton soil were $60\frac{1}{2}^O$ and 53^O respectively. It can be seen from Table 6.14 that for a 100mm width blade, the maximum horizontal component of force acting on the blade with $\beta = 30^O$ for Ogun river sand occurred at a horizontal blade displacement of 2.75cm. Whereas the passive Rankine force was mobilised at a horizontal blade displacement of 0.6cm. Wall displacement at passive failure was 0.017cm (Terzaghi, 1947). Similarly at same blade inclination, the maximum horizontal component of force and passive Rankine force for beach sand and black cotton soil occurred at horizontal blade displacements taken in pairs of (2.5cm, 0.4cm), (4cm, 2.6cm) respectively. Wall displacements at passive failure for beach sand and black cotton soil were 0.017cm and 0.26cm respectively (Terzaghi, 1947). Passive failure was fully mobilised in soil cutting. At a blade width of 100mm and inclination of $\beta = 73^O$, the calculated horizontal force components for Ogun river sand, beach sand, and black cotton soil were 47.6N, 47.6N and 60.1N respectively.

7.1.4 Effect of Soil Type on Maximum Horizontal Force

The shear strength at failure is expressed as follows:

$$\tau = k \exp\left(\frac{-e}{\lambda}\right) + \sigma' \tan \phi \quad \text{(Hvorslev, 1922)} \qquad (7.7a)$$

where

$$k = k_o \exp(-\frac{e_o}{\lambda}) \qquad (7.7b)$$

From the mathematics of averages applied to sieve analysis

$$\sum_{i=0}^{n} D_i p_i = \bar{p}\,(D_n - D_o)$$ (Sokolnikoff and Redheffer, 1982) (7.8)

Applying this to sieve analysis test (see Figure 6.2), equation (7·8) can be written as follows:

$$\sum_{i=0}^{n} D_i p_i = (D_{max} - D_{min})\bar{p} \qquad (7.9)$$

The stress τ acts along the slip line and the reaction R acts at an angle ϕ to the perpendicular to the slip plane. The stress along the passive Rankine interface is $\sigma_o\, e^{2\theta\tan\phi}$ (Kötter, 1903). Resolving the forces in the passive Rankine zone in a direction perpendicular to R, the following expression is derived as follows:

$$\sigma_o = \sec\,(45 - \frac{\phi}{2})\,e^{-(\frac{\pi}{4} + \phi)\tan\phi}\,(k \exp(-\frac{e}{\lambda}) \cos\phi + \sigma' \sin\phi) \qquad (7.10)$$

Since the void ratio e decreases as

$$\frac{(D_{max} - D_{min})\ 100}{\Sigma D \times \%\ \text{distribution}}$$ increases (see Figure 6.51; then

combining this relationship with equations (7.9) and (7.10) noting that the stress σ_o acts on effective area A_e, the following expression is derived as follows:

$$H = \bar{p}A_e \sec(45^o - \frac{\phi}{2}) e^{-(\frac{\pi}{2}+\phi)\tan\phi} \frac{(D_{max} - D_{min})\ 100}{\Sigma D \times \%\ \text{distribution}}$$

$$\times (k \exp(-\frac{e}{\lambda}) \cos\phi + \sigma' \sin\phi) \qquad (7.11)$$

The term $\sigma' \sin\phi$ can be neglected when ϕ is zero or small. The stress σ' is difficult to measure and can be neglected (Hvorslev 1922).

An empirical relationship between horizontal component of force, voids ratio, blade width, depth of cut, and particle size distribution is therefore written as follows:

$$H = K\gamma\, b^m d^n \exp(-e) \exp \left| \frac{(D_{max} - D_{min})\ 100}{\Sigma D \times \%\ \text{distribution}} \right|^a \qquad (7.12)$$

The value of a is $\pm$ 0.025 for all the soil types (see Figure 6.35). A value of 1 is assigned to m, since the values of m, for Ogun river sand, beach sand, are close to 1 (see Figures 6.36 and 6.37). The value of m, for black cotton soil is 0.6 (see Figure 6.38). The value of n is 2, for all the soil types (see Figure 6.39). The value of K is 5.5, for all the soil types (See Figure 6.40), but there is an horizontal force intercept of 18N, for black cotton soil, and zero intercept for Ogun river sand and beach sand respectively. The empirical relationship for the horizontal component of force at failure for Ogun river sand and beach sand is written as follows:

$$H_1 = 5.5\gamma bd^2 \exp\left\{\left|\frac{(D_{max} - D_{min})\ 100}{\Sigma D \times \%\ \text{distribution}}\right|^{0.025} - e\right\} \quad (7.13a)$$

Similarly the empirical relationship for the horizontal component of force at failure for black cotton soil is written as follows:

$$H_2 = 5.5\gamma bd^2 \exp\left\{\left|\frac{(D_{max} - D_{min})\ 100}{\Sigma D \times \%\ \text{distribution}}\right|^{0.025} - e\right\} + 18N \quad (7.13b)$$

This empirical relationship is advantageous to the design engineer, who can quickly estimate the horizontal component of force at failure during soil cutting.

7.1.5 Effect of Constant Blade Width and Variable Blade Inclination β^0, on Maximum Vertical Forces

The vertical components of force attained peak values after small horizontal displacement of the blade (see Figures 6.5, 6.7 and 6.9). The maximum vertical force for a blade width of 100mm and $\beta = 45^o$, was 47.5N at a blade displacement of 1.1cm, for Ogun river sand. Similarly for the same blade width and blade inclination, the maximum vertical components of force were 50N at a blade displacement of 2.2cm for beach sand, and 71.5N at a blade displacement of 2.4cm for black cotton soil. Substituting equation (3.14) in equation (7.13a) noting that $H_1 = H_H$ gives the following relationships for vertical force H_{v1} for Ogun river sand and beach sand.

$$H_{v1} = \left(5.5\gamma bd^2 \exp\left[\left|\frac{(D_{max} - D_{min})\ 100}{\Sigma D \times \%\ \text{distribution}}\right|^{0.025} - e\right\}\right) \times \tan(\beta - \delta) \quad (7.14a)$$

Similarly sustituting equation (3.14) in equation (7.13b), gives the following relationships H_{v2} for black cotton soil.

$$H_{v2} = (5.5\gamma bd^2 \exp \left\{ \left| \frac{(D_{max} - D_{min})\ 100}{\Sigma D \times \%\ distribution} \right|^{0.025} - e \right\} + 18N) \tan (\beta - \delta) \qquad (7.14b)$$

The vertical force for Ogun river sand for blade width 100mm and $\beta = 45^{o}$ was 45.2N. The vertical forces for beach sand and black cotton soil were 45.3N and 79.1N respectively. The empirical formula predicted vertical forces close to the measured vertical forces.

7.1.6 Effect of Blade Width on Maximum Vertical Force

At a given angle of blade inclination β^{o}, horizontal and vertical components of force increased with increase in the width of blade. The ratio of the maximum vertical components of force of 75mm width blade at inclination $\beta = 45^{o}$, and 100mm width blade at same inclination was 84.2%. Similarly the ratio of the maximum vertical component of force of 50mm and 100mm width blade at same inclination was 68.8%. At same blade inclination, the ratio of the maximum vertical components of force of 75mm width blade, and also of 50mm width blade to 100mm width blade, taken in pairs for beach sand and black cotton soil were (80%, 60%) and (76.9%, 66.4%) respectively. When m = 0.91 is substituted in equation (7.14a), the ratio of the maximum vertical component of force of 75mm width blade at inclination $\beta = 45^{\circ}$, and 100mm width blade at same inclination was 77%. Similarly the ratio of the maximum vertical component of force of 50mm and 100mm width blade at same blade inclination was 53%. At same blade inclination the ratio of the maximum vertical components of force of 75mm width blade, and also of 50mm width blade to 100mm width blade, taken in pairs for beach sand (m = 0.9) and black cotton soil (m = 0.6) were (77.1%, 53.0%) and (83.9%, 65.5%) respectively. This followed a similar trend by the maximum horizontal component of forces.

7.1.7 Effect of Soil Type on Vertical Component on Force

For black cotton soil, the maximum vertical force decreased gradually with increase in the maximum horizontal force, until at a blade inclination $\beta = 45^{0}$, it decreased more steeply as the blade inclination β^{0} decreased (see Figure 6.41). The maximum vertical force for a blade width of 100mm and blade inclination $\beta = 75^{\circ}$ and $\beta = 45^{\circ}$, were 77.5N and 71.5N respectively. However the value decreased to 25N for a blade inclination $\beta = 15^{\circ}$. For Ogun river sand and beach sand, the maximum vertical force increased with increase in maximum horizontal force, for the blade inclination $\beta = 75^{\circ}$ to $\beta = 45^{\circ}$. Thereafter as the blade inclination decreased, the maximum vertical force decreased (see Figure 6.41). This followed the same trend as predicted by equation (3.14). The maximum vertical force for a blade inclination $\beta = 75^{o}$ and $\beta = 45^{o}$ were 30N and 47.5N respectively. However the value decreased to 37.5N for a blade inclination $\beta = 30^{o}$. For beach sand the maximum vertical force for blade inclination $\beta = 75^{o}$ and $\beta = 45^{o}$ were 25N and 50N respectively. Whilst the value for a blade inclination $\beta = 30^{o}$ was 40N. Similar trends were observed in the relationships between the maximum vertical and the maximum horizontal forces, for blades widths of 75mm and 50mm respectively (see Figures 6.42 and 6.43). At a maximum horizontal force of 135N, black cotton soil and Ogun river sand developed maximum vertical forces of 58N and 37.5N respectively at a blade inclination of about $\beta = 30^{o}$ (see Figure 6.41). This was due to the fact that the soil blade friction δ^{o} of black cotton soil is less than that of Ogun river sand, and therefore it developed higher vertical force (see Equation (3.14)). This shows that the model of boundary energy theory is close to the behaviour of soils in soil cutting.

7.1.8 Optimum Performance of Soil Cutting Blade

For a blade width of 100mm, the energy per unit volume for Ogun river sand initially decreased as the depth of cut increased, until a maximum value of 0.065N cm/cm^{3} was reached at a depth of cut 5.4cm. Beyond this point the energy per unit volume increased with depth of cut (see Figure 6.44). Similarly a minimum energy per unit volume for beach sand was 0.105N cm/cm^{3} at a depth of cut of 5.4cm. The minimum energy per unit volume for black cotton soil was 0.281N cm/cm^{3}, at a depth of cut of 7.1cm. At these depths of cut associated with minimum soil cutting energies per unit volume, the optimum performance of the blades occurred at blade inclination $\beta = 45^{o}$ for black cotton soil, and at a blade inclination $\beta = 57^{o}$ for Ogun river sand and beach sand. It was also observed from Figures 6.. and 6.7, that $\beta = 45^o$ defines the inclination of maximum vertical force for Ogun river sand and beach sand. From Figure 6.9, $\beta = 60^o$ defines the inclination of maximum vertical force for black cotton soil for acute β^0.

7.2 Comparison of Different Theories with Experimental Results

Horizontal forces were evaluated using boundary energy method, for soil-blade friction δ^o varying from $\frac{1}{2}\phi$ to $\frac{2}{3}\phi$ (values generally used in soil mechanics). The horizontal component of force depended on the soil-blade friction δ^o, for Ogun river sand (see Figure 6.18). Similar trend was observed for beach sand (see Figure 6.19). However there was a negligible variation of horizontal component of force with soil-blade friction δ^o for black cotton soil (see Figure 6.20). Similar trends were observed for vertical forces for Ogun river sand, beach sand and black cotton soil (see Figures 6.21 to 6.23). The soil parameters and blade geometry were substituted in the different theories to obtain the curves of horizontal component of force versus blade inclination β^o (see Figures 6.24 to 6.26), and also curves of vertical component of forces versus blade inclination β^o (see Figures 6.27 to 6.29). It is assumed that the soil-blade friction δ^o mobilised is $\frac{1}{2}\phi$. It can be seen from Figure 6.55, that for friction angle $\delta = 17°$, which is $\phi/2$, the horizontal forces as derived from the boundary energy theory (least work) are closest to the experimental values.

An accurate prediction of both the horizontal and vertical components of forces is important for safety and economy and also in the design of mechanical linkages and connections of soil engaging implements to cater for the induced bending moments.

7.2.1 Maximum Horizontal Component of Force

The theoretical curves are drawn in order of improvement of the theories. It is observed that Boundary Energy theory gives the closest values to experimental curves for all the soil types.

7.2.2 Maximum Vertical Component of Forces

The theories developed by various researchers were again drawn in order of improvement. The Boundary Energy theory appears to have the closest values to experimental results. The Boundary Energy theory therefore appears to be the most appropriate theory in predicting both the maximum horizontal and the vertical components of forces in soil cutting.

7.3 Pull Out Capacity of Vertically Loaded Horizontal Plate Uplift Ground Anchors and Soil Cutting

The resistance of the soil to movement of the plate, acting normally to the plate could result in the following:

(1) $\beta = -90^{o}$: bearing capacity of shallow foundation.

(2) $-90^{o} < \beta < 0^{o}$: plough blade in reverse, or grain silo discharging its contents through gate.

(3) $\beta = 0^{o}$: passive pressure on retaining wall or horizontally loaded vertical plate ground anchors.

(4) $0^{o} < \beta < 90^{o}$: problem of plough, blade cutting through soil.

(5) $\beta = +90^{o}$: pullout capacity of vertically loaded horizontal plate uplift ground anchors.

By substituting $\beta = +90^{o}$, into the boundary energy theory the vertical force was zero for Ogun river sand and beach sand, but it was 73.6N, for black cotton soil. This compares with the value of 30N obtained from Ballas equation, (1961), and much less than 520N obtained from Byrne (1978), which has suction effect at the base of the plate. The boundary energy equation can therefore be used to predict pullout capacity of horizontal plate where suction effect is absent.

7.3.1 Bearing Capacity of Shallow Foundations

The boundary energy theory can be used to predict the bearing capacity of shallow foundations. For soils with cohesion C and angle of internal friction ϕ, the bearing capacity is the value of the vertical force at blade inclination $\beta = -90^{o}$. The bearing capacity of shallow foundations for cohesionless soils and cohesive soils can generally be predicted by the boundary energy theory by considering the equilibrium of the wedge under the foundation, with wedge angles of $45^{o} + \frac{\phi}{2}$ to the horizontal, in accordance with the theory of plasticity. The bearing capacity, according to Terzaghi, for Ogun river sand was calculated to be 288N, whilst the boundary energy theory gave 300N. Similarly the bearing capacities for beach sand and black cotton soils were 200N and 1391N respectively. Whilst the boundary energy theory gave the bearing capacities for beach sand and black cotton soil as 240N and 1473N respectively.

7.4 Comparison of this Work on Soil Cutting with Work by previous Researchers

This work is similar to work by other researchers in the use of straight blades in the experiments. This is necessary to verify the theory by other researchers and to cross check that it is applicable under different soil types. It is also necessary to check the accuracy of the fabricated soil cutting apparatus, SCA. Applicability of the work to soil engaging implements like tines, requires the use of straight blades with different angles of rake.

This work differs from work by other researchers in the choice of soil type. Artificial soil was used by most researchers. Payne and Tanner (1959) used granite dust mixed with motor oil, to simulate angle of friction ϕ, and cohesion C of the soil. Yong et al. (1969) used plastercine and blended Ottawa sand. The soils used in this work are Ogun river sand, beach sand and black cotton soil. Ogun river sand and beach sand are cohesionless soils, but with different angles of internal friction. These soils were chosen to study the influence of angle of soil friction ϕ, on the horizontal and vertical components of operative forces in soil cutting. Ogun river sand, with soil classification A - 1 (0), coefficient of uniformity 2.40, and coefficient of curvature 1.22, has a mobilised angle of friction of 34^{o}. Beach sand, with classification A - 3 (0), coefficient of uniformity 3.15, coefficient of curvature 1.33, has a mobilised angle of friction of 31^{o}. Black cotton soil, with soil classification A- 7 - 6 (20) was chosen to study the influence of angle of soil friction ϕ and cohesion C on horizontal and vertical components of operative forces in soil cutting. Black cotton soil has a cohesion of 6.9 kN/m^2 and angle of friction of 16^{o}.

This work is to scrutinise theory and experiments by other researchers, in order to formulate a new theory in soil cutting. It is found by this work that the optimum performance of the blades occur at blade inclination β = 57^{o} for cohesionless soils typified by Ogun river sand and beach sand and at $\beta = 45^{o}$ for cohesive soil, typified by black cotton soil. This finding is applicable in the design of soil engaging implements and shallow foundations. The boundary energy theory was formulated to predict accurately the horizontal and vertical components of operative forces during soil cutting.

The length of the soil bin allowed the failure plane to be developed further from the edge of the soil bin, thus making side effects negligible. Apart from the work done by other researchers, of which references were made, in the fundamental basis for this work, the boundary energy theory was synthesized and logically applied to soil cutting. The boundary energy theory was able to predict the operative horizontal and vertical forces in soil cutting. Although energy methods had been applied in engineering analysis,this study shows that boundary energy theory is applicable to soil cutting, and gives good results. Most of the work in soil cutting was on artificial soils and soils in wet conditions. Although there are limitations in the use of air dry Ogun river sand, beach sand, and black cotton soil, as compared with actual field conditions, this work is a pilot study using local materials in soil cutting. Empirical formulae in soil cutting were derived to predict the horizontal and vertical forces in soil cutting. Aluminium blades, develop angle of friction $\delta = \frac{1}{2}\phi$, at the blade soil interface in soil cutting for cohesionless and cohesive soils typified by Ogun river sand, beach and black cotton soil respectively.

CHAPTER 8

8. Conclusion.

It has been found from this study that the soil parameters of cohesion C, and angle of internal friction ϕ, used by Coulomb and Terzaghi are found to be true. The rupture configuration in soil cutting showed that whereas 100% angle of internal friction ϕ, is mobilised at failure for cohesive soils, about 80% angle of internal friction ϕ, is mobilised at failure for cohesionless soils. The parameters, cohesion, and mobilised angle of internal friction were therefore used in evaluating the horizontal and vertical components of operative forces on the blade during soil cutting.

This study also shows that other soil parameters like void ratio e and soil particle size distribution as regards soil particle sizes, fractional gradation and textural classification are also soil index properties which are also true. As a result of these findings, empirical formulae were derived in terms of these soil parameters to evaluate the horizontal and vertical components of the operative forces in soil cutting. This is beneficial and advantageous to design engineers, who can quickly estimate these operative force components.

It is also found by this study that the optimum performance of the blade occurred at a blade inclination $\beta = 57^{o}$ for Ogun river sand and beach sand which are cohesionless soils, but with different angles of internal friction ϕ. Similarly the optimum performance of the blade occurred at a blade inclination $\beta = 45^{o}$ for a cohesive soil of black cotton soil.

The boundary energy theory which considers the kinematics of the soil medium predicts more accurately the horizontal and vertical components of the operative forces in soil cutting, than any other theory hitherto in use.

8.1 Recommendation:

In soil mechanics and code of practice, the soil-metal friction δ^0 is generally assumed to vary from half angle of internal friction ($\frac{1}{2}\phi$) to two thirds angle of internal friction ($\frac{2}{3}\phi$). The lowest value $\delta = \frac{1}{2}\phi$ was assumed in this study for aluminium blades. Although this assumption was found to be correct, further research should be carried out to study in details the effect of blades of varying degree of roughness, hence δ, on the horizontal and vertical components of the operative forces during soil cutting.

Further research should also be carried out using curved blades, and blades with negative inclination, $-\beta^o$, which will help to select the blade geometry for any particular application of soil cutting problems, be it bulldozer, grader, grouser tracts for military amoured vehicles, cultivators, silos, and bearing capacity estimation of foundations. Future work should also be carried out to study the effect of scouring on design and shape of soil engaging parts of the implements in soil cutting.

Further work should be carried out to study the effect of strain rate on the operative horizontal and vertical forces in soil cutting.

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APPENDIX A

Soil Property Tests.

UNIVERSITY OF LAGOS

Soil Mechanics Laboratory

DETERMINATION OF THE NATURAL AND AIR-DRY MOISTURE CONTENT AND THE LIQUID AND PLASTIC LIMITS OF A SOIL

Job:

Date: 16/8/83

Site:

Operator: P. A. Osho

Sample No:

Description of soil: Black Cotton Soil

LL. machine No.

Proportion of sample retained on No. 36 B·S. sieve per cent.

Soil condition: Air dried, Natural, Oven dried, Unknown (delete as necessary).

Number of blows refers to liquid limit determination.

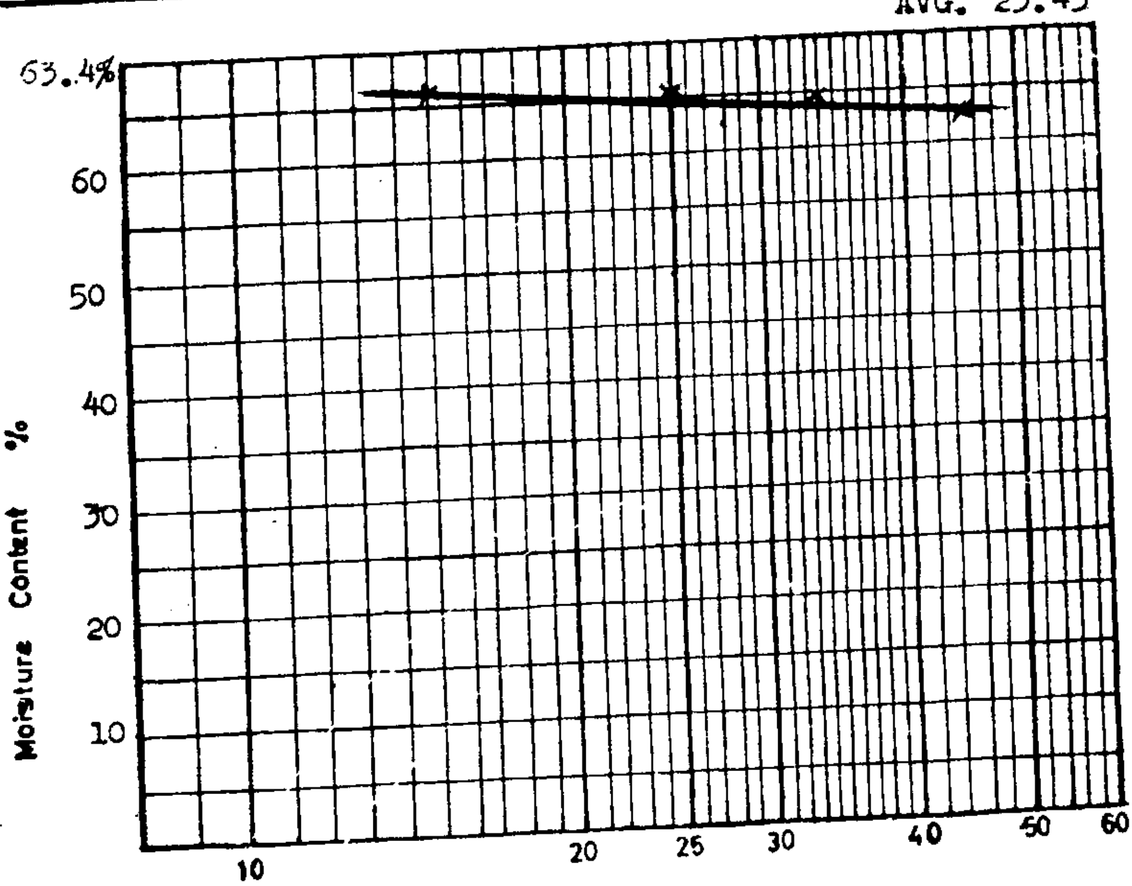
Air-dry moisture content to be marked A. Liquid limit test to be marked LL.

Moisture content test to be marked *m*. Plastic limit test to be marked PL.

Type of test	LL	LL	LL	LL		PL	PL
No. of blows	15	25	34	45			
Container No.	11	40	67	72		44	34
Wt. of wet soil + container g	41.6	41.2	41.7	42.0		34.3	35.0
Wt. of dried soil + container g	36.5	36.1	36.6	37.0		33.4	33.7
Wt. of container g	28.8	28.2	28.7	29.0		29.2	28.6
Wt. of dry soil (W_d) g	7.7	7.8	7.9	8.0		4.2	5.1
Wt. of moisture (W_m) g	5.1	5.1	5.1	5.0		0.9	1.3
Moisture content 100 (W_m/W_d) %	66.2	65.4	65.4	62.5		21.4	25.5

AVG. 23.45

LL = 63.4%



DETERMINATION OF THE SPECIFIC GRAVITY OF SOIL PARTICLES. [STANDARD LABORATORY TEST].

Operator: P. A. Osho　　Date: 5-9/8/83

Temperature of test: 25 °C

Sample No.	Ogun River Sand			Beach Sand			Black Cotton Soil			
Bottle No.										
Wt. of bottle W_1 gm.	548	548		515	515		34.7	34.7		
Wt. of bottle + water [full] W_4 gm.	1415	1415		1375	1375		84.0	84.0		
Wt. of bottle + soil W_2 gm.	1044	1035		1015	1015		59.7	59.7		
Wt. of bottle + soil + water W_3 gm.	1715	1705		1685	1685		98.0	98.0		
Wt. of water to fill bottle $[W_4-W_1]$ gm	867	867		860	860		49.3	49.3		
Wt. of water added to soil $[W_3-W_2]$ gm	671	670		670	670		38.3	38.3		
Wt. of soil $[W_2-W_1]$ gm	496	487		500	500		25.0	25.0		
Wt. of water displaced by soil $W=[W_4-W_1]-[W_3-W_2]$ gm	196	197		190	190		11	11		
specific gravity $G=\frac{[W_2-W_1]}{W}$	2.53	2.50		2.63	2.63		2.27	2.27		

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SOIL MECHANICS LABORATORY

Operator P. A. Osho
Date 19/10/83

Determination of Moisture Content

Test No.	Ogun River Sand			Beach Sand			Black Cotton Soil							
Bore hole No.														
Depth of Sample														
Container No	10	30		63	33		E23	L20						
Wt. of wet soil + Container W1 g	121.1	131		112.6	125.2		86.0	82.0						
Wt. of dried soil + Container W2 g	120.5	130.5		112.5	125.1		83.5	79.7						
Wt. of container W3 g	27.5	28.6		28.0	27.6		36.0	36.0						
Wt. of moisture W1-W2 g	0.6	0.5		0.1	0.1		2.5	2.3						
Wt. of direct soil W2 - W3 g	93.0	101.9		84.5	97.5		47.5	43.7						
Moisture content % - $\frac{W1 - W2}{W2 - W3}$ X 100	0.64	0.49		0.12	0.1		5.26	5.26						

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FINE SIEVE ANALYSIS

DATA AND CALCULATION SHEET

OPERATOR: ....P. A. Oabo.............JOB: ....

DATE: ....25/7/83.......... SAMPLE NO. Ogun River Sand

TOTAL WEIGHT OF SAMPLE: ....1000 g....................

B. S. Sieve	Weight Retained (g)	Percentage Retained	Percentage Passing	Cumulative Percentage Passing
NO 7 2.36	0	0	100	
No. 10 ...	–	–	–	
No. 14 1.18	330	33.4	66.6	
No. 18 ...	–	–	–	
No. 25 600	348	35.2	31.4	
No. 36 425	110	11.1	20.3	
No. 52 300	87	8.8	11.5	
No. 72 212	55	5.6	5.9	
No. 85 ...	–	–	–	
No. 100 150	33	3.3	2.6	
No. 120 ..	–	–	–	
No. 150 ..	–	–	–	
No. 170 ..	–	–	–	
No. 200 75	20	2.0	0.6	
Passing No. 200	5	0.51	0.09	
TOTAL......	988			

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SOIL MECHANICS LABORATORY

FINE SIEVE ANALYSIS

DATA AND CALCULATION SHEET

OPERATOR: P. A. Osho JOB:

DATE: 2/8/83 SAMPLE NO. Beach Sand

TOTAL WEIGHT OF SAMPLE: 1000 g

B. S. Sieve	Weight Retained (g)	Percentage Retained	Percentage Passing	Cumulative Percentage Passing
NO. 7 2.36	0	0	0	
No. 10 . ..	–	–	–	
No. 14 1.18	76.4	7.7	92.3	
No. 18 ...	–	–	–	
No. 25 600	278.0	27.9	64.4	
No. 36 425	164.0	16.4	48.0	
No. 52 300	163.0	16.4	31.6	
No. 72 212	126.3	12.7	18.9	
No. 85 ...	–	–	–	
No. 100 150	98.7	9.9	9.9	
No. 120 ..	–	–	–	
No. 150 ..	–	–	–	
No. 170 ..	–	–	–	
No. 200 75	80.3	8.1	0.9	
Passing No. 200	9.0	0.9	0	
TOTAL......	995.7			

Remoulded to 2.05 mg/m^3

CONSOLIDATED ~~UNDRAINED~~ / DRAINED TRIAXIAL COMPRESSION TEST.

JOB: BEACH SAND

SAMPLE NO: A | TEST NO: A | CELL NO: 20

INITIAL DIMENSIONS

Ave Height (Ho) 76.2 mm
Ave Diameter (Do) 38.1 mm
Volume (Vo) 86.87 c.cm
Wet Density 2.05 mg/c.m

MOISTURE CONTENTS INITIAL FINAL

Wet Weight (gm)
Dry Weight "
Moisture "
Moisture Content %

DATE	TIME	P.W.P GAUGE READING KN/m^2	VOLUMETRIC STRAIN: BURETTE READING C.cm	VOL CHANGE ΔV C.cm	ΔV/Vc %	AXIAL STRAIN: STRAIN DIAL READING	$\epsilon=\frac{\Delta h}{Hc}$ %	APPLIED LOAD (PR No 0.00156KN/div FACTOR): DIAL READING	LOAD KN	CROSS SECTIONAL AREA: $100\pm\frac{\Delta V}{V}$ %	100-ε% %	C.S.A $Ac\frac{100\pm\Delta V}{100-\epsilon\%}$ Sq.cm	$\sigma_1-\sigma_3$ Deviator Stress KN/m^2	σ_1' MAJOR PRIN'L STRESS KN/m^2	σ_3' MINOR PRIN'L STRESS KN/m^2
18/5/84	09.00	0	97.4	0	0	0	0	0	0	100	100	11.34	0	-	50
	10.30		98.0	+0.6	0.71	30	1.01	190	0.29	100.71	98.97	11.54	251.3		50
	11.30		98.2	+0.8	0.94	60	2.02	194	0.30	100.94	97.95	11.68	256.9		50
	12.30		98.4	+1.0	1.18	90	3.03	194	0.30	101.18	96.92	11.84	253.4		50

$\sigma_1-\sigma_3$ = 256.9 - 1.1 = 255.8 KN/M^2

σ_3 = 50.0 - 0 = 50 KN/M^2

σ_f = 255.8 + 50 = 306 KN/M^2

SATURATION STAGE

By Flooding
By Back Pressure
Assumed
B - Value %

CONSOLIDATION STAGE

Cell Pressure 50 KN/m^2
Back Pressure - "
Cons Pressure 50 "
Drainage: Top/~~Base~~/~~Both~~
Filter Drains: ~~Yes~~/No

SAMPLE DIMENSIONS AFTER CONSOLIDATION

Volume Change (ΔV) = 2.20 cm^3
Final Volume (Vc) = 84.7 cm^3
(Vc - ΔV) =
Final Height (Hc) = 74.3 mm
Ho - (1-ΔV/3V) =
Final Area (Ac) = 11.4 cm^2
(Vc/Hc) =

STRAIN 0.0021 mm/sec

TEST CELL PRESSURE 50 (KN/m^2)

c' = 0 (KN/m^2)
φ' = 47 degrees

TESTS A.B.C. A SATURATION & CONSOLIDATION OF SAMPLE IN TRIAXIAL CELL. B PERMEABILITY IN TRIAXIAL CELL C DISSIPATION TEST.

JOB: BEACH SAND | SAMPLE No: A | TEST No: A – C | CELL No.: 20

INITIAL	INITIAL	FINAL	CONSOLIDATION
AVERAGE HEIGHT 'Ho' 76.2 mm	Wet Weight gms	Wet Weight gms	Time for consolidation min
AVERAGE DIAMETER 38.1 mm	Moisture Content %	Dry Weight gms	Coefficient of consolidation (Cv =)
VOLUME OF SAMPLE 'Vo' 86.87 Cu.cm	Wet Density Mg/c.m.	Moisture gms	Mv =
	Dry Density "	Moisture Content %	K =
	Weight of Porous plate grm		

DATE	TIME	t (min)	σ_3 KN/Sq.m Guage No	Pore Pressure Base of Sample Gauge No Zero: Gauge (KN/Sq.m)	Diff	Dissi	Applied Pre TOP Gauge No (KN/Sq.m)	Applied Pre BASE Gauge No	B $\frac{\Delta u}{\Delta \sigma_3}$	Volume Measurements CELL Gauge Readg	CELL Volume Cu.cm	TOP Gauge Readg	TOP Volume Cu.cm	BASE Gauge Readg	BASE Volu Cu.cm	Permeability Coefficient K: Differential Head 'h' $i = \frac{h}{Ho}$ KN/L²	cm	Hydraulic Gradient	Quantity of flow (q) Cu.cm/Sec	K =q/iA cm/sec	Type of Test
16/5/84	11.30	0	300				0	250							DV	= 2.2 cc					
17/5/84			"	250			closed														
			400	350	100			"	1.00						VC	= 86.87 − 2.20					
"	08.45	0	50									99.6									
		1/4										98.0				= 84.62 cc					
		1										97.8									
		2 1/4										97.8			HC	= 7.62 (	1 − $\frac{2.2}{86.87}$)				
		4										97.8									
		6 1/4										97.8									
		9										97.8				= 7.43 cm					
		12 1/4										97.8									
		16										97.8									
		25										97.8			AC	= $\frac{84.67}{7.43}$					
		36										97.6									
		49										97.6									
		64										97.6									
		81										97.6				= 11.40 cm²					
		100										97.6									
	8 am											97.4	2.2								

Remarks

CONSOLIDATED ~~UNDRAINED~~ / DRAINED TRIAXIAL COMPRESSION TEST.

JOB: BEACH SAND

SAMPLE NO: A | TEST NO: B | CELL NO: 20

INITIAL DIMENSIONS

Ave Height (Ho) 76.2 mm
Ave Diameter (Do) 38.1 mm
Volume (Vo) 86.87 c.cm
Wet Density 2.05 mg/c.m

MOISTURE CONTENTS		INITIAL	FINAL
Wet Weight	(gm)		
Dry Weight	"		
Moisture	"		
Moisture Content	%		

DATE	TIME	P.W.P. GAUGE READING kN/m^2	VOLUMETRIC STRAIN: BURETTE READING C.cm	VOL CHANGE ΔV C.cm	$\Delta V/V_c$ %	AXIAL STRAIN: STRAIN DIAL READING x.03=	$E=\frac{\Delta h}{H_c}$ %	APPLIED LOAD (PR No 0.00156 kN/div FACTOR): DIAL READING	LOAD kN	CROSS SECTIONAL AREA: $100 \pm \frac{\Delta V}{V}$ %	100-E%	C.S.A $A_c\frac{100\pm\Delta V/V}{100-E\%}$ Sq.cm	$\sigma_1-\sigma_3$ Deviator Stress kN/m^2	σ_1' MAJOR PRIN'L STRESS kN/m^2	σ_3' MINOR PRIN'L STRESS kN/m^2
21/5/84	08.30	0	97.4	0	0	90	3.08	194	0.30	100	100	11.40	253.8		
	09.40		97.6	40.2	0.23	120	4.05	396	0.62	100.23	95.95	11.90	517.7		
"	10.40		98.0	40.6	0.70	150	5.06	404	0.63	100.70	94.94	12.09	520.3		
			98.0	40.6	0.70	180	6.07	406	0.63	100.70	93.93	12.24	517.3		

$\sigma_1 - \sigma_3$ = 520.3 − 2.3 = 518 KN/M^2

σ_3 = 100 − 0 = 100 "

σ_f = 518.0 + 100 = 618 KN/M^2

SATURATION STAGE

By Flooding ☐
By Back Pressure ☐
Assumed ☐
B − Value %

CONSOLIDATION STAGE

Cell Pressure 100 kN/m^2
Back Pressure − "
Cons Pressure 100 "
Drainage: Top/~~Base~~/Both
Filter Drains: ~~Yes~~/No

SAMPLE DIMENSIONS AFTER CONSOLIDATION

Volume Change (ΔV) = 3.[illegible] cm^2
Final Volume (V_c) = ($V_o - \Delta V$) = 83.[illegible]7 cm^2
Final Height (H_c) = $H_o - (1-\Delta V/3V)$ = 75.3 mm
Final Area (A_c) = (V_c/H_c) = 11.4 cm^2

STRAIN = mm/sec

TEST CELL PRESSURE (kN/m^2): 100

c' = 0 (kN/m^2)
ϕ' = 47 degrees

TESTS A.B.C. A SATURATION & CONSOLIDATION OF SAMPLE IN TRIAXIAL CELL. B PERMEABILITY IN TRIAXIAL CELL C DISSIPATION TEST.

JOB BEACH SAND | SAMPLE No A | TEST No B | CELL No. 20

INITIAL	INITIAL	FINAL	CONSOLIDATION
AVERAGE HEIGHT 'Ho' 76.2 mm	Wet Weight gms	Wet Weight gms	Time for consolidation min
AVERAGE DIAMETER 38.1 mm	Moisture Content %	Dry Weight gms	Coefficient of consolidation (Cv =)
VOLUME OF SAMPLE 'Vo' 86.87 Cu.cm	Wet Density Mg/c.m.	Moisture gms	Mv =
	Dry Density "	Moisture Content %	K =
	Weight of Porous plate grm		

DATE	TIME	t (min)	σ_3 KN/Sq.m Gauge No	PORE PRESSURE BASE OF SAMPLE GAUGE No ZERO: Gauge (KN/Sq.m)	Diff	Dissi	Applied Pre TOP Gauge No (KN/Sq.m)	BASE Gauge No	B $\frac{\Delta u}{\Delta \sigma_3}$	VOLUME MEASUREMENTS CELL Gauge Readg	CELL Volume Cu.cm	TOP Gauge Readg	TOP Volume Cu.cm	BASE Gauge Readg	BASE Volu Cu.cm	PERMEABILITY COEFFICIENT K DIFFERENTIAL HEAD 'h' $i = \frac{h}{Ho}$ KN/m²	cm	Hydraulic Gradient	Quantity of flow (q) Cu.cm/Sec	K = q/iA cm/sec	Type of Test
18/5/84	12.30	0	100				closed					98.4		DV	= 1.	0 - 2	2 =	3.2c	c		
		1/4										98.4									
		1										98.4		VC	= 8	6.87	- 3.	20 =			
		2 1/4										98.4				83.67	cc				
		4										98.4									
		6 1/4										98.2		HC	= 7	62	(1 -	3.20			
		9										98.2						86.87)			
		12 1/4										98.2									
		16										98.1			= 7	53 cm					
		25										98.1									
		36										98.0									
		49										98.0		AC	= 83	67					
		64										98.0			7	53					
		81										98.0									
		100										98.0			= 11	40 cm²					
	8a.m.											97.4									

Remarks

CONSOLIDATED ~~UNDRAINED~~ / DRAINED TRIAXIAL COMPRESSION TEST.

JOB: BEACH SAND

SAMPLE NO: A | TEST NO: C | CELL NO: 20

INITIAL DIMENSIONS

Ave Height (Ho) 76.2 mm
Ave Diameter (Do) 38.1 mm
Volume (Vo) 86.87 c.cm
Wet Density 2.05 Mg/c.m

MOISTURE CONTENTS | INITIAL | FINAL

Wet Weight (grm)
Dry Weight "
Moisture "
Moisture Content %

DATE	TIME	P.W.P. GAUGE READING KN/m^2	VOLUMETRIC STRAIN: BURETTE READING C.cm	VOL CHANGE ΔV C.cm	$\Delta V/Vc$ %	AXIAL STRAIN: STRAIN DIAL READING X mm	$E=\frac{\Delta h}{Hc}$ %	APPLIED LOAD (PR No 0.00156KN FACTOR div): DIAL READING	LOAD KN	CROSS SECTIONAL AREA: $100\pm\frac{\Delta V}{V}$ %	100-E% %	C.S.A $Ac\frac{100\pm\Delta V/V}{100-E\%}$ Sq.cm	$\sigma_1-\sigma_3$ Deviator Stress KN/m^2	σ_1' MAJOR PRIN'L STRESS KN/m^2	σ_3' MINOR PRIN'L STRESS KN/m^2
22/9/84	08.30	0	97.2	0	0	180	6.07	406	0.63	100	100	11.40	517.3		
	10.00		97.2	0	0	210	7.34	820	1.28	100	92.6	12.30	1037.7		
	10.56		97.2	0	0	240	8.39	835	1.29	100	91.66	12.45	1044.8		
	12.00		97.2	0	0	270	9.43	836	1.30	100	90.57	12.59	1034.1		
	13.00		97.2	0	0	300	10.48	836	1.30	100	89.52	12.74	1022.0		
	14.00		97.4	+0.2	0.24	330	11.53	834	1.30	100.24	88.47	12.92	1005.3		
			97.4	+0.2	0.24	360	12.58	830	1.29	100.24	87.42	13.07	988.6		

$\sigma_1 - \sigma_3$ = 1044.8 - 4.8 = 1040 KN/M^2

σ_3 = 200 - 0 = 200 KN/M^2

σ_1 = 1040 + 200 = 1240 KN/M^2

SATURATION STAGE

By Flooding
By Back Pressure
Assumed
B - Value %

CONSOLIDATION STAGE

Cell Pressure 200 KN/m^2
Back Pressure - "
Cons Pressure 200 "
Drainage: Top/~~Base~~/~~Both~~
Filter Drains; ~~Yes~~/No

SAMPLE DIMENSIONS AFTER CONSOLIDATION

Volume Change (ΔV) = 4.00 cm^3
Final Volume (Vc) = 82.9 cm^3
(Vo - ΔV) =
Final Height (Hc) = 72.7 mm
Ho - (1-ΔV/3V) =
Final Area (Ac) = 11.4 cm^2
(Vc/Hc) =

STRAIN = 0.00021 mm/sec

TEST CELL PRESSURE 200 (KN/m^2)

c' = 0 (KN/m^2)
ϕ' = 47 degrees

178

JOBS A.B.C. A SATURATION & CONSOLIDATION OF SAMPLE IN TRIAXIAL CELL. B PERMEABILITY IN TRIAXIAL CELL C DISSIPATION TEST.

JOB: BEACH SAND | SAMPLE No: A | TEST No: C | CELL No.: 20

INITIAL	INITIAL	FINAL	CONSOLIDATION
AVERAGE HEIGHT 'Ho' 76.2 cm	Wet Weight gms	Wet Weight gms	Time for consolidation min
AVERAGE DIAMETER 38.1 mm	Moisture Content %	Dry Weight gms	Coefficient of consolidation (Cv =)
VOLUME OF SAMPLE 'Vo' 86.87 cu.c	Wet Density Mg/c.m	Moisture gms	Mv =
	Dry Density "	Moisture Content %	K =
	Weight of Porous plate grm		

DATE	TIME	t (min)	σ_3 KN/Sq.m Guage No	PORE PRESSURE BASE OF SAMPLE GAUGE No ZERO Gauge (KN/Sq.m)	Diff	Dissi	Applied Pre TOP Gauge No (KN/Sq.m)	BASE Gauge No	B $\frac{\Delta u}{\Delta\sigma_3}$	VOLUME MEASUREMENTS CELL Gauge Readg	CELL Volume Cu.cm	TOP Gauge Readg	TOP Volume Cu.cm	BASE Gauge Readg	BASE Volu Cu.cm	PERMEABILITY COEFFICIENT K DIFFERENTIAL HEAD 'h' $i = \frac{h}{Ho}$ KN/m²	cm	Hydraulic Gradient	Quantity of flow (q) Cu.cm/Sec	K =q/iA cm/sec	Type of Test
21/5/84	11.30	0	200				closed					98.0		DV	=	0.8 +	3.20	= 4.0cc			
												97.6									
												97.6		VC	=	86.87 –	40	= 82.87 cc			
												97.6									
"	08.30		"									97.2	0.8								
														HC	=	7.62 (1 –	4.0 / 86.87)				
															=	7.27 cm					
														AC	=	82.87 / 7.27					
															=	11.40 cm²					

Remarks

CONSOLIDATED ~~UNDRAINED~~ / DRAINED TRIAXIAL COMPRESSION TEST.

JOB: BEACH SAND

SAMPLE NO: B TEST NO: A CELL NO: 20

INITIAL DIMENSIONS		
Ave Height (H_c)	76.2	mm
Ave Diameter (D_o)	38.1	mm
Volume (V_o)	86.87	c.cm
Wet Density	1.91	Mg/c.m

MOISTURE CONTENTS		INITIAL	FINAL
Wet Weight	(gm)		
Dry Weight	"		
Moisture	"		
Moisture Content	%		

DATE	TIME	P.W.P GAUGE READING KN/m^2	VOLUMETRIC STRAIN BURETTE READING C.cm	VOL CHANGE ΔV C.cm	ΔV/Vc %	AXIAL STRAIN STRAIN DIAL READING X mm	$E=\frac{\Delta h}{Hc}$ %	APPLIED LOAD (PRING FACTOR 0.00338KN/div) DIAL READING	LOAD KN	CROSS SECTIONAL AREA $100\pm\frac{\Delta V}{V}$ %	100-E% %	C.S.A $Ac\frac{100\pm\Delta V}{100-E\%}$ Sq.cm	$\sigma_1-\sigma_3$ Deviator Stress KN/m^2	σ_1' MAJOR PRIN'L STRESS KN/m^2	σ_3' MINOR PRIN'L STRESS KN/m^2
25/4/84	09.25	0	92.0	0	0	0	0	0	0	100	100	11.40	0		
"	12.24		92.6	+0.6	0.70	30	1.01	62	0.21		98.99	11.60	180.6		
"	13.30		92.8	+0.8	0.93	60	2.02	67	0.23	100.93	97.98	11.74	192.8		
"	14.40		93.2	+1.2	1.40	90	3.03	70	0.24	100.40	96.97	11.92	198.7		
	15.40		93.6	+1.6	1.86	120	4.05	71	0.24	101.86	95.95	12.01	198.5		
	16.40		94.0	+2.0	2.33	150	5.06	70	0.24	102.33	94.94	12.29	192.6		

SATURATION STAGE

By Flooding

By Back Pressure

Assumed

B - Value %

CONSOLIDATION STAGE

Cell Pressure 50 KN/m^2

Back Pressure - "

Cons Pressure 50 "

Drainage: Top/~~Base~~/~~Both~~

Filter Drains: ~~Yes~~/No

SAMPLE DIMENSIONS AFTER CONSOLIDATION

Volume Change (ΔV) = 1.0cc

Final Volume (V_c) = 85.87cc

(V_o - ΔV) =

Final Height (H_c) = 75.3mm

H_o - (1-ΔV/3V) =

Final Area (A_c) = 11.4cm^2

(V_c/H_c) =

STRAIN = 0.00021mm/sec

TEST CELL PRESSURE (KN/m^2) 50

c' = 0 (KN/m^2)

ø' = 40 degrees

180

TESTS A.B.C. A SATURATION & CONSOLIDATION OF SAMPLE IN TRIAXIAL CELL. B PERMEABILITY IN TRIAXIAL CELL C DISSIPATION TEST.

JOB: BEACH SAND | SAMPLE No: B | TEST No: A - C | CELL No.: 20

INITIAL		INITIAL		FINAL		CONSOLIDATION	
AVERAGE HEIGHT 'Ho'	76.2 mm	Wet Weight	gms	Wet Weight	gms	Time for consolidation	min
AVERAGE DIAMETER	38.1 mm	Moisture Content	%	Dry Weight	gms	Coefficient of consolidation (=)	
VOLUME OF SAMPLE 'Vo'	86.87 Cu.cm	Wet Density	Kg/c.m.	Moisture	gms	Mv =	
		Dry Density	"	Moisture Content	%	K =	
		Weight of Porous plate	grm				

DATE	TIME	t (min)	σ_3 KN/Sq.m Gauge No	PORE PRESSURE BASE OF SAMPLE GAUGE No ZERO: Gauge (KN/Sq.m)	Diff	Dissi	Applied Pre TOP Gauge No (KN/Sq.m)	Applied Pre BASE Gauge No (KN/Sq.m)	B $\frac{\Delta u}{\Delta \sigma_3}$	VOLUME MEASUREMENTS CELL Gauge Readg	CELL Volume Cu.cm	TOP Gauge Readg	TOP Volume Cu.cm	BASE Gauge Readg	BASE Volu Cu.cm	PERMEABILITY COEFFICIENT K: DIFFERENTIAL HEAD 'h' $i = \frac{h}{Ho}$ KN/m²	cm	Hydraulic Gradient	Quantity of flow (q) Cu.cm/Sec	K =q/iA cm/sec	Type of Test
17/4/84	16.00	0	300				0	250						DV	=	1.0cc					
18/4/84	14.00		"	110			closed														
"			400	155	45			"	0.45					VC	=	86.87 -	1.0				
"			300				0	250													
24/4/84			"	160			closed								=	85.87cc					
"			400	260	100		"	"	1.00												
"		0	50				"	"				93.0		HC	=	7.62 (1	- 1.0/86.87)				
		1/4										92.8									
		1										92.7			=	7.53cm					
		2 1/4										92.7									
		4										92.6									
		6 1/4										92.6		Ac	=	85.87/7.53					
		9										92.6									
		12 1/4										92.6				=	11.40cm²				
		16										92.6									
		25										92.6									
		36										92.6									
		49										92.6									
		64										92.5									
		81										92.5									

Remarks 100 92.5

8a.m 92.0 DV = 1.00cc

CONSOLIDATED ~~UNDRAINED~~/ DRAINED TRIAXIAL COMPRESSION TEST.

JOB: BEACH SAND

SAMPLE NO: B | TEST NO: B | CELL NO: 20

INITIAL DIMENSIONS

- Ave Height (Ho) 76.2 mm
- Ave Diameter (Do) 38.1 mm
- Volume (Vo) 86.87 c.cm
- Wet Density 1.91 Mg/c.m

MOISTURE CONTENTS — INITIAL — FINAL

- Wet Weight (gm)
- Dry Weight "
- Moisture "
- Moisture Content %

DATE	TIME	P.W.I GAUGE READING KN/m^2	VOLUMETRIC STRAIN: BURETTE READING C.cm	VOLUMETRIC STRAIN: VOL CHANGE ΔV C.cm	VOLUMETRIC STRAIN: $\Delta V/Vc$ %	AXIAL STRAIN: STRAIN DIAL READING X mm	AXIAL STRAIN: $E=\frac{\Delta h}{Hc}$ %	APPLIED LOAD (PR No FACTOR div): DIAL READING	APPLIED LOAD: LOAD KN	CROSS SECTIONAL AREA: $100+\frac{\Delta V}{V}$ %	CROSS SECTIONAL AREA: 100−E% %	C.S.A $Ac\frac{100+\Delta V}{100-E\%}$ Sq.cm	$\sigma_1-\sigma_3$ Deviator Stress KN/m^2	σ_1' MAJOR PRIN'L STRESS KN/m^2	σ_3' MINOR PRIN'L STRESS KN/m^2
22/9/84	08.40	0	93.8	0	0	150	5.06	70	0.24	100	100	11.40	192.6		
"	09.40		93.8	0	0	180	6.07	124	0.42	100	93.93	12.14	345.3		
"	10.40		94.0	+0.2	0.23	210	7.08	128	0.43	99.77	92.92	12.24	353.7		
	12.00		94.0	+0.2	0.23	240	8.09	128	0.43	99.77	91.91	12.37	349.8		
	13.00		94.2	+0.4	0.47	270	9.10	128	0.43	99.53	90.90	12.48	346.7		
	14.00		94.2	+0.4	0.47	300	10.11	128	0.43	99.53	89.89	12.62	343.0		
	15.00		94.2	+0.4	0.47	330	11.13	128	0.43	99.53	88.87	12.77	339.0		

$\sigma_1-\sigma_3 = 353.7 - 3.9 = 349.8 KN/M^2$

$\sigma_1 = 349.8 + 100 = 450 KN/M^2$

SATURATION STAGE

- By Flooding
- By Back Pressure
- Assumed
- B − Value %

CONSOLIDATION STAGE

- Cell Pressure 100 KN/m^2
- Back Pressure − "
- Cons Pressure 100 "
- Drainage: Top/Base/Both
- Filter Drains: Yes/No

SAMPLE DIMENSIONS AFTER CONSOLIDATION

- Volume Change (ΔV) 11.2 [illegible] cm^3
- Final Volume (Vc) = 85.[illegible]7 cm^3 ($Vo - \Delta V$)
- Final Height (Hc) = 75.[illegible]16 mm ($Ho - (1-\Delta V/3V)$)
- Final Area (Ac) = 11.[illegible]0 cm^2 (Vc/Hc)

STRAIN = 0.0002 in/sec

TEST CELL PRESSURE (KN/m^2): 100

c' = 0 (KN/m^2)

ϕ' = 40 degrees

TESTS A.B.C. A SATURATION & CONSOLIDATION OF SAMPLE IN TRIAXIAL CELL. B PERMEABILITY IN TRIAXIAL CELL C DISSIPATION TEST.

JOB: BEACH SAND | SAMPLE No: B | TEST No: B | CELL No.: 20

INITIAL	INITIAL	FINAL	CONSOLIDATION
AVERAGE HEIGHT 'Ho' 76.2 cm	Wet Weight gms	Wet Weight gms	Time for consolidation min
AVERAGE DIAMETER 38.1 mm	Moisture Content %	Dry Weight gms	Coefficient of consolidation (Cv =)
VOLUME OF SAMPLE 'Vo' 86.87 cu.cm	Wet Density Kg/c.m	Moisture gms	Mv =
	Dry Density "	Moisture Content %	K =
	Weight of Porous plate grm		

DATE	TIME	t (min)	σ_3 KN/Sq.m Gauge No	PORE PRESSURE BASE OF SAMPLE (GAUGE No ZERO) Gauge (KN/Sq.m)	Diff	Dissip	Applied Pre TOP Gauge No (KN/Sq.m)	Applied Pre BASE Gauge No	B $\frac{\Delta u}{\Delta\sigma_3}$	VOLUME MEASUREMENTS CELL Gauge Readg	CELL Volume Cu.cm	TOP Gauge Readg	TOP Volume Cu.cm	BASE Gauge Readg	BASE Volu Cu.cm	PERMEABILITY COEFFICIENT K: DIFFERENTIAL HEAD 'h' $i = \frac{h}{Ho}$ KN/m^2	cm	Hydraulic Gradient	Quantity of flow (q) Cu.cm/Sec	K $= q/iA$ cm/sec	Type of Test
25/4/84	17.00		100				closed					94.0		DV	= 0.241.0		= 1.2cc				
26/4/84	08.15		"				"	"				93.8	0.2								
														VC	= 86.87 −		1.2				
															= 85.67 cm^3						
														HC	= 7.62 (1 −		$\frac{1.2}{86.87}$)				
															= 7.52 cm						
														AC	= $\frac{85.67}{7.52}$						
															= 11.40cm^2						

Remarks

CONSOLIDATED ~~UNDRAINED~~ / DRAINED TRIAXIAL COMPRESSION TEST.

JOB: BEACH SAND

SAMPLE NO: B TEST NO: C CELL NO: 20

INITIAL DIMENSIONS

- Ave Height (Hc) 76.2 mm
- Ave Diameter (Do) 38.1 mm
- Volume (Vo) 86.87 c.cm
- Wet Density 1.908 mg/c.m

MOISTURE CONTENTS INITIAL FINAL

- Wet Weight (gm)
- Dry Weight "
- Moisture "
- Moisture Content %

DATE	TIME	P.W.P. GAUGE READING kN/m^2	VOLUMETRIC STRAIN: BURETTE READING C.cm	VOL CHANGE ΔV C.cm	ΔV/Vc %	AXIAL STRAIN: STRAIN DIAL READING x.025mm	$E=\frac{\Delta h}{Hc}$ %	APPLIED LOAD (PR No 0.00338KN/div FACTOR): DIAL READING	LOAD KN	CROSS SECTIONAL AREA: 100+ΔV %	100−E% %	C.S.A $Ac\frac{100+\Delta V}{100-E\%}$ Sq.cm	$\sigma_1-\sigma_3$ Deviator Stress kN/m^2	σ_1' MAJOR PRIN'L STRESS kN/m^2	σ_3' MINOR PRIN'L STRESS kN/m^2
30/4/84	08.50	0	93.2	0	0	330	11.13	128	0.43	100	100	11.40	339.0		
	09.50		92.8	-0.4	0.47	360	12.14	208	0.70	99.53	87.86	12.92	544.5		
	10.53		92.8	-0.4	0.47	390	13.15	277	0.94	99.53	86.85	13.06	716.7		
	11.58		92.8	-0.4	0.47	420	14.16	284	0.96	99.53	85.84	13.22	726.2		
	12.53		92.8	-0.4	0.47	450	15.17	284	0.96	99.53	84.83	13.44	714.3		
	13.52		92.8	-0.4	0.47	480	16.18	284	0.96	99.53	83.82	13.54	709.2		
	14.50		92.8	-0.47	0.47	510	17.20	284	0.96	99.53	82.80	13.70	700.5		
	15.56		92.8	-0.4	0.47	540	18.21	285	0.96	99.53	81.79	13.87	689.8		
	16.52		92.8	-0.4	0.47	570	19.22	281	0.95	99.53	80.28	14.05	676.8		

$\sigma_1-\sigma_3$ = 726.2 − 6.2 = 720.0KN/M²

σ_3 = 200KN/M²

σ_1 = 720 + 200 = 920KN/M²

SATURATION STAGE

- By Flooding ☐
- By Back Pressure ☐
- Assumed ☐
- B − Value %

CONSOLIDATION STAGE

- Cell Pressure 200 kN/m^2
- Back Pressure 200 "
- Cons Pressure "
- Drainage: Top/Base/Both
- Filter Drains: Yes/No

SAMPLE DIMENSIONS AFTER CONSOLIDATION

- Volume Change (ΔV) = 1.00cm³
- Final Volume (Vc) = 85.87cm³ (Vo − ΔV)
- Final Height (Hc) = 75.34mm Ho − (1−ΔV/3V)
- Final Area (Ac) = 11.40cm² (Vc/Hc)

STRAIN = 0.00021mm/sec

TEST CELL PRESSURE (kN/m^2) 200

c' = 0 (kN/m^2)

ϕ' = 40 degrees

TESTS A.B.C. A SATURATION & CONSOLIDATION OF SAMPLE IN TRIAXIAL CELL B PERMEABILITY IN TRIAXIAL CELL C DISSIPATION TEST.

JOB: BEACH SAND SAMPLE No: B TEST No: C CELL No.: 20

INITIAL	INITIAL	FINAL	CONSOLIDATION
AVERAGE HEIGHT 'Ho' 76.2 mm	Wet Weight 165.8 gms	Wet Weight gms	Time for consolidation min
AVERAGE DIAMETER 38.1 mm	Moisture Content %	Dry Weight gms	Coefficient of consolidation (Cv =)
VOLUME OF SAMPLE 'Vo' 86.87 Cu.cm	Wet Density Mg/c.m	Moisture gms	Mv =
	Dry Density "	Moisture Content %	X =
	Weight of Porous plate grm		

DATE	TIME	t (min)	σ_3 KN/Sq.m Guage No	PORE PRESSURE BASE OF SAMPLE GAUGE No ZERO: Gauge (KN/Sq.m)	Diff	Dissi	Applied Pre TOP: Gauge No (KN/Sq.m)	Applied Pre BASE: Gauge No (KN/Sq.m)	B $\frac{\Delta u}{\Delta \sigma_3}$	VOLUME MEASUREMENTS CELL: Gauge Readg	CELL: Volume Cu.cm	TOP: Gauge Readg	TOP: Volume Cu.cm	BASE: Gauge Readg	BASE: Volu Cu.cm	PERMEABILITY COEFFICIENT K: DIFFERENTIAL HEAD 'h' $i = \frac{h}{Ho}$ KN/m²	cm	Hydraulic Gradient	Quantity of flow (q) Cu.cm/Sec	K = q/iA cm/sec	Type of Test
26/4/84	15.00	0	200				closed					94.2		DV	=	1.0cc					
27/4/84	09.25											94.0									
"	15.00											94.0									
												93.2	1.00	VC	= 86	.87 −	1.0	= 85.87cc			
														HC	= 7.62	(1 − 1.0					
																	86.87)				
															= 7.53cm						
														AC	= 85.87						
																7.53					
															= 11.40cm²						

Remarks

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CONSOLIDATED UNDRAINED / DRAINED TRIAXIAL COMPRESSION TEST.

JOB: BEACH SAND

SAMPLE NO: C | TEST NO: A | CELL NO: 9

INITIAL DIMENSIONS

Ave Height (Hc) 76.2 mm
Ave Diameter (Do) 38.1 mm
Volume (Vo) 86.87 c.cm
Wet Density ' 61 Mg/c.m

MOISTURE CONTENTS		INITIAL	FINAL
Wet Weight	(gm)	139.9	
Dry Weight	"		
Moisture	"		
Moisture Content	%		

DATE	TIME	P.W.P. GAUGE READING KN/m^2	VOLUMETRIC STRAIN: BURETTE READING C.cm	VOLUMETRIC STRAIN: VOL CHANGE ΔV C.cm	VOLUMETRIC STRAIN: $\Delta V/Vc$ %	AXIAL STRAIN: STRAIN DIAL READING X mm	AXIAL STRAIN: $E=\frac{\Delta h}{Hc}$ %	APPLIED LOAD (PR No 0.00156KN FACTOR div): DIAL READING	APPLIED LOAD: LOAD KN	CROSS SECTIONAL AREA: $100+\frac{\Delta V}{V}$ %	CROSS SECTIONAL AREA: 100-E% %	CROSS SECTIONAL AREA: C.S.A $Ac\frac{100+\Delta V}{100-E\%}$ Sq.cm	$\sigma_1-\sigma_3$ Deviator Stress KN/m^2	σ_1' MAJOR PRIN'L STRESS KN/m^2	σ_3' MINOR PRIN'L STRESS KN/m^2
25/4/84	09.25	0	42.6	0	0	0	0	0	0	100	100	11.40	0		
	11.25		42.6	0	0	30	1.0	92-	0.14	100	98.99	11.52	124.4		
	12.31		42.7	+0.1	0.12	60	2.03	109	0.17	100.12	97.97	11.65	145.8		
	13.30		43.0	+0.4	0.47	90	3.04	115	0.18	100.47	96.96	11.81	151.8		
	14.40		43.2	+0.6	0.70	120	4.05	107	0.17	100.70	95.95	11.76	139.5		

$\sigma_1-\sigma_3$ = 151.8 - 1.7 = 150.1 KN/M^2

σ_3 = 50.0 - 0 = 50 KN/M^2

σ_1 = 150.1 + 50 = 200.1 KN/M^2

SATURATION STAGE

By Flooding
By Back Pressure
Assumed
B - Value %

CONSOLIDATION STAGE

Cell Pressure 50 KN/m^2
Back Pressure - "
Cons Pressure 50 "
Drainage: Top/~~Base~~/~~Both~~
Filter Drains; ~~Yes~~/No

SAMPLE DIMENSIONS AFTER CONSOLIDATION

Volume Change (ΔV) = 1. cm^3
Final Volume (Vc) = ($Vo - \Delta V$) = 85 77cm^3
Final Height (Hc) = $Ho - (1-\Delta V/3V)$ = 75 2mm
Final Area (Ac) = (Vc/Hc) = 11 40cm^2

STRAIN = 0.00021 m/sec

TEST CELL PRESSURE (KN/m^2) 50

c' = 6 (KN/m^2)
ϕ' = 33 degrees

TESTS A.B.C. A SATURATION & CONSOLIDATION OF SAMPLE IN TRIAXIAL CELL. B PERMEABILITY IN TRIAXIAL CELL C DISSIPATION TEST.

JOB: BEACH SAND | SAMPLE No: C | TEST No: A - C | CELL No.: 9

INITIAL	INITIAL	FINAL	CONSOLIDATION
AVERAGE HEIGHT 'Ho' 76.2 mm	Wet Weight 139.9 gms	Wet Weight gms	Time for consolidation min
AVERAGE DIAMETER 38.1 mm	Moisture Content %	Dry Weight gms	Coefficient of consolidation (Cv =)
VOLUME OF SAMPLE 'Vo' 86.87 cu.cm	Wet Density Kg/c.m.	Moisture gms	Mv =
	Dry Density "	Moisture Content %	K =
	Weight of Porous plate grm		

DATE	TIME	t (min)	σ_3 KN/Sq.m	Gauge No	PORE PRESSURE BASE OF SAMPLE GAUGE No ZERO Gauge (KN/Sq.m)	Diff	Dissi	Applied Pre TOP Gauge No (KN/Sq.m)	Applied Pre BASE Gauge No	B $\frac{\Delta u}{\Delta \sigma_3}$	VOLUME MEASUREMENTS CELL Gauge Readg	CELL Volume Cu.cm	TOP Gauge Readg	TOP Volume Cu.cm	BASE Gauge Readg	BASE Volu Cu.cm	PERMEABILITY COEFFICIENT K DIFFERENTIAL HEAD 'h' $i = \frac{h}{Ho}$ KN/m²	cm	Hydraulic Gradient	Quantity of flow (q) Cu.cm/Sec	K =q/iA cm/sec	Type of Test
17/4/84	16.00	0	300					0	250							DV	= 1.1cc					
18/4/84	14.00		"		140			closed														
"			400		240				"	1.00						VC	= 86.87 -		1.1			
"			300					0	250													
24/4/84		0	50					closed					43.1				= 85.76cm³					
		1/4											42.5									
		1											42.4			HC	= 7.62 (1		- 1.1			
		2 1/4											42.4						86.87)			
		4											42.4									
		6 1/4											42.4				= 7.52cm					
		9											42.3									
		12 1/4											42.3			AC	= 85.76					
		16											42.3				7.52					
		25											42.3									
		36											42.2				= 11.40cm²					
		49											42.2									
		64											42.1									
		81											42.0									
		100											42.0									
	8a.m												42.0	1.1								

Remarks

CONSOLIDATED ~~UNDRAINED~~ / DRAINED TRIAXIAL COMPRESSION TEST.

JOB: BEACH SAND

SAMPLE NO: C TEST NO: B CELL NO: 9

INITIAL DIMENSIONS

Ave Height (Hc) 76.2 mm
Ave Diameter (Do) 38.1 mm
Volume (Vo) 86.87 c.cm
Wet Density 1.61 mg/c.m

MOISTURE CONTENTS INITIAL FINAL

Wet Weight (gm)
Dry Weight "
Moisture "
Moisture Content %

DATE	TIME	P.W.P	VOLUMETRIC STRAIN			AXIAL STRAIN		APPLIED LOAD PR No FACTOR 0.00156 KN/div		CROSS SECTIONAL AREA			$\sigma_1 - \sigma_3$	σ_1'	σ_3'
		GAUGE READING KN/m²	BURETTE READING C.cm	VOL CHANGE ΔV C.cm	ΔV/Vc %	STRAIN DIAL READING x.025 mm	$E = \frac{\Delta h}{Hc}$ %	DIAL READING	LOAD KN	$100 \pm \frac{\Delta V}{V}$ %	100−E%	C.S.A $Ac\frac{100 \pm \Delta V}{100 - E\%}$ Sq.cm	Deviator Stress KN/m²	MAJOR PRIN'L STRESS KN/m²	MINOR PRIN'L STRESS KN/m²
26/3/87	08.30	0	42.6	0	0	120	4.05	107	0.17	100	100	11.40	139.5		
"	09.30		42.6	0	0	150	5.06	204	0.31	100	94.94	12.01	264.5		
"	10.30		42.6	0	0	180	6.08	207	0.32	100	93.92	12.14	265.8		
"	11.30		42.7	0.1	0.12	210	7.09	206	0.32	100.12	92.91	12.28	261.1		
"	12.30		42.7	+0.1	0.12	240	8.10	202	0.31	100.12	91.90	12.42	253.2		

$\sigma_1 - \sigma_3 = 265.8 - 3.3 = 263 KN/M^2$

$\sigma_3 = 100 - 0 = 100$

$\sigma_1 = 263 + 100 = 363 KN/M^2$

SATURATION STAGE

By Flooding
By Back Pressure
Assumed
B - Value %

CONSOLIDATION STAGE

Cell Pressure 100 KN/m²
Back Pressure - "
Cons Pressure 100 "
Drainage: Top/Base/Both
Filter Drains: Yes/No

SAMPLE DIMENSIONS AFTER CONSOLIDATION

Volume Change (ΔV) = 1. cm³
Final Volume (Vc) = 85 16cm³
(Vo − ΔV) =
Final Height (Hc) = 74 7mm
Ho − (1−ΔV/3V) =
Final Area (Ac) = 11 40cm²
(Vc/Hc) =

STRAIN = 0.00021 mm/sec

TEST CELL PRESSURE (KN/m²) 100

c' = 6 (KN/m²)
ø' = 33 degrees

TESTS A.B.C. A SATURATION & CONSOLIDATION OF SAMPLE IN TRIAXIAL CELL. B PERMEABILITY IN TRIAXIAL CELL C DISSIPATION TEST.

JOB: BEACH SAND | SAMPLE No: C | TEST No: B | CELL No.: 9

INITIAL		INITIAL		FINAL		CONSOLIDATION
AVERAGE HEIGHT 'Ho'	76.2 cm	Wet Weight	gms	Wet Weight	gms	Time for consolidation min
AVERAGE DIAMETER	38.1 mm	Moisture Content	%	Dry Weight	gms	Coefficient of consolidation (Cv =)
VOLUME OF SAMPLE 'Vo'	86.87 Cu.c	Wet Density	Kg/c.m.	Moisture	gms	Mv =
		Dry Density	"	Moisture Content	%	K =
		Weight of porous plate	gm			

DATE	TIME	t (min)	σ_3 KN/Sq.m Guage No	Pore Pressure Base of Sample Gauge No Zero: Gauge (KN/Sq.m)	Diff	Dissi	Applied Pre Top Gauge No (KN/Sq.m)	Applied Pre Base Gauge No	B $\frac{\Delta u}{\Delta \sigma_3}$	Volume Measurements Cell Gauge Readg	Cell Volume Cu.cm	Top Gauge Readg	Top Volume Cu.cm	Base Gauge Readg	Base Volume Cu.cm	Permeability Coefficient K Differential Head 'h' $i = \frac{h}{Ho}$ KN/m²	cm	Hydraulic Gradient	Quantity of flow (q) Cu.cm/Sec	K =q/iA cm/sec	Type of Test
24/4/84	17.00	0	100				closed					43.2									
			"				"	"				42.6	0.6								

DV = 0.6 + 1.1 = 1.7cc

VC = 86.87 − 1.7 = 85.17cc

HC = 7.62 (1 − $\frac{1.7}{86.87}$)

= 7.47cm

AC = $\frac{85.17}{7.47}$

= 11.40cm²

Remarks

CONSOLIDATED ~~UNDRAINED~~/ DRAINED TRIAXIAL COMPRESSION TEST.

JOB: BEACH SAND

SAMPLE NO: C TEST NO: C CELL NO: 9

INITIAL DIMENSIONS

Ave Height (Hc) 76.2 mm
Ave Diameter (Do) 38.1 mm
Volume (Vo) 86.87 c.cm
Wet Density 1.61 mg/c.m

MOISTURE CONTENTS INITIAL FINAL

Wet Weight (gm) 139.9
Dry Weight "
Moisture "
Moisture Content %

DATE	TIME	P.W.P	VOLUMETRIC STRAIN			AXIAL STRAIN		APPLIED LOAD		CROSS SECTIONAL AREA			$\sigma_1-\sigma_3$	σ_1'	σ_3'
		GAUGE READING	BURETTE READING	VOL CHANGE ΔV	ΔV/Vc	STRAIN DIAL READING	$E=\frac{\Delta h}{Hc}$	PR No FACTOR div DIAL READING	LOAD	$100\pm\frac{\Delta V}{V}$	100−E%	C.S.A $Ac\frac{100\pm\Delta V}{100-E\%}$	Deviator Stress	MAJOR PRIN'L STRESS	MINOR PRIN'L STRESS
		KN/m²	C.cm	C.cm	%	X mm	%		KN	%	%	Sq.cm	KN/m²	KN/m²	KN/m²
30/4/84	08.50	0	39.9	0	0	24.0	8.10	202	0.31	100	100	11.40	253.2		
	10.25	39.7	39.7	-02	0.24	270	9.12	400	0.62	99.76	91.90	12.37	503.3		
	11.34		39.6	-0.3	-0.36	300	10.13	407	0.63	99.64	89.87	12.64	501.6		
	12.29		39.3	-0.4	0.48	330	11.14	414	0.64	99.52	88.86	12.77	504.8		
	13.30		39.5	-0.4	0.48	360	12.55	413	0.64	99.52	87.85	12.92	498.0		
	14.35		39.4	-0.5	0.60	390	13.17	417	0.65	99.40	86.83	13.05	497.0		
	15.40		39.4	-0.5	0.60	420	14.18	416	0.65	99.40	85.82	13.21	490.4		
	16.30		39.4	-0.5	0.60	450	15.19	419	0.65	99.40	84.81	13.36	488.4		
	17.00		39.4	-0.5	0.60	464	15.67	424	0.66	99.40	84.33	13.44	491.2		
1/5/84	9.15		39.3	-0.6	0.71	480	16.21	420	0.67	99.29	83.79	13.51	493.3		
	10.15		39.1	-0.8	0.95	510	17.22	427	0.67	99.05	82.78	13.64	487.6		
	11.20		39.0	-0.9	1.07	540	18.23	429	0.67	98.93	81.77	13.79	484.4		
	12.33		38.9	-1.0	1.19	570	19.24	432	0.67	98.81	80.76	13.95	482.2		
	13.35		38.8	-1.1	1.31	600	20.26	438	0.68	98.69	79.74	14.11	483.3		

$\sigma_1 - \sigma_3 = 504.8 - 6.1 = 498.7$ KN/M²

$\sigma_3 = 200$ KN/m²

$\sigma_1 = 498.7 + 200 = 699$ KN/m²

SATURATION STAGE

By Flooding
By Back Pressure
Assumed
B - Value %

CONSOLIDATION STAGE

Cell Pressure 200 KN/m²
Back Pressure - "
Cons Pressure 200 "
Drainage: Top/Base/Both
Filter Drains: Yes/No

SAMPLE DIMENSIONS AFTER CONSOLIDATION

Volume Change (ΔV) = 2.8 cm³
Final Volume (Vc) = 84.07 cm³
(Vo − ΔV) =
Final Height (Hc) = 73.8 mm
Ho − (1−ΔV/3V) =
Final Area (Ac) = 11.40 cm²
(Vc/Hc) =

STRAIN RATE 0.0021 mm/sec

TEST CELL PRESSURE 200 (KN/m²)

C' = 6 (KN/m²)
ϕ' = 33 degrees

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..STS A.B.C. A SATURATION & CONSOLIDATION OF SAMPLE IN TRIAXIAL CELL. B PERMEABILITY IN TRIAXIAL CELL C DISSIPATION TEST.

JOB: BEACH SAND — SAMPLE No: C — TEST No: C — CELL No.: 9

INITIAL		INITIAL		FINAL		CONSOLIDATION
AVERAGE HEIGHT 'Ho'	mm	Wet Weight	gms	Wet Weight	gms	Time for consolidation min
AVERAGE DIAMETER	mm	Moisture Content	%	Dry Weight	gms	Coefficient of consolidation (Cv =)
VOLUME OF SAMPLE 'Vo'	Cu.c	Wet Density	Mg/c.m	Moisture	gms	Mv =
		Dry Density	"	Moisture Content	%	K =
		Weight of Porous plate	grm			

DATE	TIME	t (min)	σ_3 KN/Sq.m Guage No	PORE PRESSURE BASE OF SAMPLE GAUGE No ZERO: Gauge (KN/Sq.m)	Diff	Dissi	Applied Pre TOP Gauge No (KN/Sq.m)	BASE Gauge No	B $\frac{\Delta u}{\Delta \sigma_3}$	VOLUME MEASUREMENTS CELL Gauge Readg	CELL Volume Cu.cm	TOP Gauge Readg	TOP Volume Cu.cm	BASE Gauge Readg	BASE Volu Cu.cm	PERMEABILITY COEFFICIENT K: DIFFERENTIAL HEAD 'h' $i = \frac{h}{Ho}$ KN/m²	cm	Hydraulic Gradient	Quantity of flow (q) Cu.cm/Sec	K =q/iA cm/sec	Type of Test
26/4/84	14.00	0	200				Closed					42.7			Dv	=	2.8cc				
29/4/84	09.2?											41.8									
												41.6			Vc	=	86.87	- 2.80			
												39.9	2.8								
																	=	84.07cc			
																		84.07cc			
															Hc	=	7.62	(1 - 2.80	)		
																			86.87		
																=	7.38cm				
															Ac	=	84.07				
																	7.38				
																		=	11.40cm²		

Remarks

CONSOLIDATED ~~UNDRAINED~~ / DRAINED TRIAXIAL COMPRESSION TEST.

JOB: OGUN RIVER SAND

SAMPLE NO: C TEST NO: C CELL NO: 9

INITIAL DIMENSIONS

Ave Height (H_o) 76.2 mm
Ave Diameter (D_o) 38.1 mm
Volume (V_o) 86.87 c.cm
Wet Density 1.99 Mg/c.m

MOISTURE CONTENTS INITIAL FINAL

Wet Weight (gm) 173.0
Dry Weight "
Moisture "
Moisture Content %

DATE	TIME	P.W.P GAUGE READING kN/m^2	VOLUMETRIC STRAIN: BURETTE READING C.cm	VOL CHANGE ΔV C.cm	$\Delta V/V_c$ %	AXIAL STRAIN: STRAIN DIAL READING X mm	$\varepsilon = \frac{\Delta h}{H_c}$ %	APPLIED LOAD: PR No FACTOR div / DIAL READING	LOAD kN	CROSS SECTIONAL AREA: $100 \pm \frac{\Delta V}{V}$ %	100−ε% %	C.S.A $A_c \frac{100 \pm \Delta V/V}{100 - \varepsilon\%}$ Sq.cm	$\sigma_1 - \sigma_3$ Deviator Stress kN/m^2	σ_1' MAJOR PRIN'L STRESS kN/m^2	σ_3' MINOR PRIN'L STRESS kN/m^2
3/5/84	09.00	0	42.6	0	0	0	0	0	0	100	100	11.40	0		
	12.00		42.0	-0.6	0.71	30	1.03	28	0.09	99.29	98.97	11.44	82.8		
	13.20		41.7	-0.9	1.06	60	2.05	48	0.16	98.94	97.95	11.52	141.0		
	14.40		41.1	1 .5	1.77	90	3.07	70	0.24	98.23	96.93	11.55	204.9		
4/5/84	09.30		39.4	-3.2	3.77	120	4.10	77	0.26	96.23	95.90	11.57	234.7		
	10.30		39.0	-3.0	3.54	150	5.12	76	0.26	96.46	94.88	11.59	227.7		
	11.30		39.2	-3.4	4.01	180	6.15	85	0.29	95.99	93.85	11.60	24[illegible].5		
	12.30		39.5	-3.1	3.60	210	7.17	94	0.32	96.34	92.83	11.83	268.4		
	13.30		39.6	-3.0	3[illegible]4	240	8.20	99	0.33	96.46	91.80	11.98	279.2		
	14.30		39.9	-[illegible].7	3.18	270	9.22	100	0.34	96.82	90.78	12.16	278.0		
	15.27		40.2	-2.4	2.83	300	10.25	101	0.3[illegible]	9717	8[illegible].75	12.34	276.8		
	16.27		40.9	-1.7	2.01	330	11.27	99	0.33	97.99	88.73	12.59	265.8		
	17.27		41.2	-1.4	1.6[illegible]	360	12.30	96	0.32	98.35	87.70	12.[illegible]9	254.0		

$\sigma_1 - \sigma_3 = 279.2 - 4.3 = 274.9\ KN/m^2$

$\sigma_3 = 50\ KN/m^2$

$\sigma_1 = 274.9 + 50 = 325\ KN/m^2$

SATURATION STAGE

By Flooding
By Back Pressure
Assumed
B - Value %

CONSOLIDATION STAGE

Cell Pressure 50 kN/m^2
Back Pressure – "
Cons Pressure 50 "
Drainage: Top/Base/Both
Filter Drains; Yes/No

SAMPLE DIMENSIONS AFTER CONSOLIDATION

Volume Change (ΔV) = 2.1 cm^3
Final Volume (V_c) = 84.7 cm^3
($V_o - \Delta V$) =
Final Height (H_c) = 74.4 mm
$H_o - (1 - \Delta V/3V)$ =
Final Area (A_c) = 11.40 cm^2
(V_c/H_c) =

STRAIN = 0.0002 in/sec

TEST CELL PRESSURE (kN/m^2) 50

c' = 0 (kN/m^2)
ϕ' = 34 degrees

3/5/84 light off at 17.00 Hrs
4/5/84 on at 06.15 Hrs

TESTS A.B.C. A SATURATION & CONSOLIDATION OF SAMPLE IN TRIAXIAL CELL. B PERMEABILITY IN TRIAXIAL CELL C DISSIPATION TEST.

JOB: OGUN RIVER SAND | SAMPLE No: A | TEST No: A - C | CELL No.: 3

INITIAL	INITIAL	FINAL	CONSOLIDATION
AVERAGE HEIGHT 'Ho' 76.2 mm	Wet Weight 173.0 gms	Wet Weight gms	Time for consolidation min
AVERAGE DIAMETER 38.1 mm	Moisture Content	Dry Weight gms	Coefficient of consolidation (Cv =)
VOLUME OF SAMPLE 'Vo' 86.87 cu.cm	Wet Density Kg/cu.m	Moisture gms	Mv =
	Dry Density "	Moisture Content %	K =
	Weight of Porous plate gm		

DATE	TIME	t (min)	σ_3 KN/Sq.m Gauge No	PORE PRESSURE BASE OF SAMPLE (GAUGE No, ZERO) Gauge (KN/Sq.m)	Diff	Dissi	Applied Pre TOP Gauge No (KN/Sq.m)	Applied Pre BASE Gauge No	B $\frac{\Delta U}{\Delta \sigma_3}$	CELL Gauge Readg	CELL Volume Cu.cm	TOP Gauge Readg	TOP Volume Cu.cm	BASE Gauge Readg	BASE Volume Cu.cm	DIFFERENTIAL HEAD 'h' $i = \frac{h}{Ho}$ KN/m²	cm	Hydraulic Gradient	Quantity of flow (q) Cu.cm/Sec	K =q/iA cm/sec	Type of Test
17/4/84	16.00		300				0	250													
	14.00		-	125				Closed													
			400	220	95		-	-	0.95												
			300				0	250													
24/4/84		0	50				Closed					144.7			Dv	2.1	cc				
		1/4										45.5									
		1										44.4			Vc	= 36.87 - 2.1					
		1/4										44.3									
		2										44.3				= [illegible].77cc					
		2 1/4										44.3									
		4										44.2				Hc	=	7.[illegible]2 (1 -	2.1 / 36.87)		
		6 1/4										44.2									
		9										44.0						7. 4cm			
		16										44.0									
		25										43.9					Ac =	84.77			
		36										43.9						7.44			
		49										43.9							=11.40cm²		
		64										43.9									
		81										43.4	2.1								
												42.6									
												42.6									

Remarks

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CONSOLIDATED UNDRAINED / DRAINED TRIAXIAL COMPRESSION TEST.

JOB: OGUN RIVER SAND

SAMPLE NO: A TEST NO: B CELL NO: 3

INITIAL DIMENSIONS

Ave Height (Hc) 76.2 mm
Ave Diameter (Do) 38.1 mm
Volume (Vo) 86.87 c.cm
Wet Density 1.99 mg/c.m

MOISTURE CONTENTS INITIAL FINAL

Wet Weight (grm) 173.8
Dry Weight "
Moisture "
Moisture Content %

DATE	TIME	P.W.P GAUGE READING kN/m^2	VOLUMETRIC STRAIN: BURETTE READING c.cm	VOL CHANGE ΔV c.cm	ΔV/Vc %	AXIAL STRAIN: STRAIN DIAL READING x mm	$E=\frac{\Delta h}{Hc}$ %	APPLIED LOAD (PR No FACTOR div): DIAL READING	LOAD kN	CROSS SECTIONAL AREA: $100+\frac{\Delta V}{V}$ %	100-E%	C.S.A $Ac\frac{100+\Delta V}{100-E\%}$ Sq.cm	$\sigma_1-\sigma_3$ Deviator Stress kN/m^2	σ_1' MAJOR PRIN'L STRESS kN/m^2	σ_3' MINOR PRIN'L STRESS kN/m^2
7/5/84	08.20	0	39.6	0	0	360	12.30	96	0.32	100	100	11.40	254		
	10.00		39.6	0	0	390	13.24	207	0.70	100	86.76	13.14	532.4		
-	11.00		39.8	+0.2	0.24	420	14.26	208	0.70	99.76	85.74	13.26	530.2		
-	12.00		40.0	+0.4	0.47	450	15.28	208	0.70	99.53	84.72	13.39	525.1		
-	13.00		40.1	+0.5	0.59	480	16.30	207	0.70	99.41	83.70	13.54	516.7		
8/5/88	09.00		40.1	+ 0.5	0.59	570	17.32	208	0.70	99.41	82.68	13.71	513.0		

$\sigma_1 - \sigma_3 = 532.4 - 6.8 = 525.6\ KN/m^2$

$\sigma_3 = 100\ KN/m^2$

$\sigma_1 = 525.6 + 100 = 626\ KN/m^2$

SATURATION STAGE

By Flooding
By Back Pressure
Assumed
B - Value %

CONSOLIDATION STAGE

Cell Pressure 100 kN/m^2
Back Pressure "
Cons Pressure 100 "
Drainage: Top/Base/Both
Filter Drains: Yes/No

SAMPLE DIMENSIONS AFTER CONSOLIDATION

Volume Change (ΔV) = 1.6 cm^3
Final Volume (Vc) = 85.26 cm^3
(Vo - ΔV) =
Final Height (Hc) = 74.8 cm^3
Ho - (1-ΔV/3V) =
Final Area (Ac) = 11.40 cm^2
(Vc/Hc) =

STRAIN @ .00021 mm/sec

TEST CELL PRESSURE (kN/m^2) 100

c' = 0 (kN/m^2)
φ' = 47 degrees

TESTS A.B.C. A SATURATION & CONSOLIDATION OF SAMPLE IN TRIAXIAL CELL. B PERMEABILITY IN TRIAXIAL CELL C DISSIPATION TEST.

JOB: OGUN RIVER SAND | SAMPLE No: A | TEST No: B | CELL No.: 3

INITIAL		INITIAL		FINAL		CONSOLIDATION
AVERAGE HEIGHT 'Ho'	76.2 cm	Wet Weight	173.0 gms	Wet Weight	gms	Time for consolidation min
AVERAGE DIAMETER	38.1 mm	Moisture Content	%	Dry Weight	gms	Coefficient of consolidation (Cv =)
VOLUME OF SAMPLE 'Vo'	86.87 Cu.cm	Wet Density	1.99 Mg/c.m	Moisture	gms	Mv =
		Dry Density	"	Moisture Content	%	K =
		Weight of Porous plate	grm			

DATE	TIME	t (min)	σ_3 KN/Sq.m Gauge No	PORE PRESSURE BASE OF SAMPLE GAUGE No ZERO: Gauge (KN/Sq.m)	Diff	Dissi	Applied Pre TOP Gauge No (KN/Sq.m)	Applied Pre BASE Gauge No	B $\frac{\Delta u}{\Delta \sigma_3}$	VOLUME MEASUREMENTS CELL Gauge Readg	CELL Volume Cu.cm	TOP Gauge Readg	TOP Volume Cu.cm	BASE Gauge Readg	BASE Volume Cu.cm	PERMEABILITY COEFFICIENT K: DIFFERENTIAL HEAD 'h' $i = \frac{h}{HO}$ KN/m²	cm	Hydraulic Gradient	Quantity of flow (q) Cu.cm/Sec	K $= q/iA$ cm/sec	Type of Test
4/5/84	17.00	0	100				Closed					41.2		Dv	=	1.6cc					
												41.1									
7/5/84	~~08.15~~											39.6	1.6	Vc	=	85.87	− 1.60				
																=85.27cc					
															Hc	= 7.62	$\left(1 - \frac{1.60}{86.87}\right)$				
																	= 7.48cm				
																Ac	$= \frac{85.27}{7.48}$				
																	= 11.4cm²				

Remarks

CONSOLIDATED ~~UNDRAINED~~ / DRAINED TRIAXIAL COMPRESSION TEST.

JOB: OGUN RIVER SAND

SAMPLE NO: A | TEST NO: C | CELL NO: 3

INITIAL DIMENSIONS

Ave Height (Hc) 762 mm
Ave Diameter (Do) 38.1 mm
Volume (Vo) 86.87 c.cm
Wet Density 1.99 Mg/c.m

MOISTURE CONTENTS — INITIAL — FINAL

Wet Weight (gm) 170.3
Dry Weight "
Moisture "
Moisture Content %

DATE	TIME	P.W.P GAUGE READING KN/m^2	VOLUMETRIC STRAIN: BURETTE READING C.cm	VOL CHANGE ΔV C.cm	ΔV/Vc %	AXIAL STRAIN: STRAIN DIAL READING X mm	$\varepsilon=\frac{\Delta h}{Hc}$ %	APPLIED LOAD: PR No FACTOR div — DIAL READING	LOAD KN	CROSS SECTIONAL AREA: $100+\frac{\Delta V}{V}$ %	100−E% %	C.S.A $Ac\frac{100+\Delta V}{100-E\%}$ Sq.cm	$\sigma_1-\sigma_3$ Deviator Stress KN/m^2	σ_1' MAJOR PRIN'L STRESS KN/m^2	σ_3' MINOR PRIN'L STRESS KN/m^2
9/5/84	08.15	0	39.4	0	0	510	17.32	208	0.70	100	100	11.40	513.0		
–	09.20		39.4	0	0	540	18.45	434	1.47	100	81.55	13.98	1049.4		
–	10.40		39.4	0	0	570	19.47	436	1.47	100	80.53	14.16	1041.5		
–	11.40		39.4	0	0	600	20.49	437	1.48	100	79.51	14.34	1030.5		
–	12.40		39.4	0	0	630	21.52	432	1.46	100	78.48	14.53	1005.2		
–	13.40		39.4	0	0	660	22.54	430	1.45	100	77.46	14.72	987.9		
–	14.40		39.4	0	0	690	23.57	431	1.46	100	76.43	14.92	977.0		

$$\sigma_1 - \sigma_3 = 1049.4 - 9.1 = 1040.3\ KN/m^2$$

$$\sigma_3 = 200\ KN/m^2$$

$$\sigma_1 = 1040.3 + 200 = 1240\ KN/m^2$$

SATURATION STAGE

By Flooding
By Back Pressure
Assumed
B - Value %

CONSOLIDATION STAGE

Cell Pressure KN/m^2
Back Pressure "
Cons Pressure "
Drainage: Top/Base/Both
Filter Drains: Yes/No

SAMPLE DIMENSIONS AFTER CONSOLIDATION

Volume Change (ΔV) = 0.7 cm^3
Final Volume (Vc) = 86.16 cm^3
(Vc − ΔV) =
Final Height (Hc) = 75.6 mm
Ho − (1−ΔV/3V) =
Final Area (Ac) = 11.40 cm^2
(Vc/Hc) =

STRAIN 0.00021 mm/sec

TEST CELL PRESSURE (KN/m^2) 200

c' = 0 (KN/m^2)
φ' = 47 degrees

TESTS A.B.C. A SATURATION & CONSOLIDATION OF SAMPLE IN TRIAXIAL CELL. B PERMEABILITY IN TRIAXIAL CELL C DISSIPATION TEST.

JOB: OGUN RIVER SAND | SAMPLE No: A | TEST No: C | CELL No. 3

INITIAL	INITIAL	FINAL	CONSOLIDATION
AVERAGE HEIGHT 'Ho' 76.2 mm	Wet Weight 175.0 gms	Wet Weight gms	Time for consolidation min
AVERAGE DIAMETER 38.1 mm	Moisture Content %	Dry Weight gms	Coefficient of consolidation (Cv =)
VOLUME OF SAMPLE 'Vo' 86.87 Cu.cm	Wet Density Kg/c.m	Moisture gms	Mv =
	Dry Density "	Moisture Content %	K =
	Weight of Porous plate grm		

DATE	TIME	t (min)	σ_3 KN/Sq.m	Gauge No	Pore Pressure Base of Sample (Gauge No / Zero) Gauge (KN/Sq.m)	Diff	Dissi	Applied Pre Top Gauge No (KN/Sq.m)	Applied Pre Base Gauge No (KN/Sq.m)	B $\frac{\Delta u}{\Delta\sigma_3}$	Cell Gauge Readg	Cell Volume Cu.cm	Top Gauge Readg	Top Volume Cu.cm	Base Gauge Readg	Base Volu Cu.cm	Differential Head 'h' $i = \frac{h}{Ho}$ KN/m²	cm	Hydraulic Gradient	Quantity of flow (q) Cu.cm/Sec	K =q/iA cm/sec	Type of Test
5/5/84	11.30	0	200					Closed					40.1									
	17.00												40.0									
9/5/84	08.15												39.4	0.7								

Av = 0.7cc

Vc = 86.87 − 0.70

= 86.17cc

= 7.62 (1 − 0.7/86.87)

= 7.56cm

Ac = 86.17/7.56

= 11.40 cm²

Remarks

CONSOLIDATED ~~UNDRAINED~~ / DRAINED TRIAXIAL COMPRESSION TEST.

JOB: OGUN RIVER SAND

SAMPLE NO: B TEST NO: A CELL NO: 16

INITIAL DIMENSIONS
- Ave Height (Hc) 76.2 mm
- Ave Diameter (Do) 38.1 mm
- Volume (Vo) 86.87 c.cm
- Wet Density 1.94 mg/c.m

MOISTURE CONTENTS | INITIAL | FINAL
- Wet Weight (gm) 168.5
- Dry Weight "
- Moisture "
- Moisture Content ς

AGE	TIME	P.W.P GAUGE READING kN/m^2	VOLUMETRIC STRAIN: BURETTE READING C.cm	VOL CHANGE ΔV C.cm	ΔV/Vc %	AXIAL STRAIN: STRAIN DIAL READING X 0.25mm	$E=\frac{\Delta h}{Hc}$ %	APPLIED LOAD (PR No 0.00178KN FACTOR div): DIAL READING	LOAD KN	CROSS SECTIONAL AREA: 100+ΔV %	100−E% %	C.S.A $Ac\frac{100+\Delta V}{100-E\%}$ Sq.cm	$\sigma_1-\sigma_3$ Deviator Stress kN/m^2	σ_1' MAJOR PRIN'L STRESS kN/m^2	σ_3' MINOR PRIN'L STRESS kN/m^2
7/5/84	12.25	0	97.2	0	0	0	0	0	0	100	100	11.40	0		
8/5/84	09.40	0	96.0	1.2	-1.42	30	1.03	128	0.22	98.88	98.97	11.36	200.6		
"	10.30		96.0	1.2	1.42	60	2.05	131	0.23	98.58	97.95	11.47	203.2		
"	11.30		96.2	1.0	-1.18	90	3.08	135	0.24	98.82	96.92	11.63	206.6		
"	12.30		96.4	0.8	-0.94	120	4.10	134	0.24	99.06	95.90	11.77	202.5		
"	13.30		96.4	0.8	-0.94	150	5.13	134	0.24	99.06	94.87	11.90	200.3		
"	14.30		96.6	0.6	-0.71	180	6.16	134	0.24	99.29	93.84	12.06	182.9		

$\sigma_1-\sigma_3$ = 206.6 − 1.7 = 205KN/M²

σ_3 = 50.0 − 0 = 50 "

σ_1 = 205 + 50 = 255KN/M²

SATURATION STAGE
- By Flooding
- By Back Pressure
- Assumed
- B – Value ς

CONSOLIDATION STAGE
- Cell Pressure 50 kN/m^2
- Back Pressure – "
- Cons Pressure 50 "
- Drainage: Top/~~Base~~/~~Both~~
- Filter Drains: ~~Yes~~/No

SAMPLE DIMENSIONS AFTER CONSOLIDATION
- Volume Change (ΔV) = 2.2cm³
- Final Volume (Vc) = (Vo − ΔV) = 84.67cm³
- Final Height (Hc) = Ho − (1−ΔV/3V) = 74.3mm
- Final Area (Ac) = (Vc/Hc) = 11.4cm²

STRAIN = 0.0002mm/sec

TEST CELL PRESSURE (kN/m^2) 50

- c' = 0 (kN/m^2)
- ɸ' = 42 degrees

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TESTS A.B.C. A SATURATION & CONSOLIDATION OF SAMPLE IN TRIAXIAL CELL. B PERMEABILITY IN TRIAXIAL CELL C DISSIPATION TEST.

JOB: OGUN RIVER SAND | SAMPLE No: B | TEST No: A | CELL No.: 16

INITIAL	INITIAL	FINAL	CONSOLIDATION
AVERAGE HEIGHT 'Ho' 76.2 mm	Wet Weight 168.5 gms	Wet Weight gms	Time for consolidation min
AVERAGE DIAMETER 38.1 mm	Moisture Content %	Dry Weight gms	Coefficient of consolidation (Cv =)
VOLUME OF SAMPLE 'Vo' 86.87 Cu.cm	Wet Density 1.94 Mg/c.m	Moisture gms	Mv =
	Dry Density "	Moisture Content %	K =
	Weight of Porous plate grm		

DATE	TIME	t (min)	σ_3 KN/Sq.m Gauge No	PORE PRESSURE BASE OF SAMPLE GAUGE No ZERO: Gauge (KN/Sq.m)	Diff	Dissi	Applied Pre TOP Gauge No (KN/Sq.m)	Applied Pre BASE Gauge No	B $\frac{\Delta u}{\Delta \sigma_3}$	VOLUME MEASUREMENTS CELL Gauge Readg	CELL Volume Cu.cm	TOP Gauge Readg	TOP Volume Cu.cm	BASE Gauge Readg	BASE Volume Cu.cm	PERMEABILITY COEFFICIENT K: DIFFERENTIAL HEAD 'h' $i = \frac{h}{Ho}$ KN/m²	cm	Hydraulic Gradient	Quantity of flow (q) Cu.cm/Sec	K =q/iA cm/sec	Type of Test
17/4/84	16.00	0	300				0	250													
18/4/84			"	180			closed														
"			400	275	95		"	"	0.95							DV	= 2.2cc				
			300				0	250													
		0	50				closed					99.4				VC	= 86.87 -	2.2			
24/4/84		1/4										99.0					= 84.67cc				
		1										98.9									
		2 1/4										98.8				HC	= 7.62 (1 -	$\frac{2.2}{86.87}$)			
		4										98.8									
		6 1/4										98.6									
		9										98.5					= 7.43cm				
		12 1/4										98.4									
		16										98.4									
		25										98.4				AC	= $\frac{84.67}{7.43}$				
		36										98.4									
		49										98.2									
		64										98.2					11.40cm²				
		81										98.2									
		100										98.4									
												98.0									
	8a.m											97.2	DV	=	2.2cm						

Remarks

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CONSOLIDATED UNDRAINED / DRAINED TRIAXIAL COMPRESSION TEST.

JOB: OGUN RIVER SAND

SAMPLE NO: B TEST NO: B CELL NO: 16

INITIAL DIMENSIONS

Ave Height (Ho) 76.2 mm
Ave Diameter (Do) 38.1 mm
Volume (Vo) 86.87 c.cm
Wet Density 1.94 mg/c.m

MOISTURE CONTENTS		INITIAL	FINAL
Wet Weight	(grm)	168.5	
Dry Weight	"		
Moisture	"		
Moisture Content	%		

DATE	TIME	P.W.P Gauge Reading kN/m²	Volumetric Strain: Burette Reading c.cm	Vol Change ΔV c.cm	ΔV/Vc %	Axial Strain: Strain Dial Reading x.025mm	$E=\frac{\Delta h}{Hc}$ %	Applied Load (PR No Factor 0.00178 kN/div): Dial Reading	Load kN	Cross Sectional Area: $100+\frac{\Delta V}{V}$ %	100−E% %	C.S.A $Ac\frac{100+\Delta V}{100-E\%}$ Sq.cm	$\sigma_1-\sigma_3$ Deviator Stress kN/m²	σ_1' Major Prin'l Stress kN/m²	σ_3' Minor Prin'l Stress kN/m²
9/5/84	08.15	0	95.6	0	0	180	6.16	124	0.22	100	100	11.40	182.9		
"	09.20		95.6	0	0	210	7.18	260	0.46	100	92.82	12.28	376.6		
"	11.00		95.6	0	0	240	8.21	267	0.48	100	91.79	12.42	382.5		
"	12.00		96.0	+0.4	0.47	270	9.23	263	0.47	99.53	90.77	12.50	374.3		
"	13.00		96.0	+0.4	0.47	300	10.26	246	0.44	99.53	89.74	12.65	346.2		

SATURATION STAGE

By Flooding
By Back Pressure
Assumed
B − Value %

CONSOLIDATION STAGE

Cell Pressure 100 kN/m²
Back Pressure – "
Cons Pressure 100 "
Drainage: Top/Base/Both
Filter Drains; Yes/No

SAMPLE DIMENSIONS AFTER CONSOLIDATION

Volume Change (ΔV) = 1.0 cm³
Final Volume (Vc) = (Vo − ΔV) = 85.87 cc
Final Height (Hc) = Ho − (1−ΔV/3V) = 75.3 mm
Final Area (Ac) = (Vc/Hc) = 11.40 cm²

STRAIN = 0.00021 mm/sec

TEST CELL PRESSURE 100 (kN/m²)

c' = 0 (kN/m²)
ϕ' = 42 degrees

TESTS A.B.C. A SATURATION & CONSOLIDATION OF SAMPLE IN TRIAXIAL CELL B PERMEABILITY IN TRIAXIAL CELL C DISSIPATION TEST.

JOB: OGUN RIVER SAND | SAMPLE No: B | TEST No: B | CELL No.: 16

INITIAL	INITIAL	FINAL	CONSOLIDATION
AVERAGE HEIGHT 'Ho' 76.2 mm	Wet Weight 168.5 gms	Wet Weight gms	Time for consolidation min
AVERAGE DIAMETER 38.1 mm	Moisture Content %	Dry Weight gms	Coefficient of consolidation (Cv =)
VOLUME OF SAMPLE 'Vo' 86.87 Cu.cm	Wet Density Mg/c.m	Moisture gms	Mv =
	Dry Density "	Moisture Content %	K =
	Weight of Porous plate grm		

DATE	TIME	t (min)	σ_3 KN/Sq.m	Gauge No	Pore Pressure Base of Sample, Gauge No, Zero: Gauge (KN/Sq.m)	Diff	Dissi	Applied Pre TOP Gauge No (KN/Sq.m)	BASE Gauge No	B $\frac{\Delta u}{\Delta \sigma_3}$	Volume Measurements CELL Gauge Readg	CELL Volume Cu.cm	TOP Gauge Readg	TOP Volume Cu.cm	BASE Gauge Readg	BASE Volu Cu.cm	Permeability Coefficient K: Differential Head 'h' $i = \frac{h}{Ho}$ KN/L²	cm	Hydraulic Gradient	Quantity of flow (q) Cu.cm/Sec	K =q/iA cm/sec	Type of Test
8/5/83	14.30	0	100					closed					96.6									
9/5/84	08.15		"					"	"				95.6	1.0								

DV = 1.0cc

VC = 86.87 − 1.0

= 85.87cc

HC = 7.62 (1 − $\frac{1.0}{86.87}$)

= 7.53cm

AC = $\frac{85.87}{7.53}$

= 11.40cm²

Remarks

CONSOLIDATED ~~UNDRAINED~~ / DRAINED TRIAXIAL COMPRESSION TEST.

JOB: OGUN RIVER SAND

SAMPLE NO: B   TEST NO: C   CELL NO: 16

INITIAL DIMENSIONS

Ave Height (Ho) 76.2 mm
Ave Diameter (Do) 38.1 mm
Volume (Vo) 86.87 c.cm
Wet Density 1.94 gm/c.cm

MOISTURE CONTENTS INITIAL FINAL

Wet Weight (gm) 168.5
Dry Weight "
Moisture "
Moisture Content %

DATE	TIME	P.W.P. GAUGE READING KN/m^2	VOLUMETRIC STRAIN: BURETTE READING C.cm	VOLUMETRIC STRAIN: VOL CHANGE ΔV C.cm	VOLUMETRIC STRAIN: ΔV/Vc %	AXIAL STRAIN: STRAIN DIAL READING X mm	AXIAL STRAIN: $E=\frac{\Delta h}{Hc}$ %	APPLIED LOAD (PR No. 00178KN/div FACTOR): DIAL READING	APPLIED LOAD: LOAD KN	CROSS SECTIONAL AREA: $100 \pm \frac{\Delta V}{V}$ %	CROSS SECTIONAL AREA: 100−E% %	C.S.A $Ac\frac{100 \pm \Delta V}{100-E\%}$ Sq.cm	$\sigma_1 - \sigma_3$ Deviator Stress KN/m^2	σ_1' MAJOR PRIN'L STRESS KN/m^2	σ_3' MINOR PRIN'L STRESS KN/m^2
10/5/84	08.15	0	94.4	0	0	300	10.26	246	0.44	100	100	11.40	346.2		
"	09.05		94.2	-0.2	0.23	330	11.29	552	0.98	99.77	88.71	12.82	766.2		
"	10.10		94.0	-0.4	0.47	360	12.31	568	1.01	99.53	87.69	12.94	780.9		
"	11.10		94.0	-0.4	0.47	390	13.34	571	1.02	99.53	86.66	13.09	776.2		
"	12.10		94.0	-0.4	0.47	420	14.36	581	1.03	99.53	85.64	13.25	780.1		
"	13.10		94.0	-0.4	0.47	450	15.39	504	1.02	99.53	84.61	13.41	761.5		
"	14.10		94.0	-0.4	0.47	480	16.42	567	1.01	99.53	83.58	13.57	743.2		
"	15.10		94.0	-0.4	0.47	510	17.44	560	1.00	99.53	82.56	13.74	725.1		

$\sigma_1 - \sigma_3$ = 780.9 − 6.9 = 774 KN/M^2

σ_3 = 200 − 0 = 200 KN/M

σ_1 = 774 + 200 = 974 KN/M^2

SATURATION STAGE

By Flooding
By Back Pressure
Assumed
B − Value %

CONSOLIDATION STAGE

Cell Pressure 200 KN/m^2
Back Pressure − "
Cons Pressure 200 "
Drainage: Top/~~Base~~/~~Both~~
Filter Drains: ~~Yes~~/No

SAMPLE DIMENSIONS AFTER CONSOLIDATION

Volume Change (ΔV) = 1.6cc
Final Volume (Vc) = 85.26cc
(Vo − ΔV) =
Final Height (Hc) = 74.8mm
Ho − (1−ΔV/3V) =
Final Area (Ac) = 11.40cm^2
(Vc/Hc) =

STRAIN = 0.00021 mm/sec

TEST CELL PRESSURE 200 (KN/m^2)

c' = 0 (KN/m^2)
ϕ' = 42 degrees

TESTS A.B.C. A SATURATION & CONSOLIDATION OF SAMPLE IN TRIAXIAL CELL. B PERMEABILITY IN TRIAXIAL CELL C DISSIPATION TEST.

JOB: OGUN RIVER SAND | SAMPLE No: B | TEST No: C | CELL No.: 16

INITIAL	INITIAL	FINAL	CONSOLIDATION
AVERAGE HEIGHT 'Ho' 76.2 mm	Wet Weight 168.5 gms	Wet Weight gms	Time for consolidation min
AVERAGE DIAMETER 38.1 mm	Moisture Content %	Dry Weight gms	Coefficient of consolidation (Cv =)
VOLUME OF SAMPLE 'Vo' 86.87 Cu.c	Wet Density Mg/c.m	Moisture gms	Mv =
	Dry Density "	Moisture Content %	K =
	Weight of Porous plate grm		

DATE	TIME	t (min)	σ_3 KN/Sq.m Gauge No	PORE PRESSURE BASE OF SAMPLE (GAUGE No / ZERO) Gauge (KN/Sq.m)	Diff	Dissi	Applied Pre TOP Gauge No (KN/Sq.m)	Applied Pre BASE Gauge No	B $\frac{\Delta u}{\Delta \sigma_3}$	VOLUME MEASUREMENTS CELL Gauge Readg	CELL Volume Cu.cm	TOP Gauge Readg	TOP Volume Cu.cm	BASE Gauge Readg	BASE Volume Cu.cm	PERMEABILITY COEFFICIENT K: DIFFERENTIAL HEAD 'h' $i = \frac{h}{Ho}$ KN/L²	cm	Hydraulic Gradient	Quantity of flow (q) Cu.cm/Sec	K =q/iA cm/sec	Type of Test
9/5/84	14.00	0	200				closed					96.0				DV	= 1.6 cc				
			"									95.8									
10/5/84	08.10		"									94.4	1.6cc			VC	= 86.87 - 1.60				
																	= 85.27 cc				
																HC	= 7.62 (1 - $\frac{1.60}{86.87}$)				
																	= 7.48cm				
																AC	= $\frac{85.27}{7.48}$				
																	= 11.40cm²				

Remarks

CONSOLIDATED UNDRAINED / DRAINED TRIAXIAL COMPRESSION TEST.

JOB: OGUN RIVER SAND

SAMPLE NO: C TEST NO: B CELL NO: 7

INITIAL DIMENSIONS

Ave Height (H_c) 76.2 mm
Ave Diameter (D_o) 38.1 mm
Volume (V_o) 86.87 c.cm
Wet Density 1.50 mg/c.m

MOISTURE CONTENTS INITIAL FINAL

Wet Weight (gm) 130.3
Dry Weight "
Moisture "
Moisture Content %

DATE	TIME	P.W.P GAUGE READING KN/m²	VOLUMETRIC STRAIN: BURETTE READING c.cm	VOL CHANGE ΔV c.cm	ΔV/Vc %	AXIAL STRAIN: STRAIN DIAL READING x mm	$\varepsilon=\frac{\Delta h}{Hc}$ %	APPLIED LOAD (PR No 0.00178KN/div factor): DIAL READING	LOAD KN	CROSS SECTIONAL AREA: $100\pm\frac{\Delta V}{V}$ %	100-E% %	C.S.A. $Ac\frac{100\pm\Delta V}{100-E}$ Sq.cm	$\sigma_1-\sigma_3$ Deviator Stress KN/m²	σ_1' MAJOR PRIN'L STRESS KN/m²	σ_3' MINOR PRIN'L STRESS KN/m²
30/4/84	08.50	0	98.0	0	0	180	6.0	76	0.135	100	100	11.40	11.7		
	09.30		97.9	-0.1	0.12	210	7.0	174	0.309	99.88	93.00	12.25	252.8		
	10.33		97.9	-0.1	0.12	240	8.0	176	0.313	99.88	92	12.37	253.1		
	11.30		97.8	-0.2	0.23	270	9.0	178	0.317	99.77	91	12.50	253.4		
	12.28		97.8	-0.2	0.23	300	10.0	180	0.320	99.77	90	12.64	253.4		
	13.53		97.6	-0.4	0.46	340	11.0	182	0.324	99.54	89	12.75	254.0		
	14.38		97.6	-0.4	0.46	360	12.0	182	0.324	99.54	88	12.90	251.1		
	15.40		97.8	-0.2	0.23	390	13.0	183	0.326	99.77	87	13.07	249.1		
	16.30		97.8	-0.2	0.23	420	14.0	183	0.326	99.77	86	13.23	246.2		
	17.00		98.0	0	0	450	15.0	182	0.324	100.00	85	13.41	241.4		
1/5/84	10.45		98.2	+0.2	0.23	480	16.0	181	0.322	100.23	84	13.60	236.8		

$\sigma_1-\sigma_3$ = 254.0 - 6.0 = 248KN/M²

σ_3 = 100 - 0 = 100 "

σ_1 = 248 + 100 = 348KN/M²

SATURATION STAGE

By Flooding
By Back Pressure
Assumed
B - Value %

CONSOLIDATION STAGE

Cell Pressure 100 KN/m²
Back Pressure - "
Cons Pressure 100 "
Drainage: Top/Base/Both
Filter Drains; Yes/No

SAMPLE DIMENSIONS AFTER CONSOLIDATION

Volume Change (ΔV) = 0.2cc
Final Volume (Vc) = 86.7cc
(Vo - ΔV) =
Final Height (Hc) = 76.0mm
Ho - (1-ΔV/3V) =
Final Area (Ac) = 11.4cm²
(Vc/Hc) =

STRAIN = 0.0002 mm/sec

TEST CELL PRESSURE 100 (KN/m²)

C' = 0 (KN/m²)
ϕ' = 34 degrees

TESTS A.B.C. A SATURATION & CONSOLIDATION OF SAMPLE IN TRIAXIAL CELL. B PERMEABILITY IN TRIAXIAL CELL C DISSIPATION TEST.

JOB: OGUN RIVER SAND | SAMPLE No: A | TEST No: B | CELL No.: 7

INITIAL		INITIAL		FINAL		CONSOLIDATION	
AVERAGE HEIGHT 'Ho'	76.2 mm	Wet Weight	130.3 gms	Wet Weight	gms	Time for consolidation	min
AVERAGE DIAMETER	38.1 mm	Moisture Content	%	Dry Weight	gms	Coefficient of consolidation (Cv =)	
VOLUME OF SAMPLE 'Vo'	86.87 Cu.cm	Wet Density	Mg/c.m.	Moisture	gms	Mv =	
		Dry Density	"	Moisture Content	%	K =	
		Weight of Porous plate	gms				

DATE	TIME	t (min)	σ_3 KN/Sq.m	Gauge No	Pore Pressure, Base of Sample (Gauge No, Zero): Gauge (KN/Sq.m)	Diff	Dissi	Applied Pre Top: Gauge No (KN/Sq.m)	Applied Pre Base: Gauge No	B $\frac{\Delta u}{\Delta \sigma_3}$	Volume Measurements Cell: Gauge Readg	Cell: Volume Cu.cm	Top: Gauge Readg	Top: Volume Cu.cm	Base: Gauge Readg	Base: Volume Cu.cm	Permeability Coefficient K: Differential Head 'h' KN/m²	cm ($i = \frac{h}{Ho}$)	Hydraulic Gradient	Quantity of flow (q) Cu.cm/Sec	K = q/iA cm/sec	Type of Test
26/4/84	09.25	0	100					closed					98.2									
27/4/84	09.25							open	closed				98.2									
"	15.00												98.0									
	8.00												98.0	0.2								

DV = 0.2cc

VC = 86.87 - 0.2
= 86.67cc

HC = 7.62 $(1 - \frac{0.2}{86.87})$
= 7.60 cm

AC = $\frac{86.67}{7.60}$
= 11.40cm²

Remarks

CONSOLIDATED ~~UNDRAINED~~ / DRAINED TRIAXIAL COMPRESSION TEST.

JOB: OGUN RIVER SAND

SAMPLE NO: C | TEST NO: A | CELL NO: 7

INITIAL DIMENSIONS

Ave Height (Hc) 76.2 mm
Ave Diameter (Do) 38.1 mm
Volume (Vo) 86.87 c.cm
Wet Density 150 kg/c.m

MOISTURE CONTENTS INITIAL FINAL

Wet Weight (gm) 130.3
Dry Weight "
Moisture "
Moisture Content %

AGE	TIME	P.W.P. Gauge Reading KN/m^2	Volumetric Strain: Burette Reading C.cm	Vol Change ΔV C.cm	$\Delta V/Vc$ %	Axial Strain: Strain Dial Reading X mm	$E=\frac{\Delta h}{Hc}$ %	Applied Load: PR No 0.00178 KN/div Factor — Dial Reading	Load KN	Cross Sectional Area: $100 \pm \frac{\Delta V}{V}$ %	100−E%	C.S.A $Ac\frac{100\pm\Delta V/V}{100-E\%}$ Sq.cm	$\sigma_1-\sigma_3$ Deviator Stress KN/m^2	σ_1' Major Prin'l Stress KN/m^2	σ_3' Minor Prin'l Stress KN/m^2
25/4/84	10.25	0	98.2	0	0	0	0	0	0	100	100	11.40	0		
	12.23		98.0	-0.2	0.23	30	1.0	69	0.12	99.77	99	11.49	106.9		
	13.45		97.8	-0.4	0.46	60	2.0	74	0.13	99.54	98	11.58	113.7		
	14.45		97.8	-0.4	0.46	90	3.0	77	0.14	99.54	97	11.70	117.1		
	15.50		97.6	-0.6	0.69	120	4.0	81	0.14	99.31	96	11.79	122.2		
	16.50		97.8	-0.4	0.46	150	5.0	80	0.14	99.54	95	11.94	119.2		
26/4/84	09.25		98.0	-0.2	0.23	180	6.0	76	0.14	99.77	94	12.10	111.7		

$\sigma_1 - \sigma_3 = 122.2 - 2.2 = 120\ KN/m^2$

$\sigma_3 = 50 - 0 = 50.0$

$\sigma_1 = 120 + 50 = 170\ KN/m^2$

SATURATION STAGE

By Flooding
By Back Pressure
Assumed
B – Value %

CONSOLIDATION STAGE

Cell Pressure 50 KN/m^2
Back Pressure "
Cons Pressure 50 "
Drainage: Top/Base/Both
Filter Drains; Yes/No

SAMPLE DIMENSIONS AFTER CONSOLIDATION

Volume Change (ΔV) = 0.2 cc
Final Volume (Vc) = 86.7 cc
(Vo − ΔV) =
Final Height (Hc) = 76.01 mm
Ho − (1−ΔV/3V) =
Final Area (Ac) = 11.40 cm^2
(Vc/Hc) =

STRAIN 0.00021 mm/sec

TEST CELL PRESSURE (KN/m^2) 50

C' = 0 (KN/m^2)
ϕ' = 34 degrees

25/4/84 light off at 17 hrs

26/4/84 light on at 08.17 hrs

TESTS A.B.C. A SATURATION & CONSOLIDATION OF SAMPLE IN TRIAXIAL CELL. B PERMEABILITY IN TRIAXIAL CELL C DISSIPATION TEST.

JOB: OGUN RIVER SAND | SAMPLE No: A | TEST No: A | CELL No.: 7

INITIAL		INITIAL		FINAL		CONSOLIDATION	
AVERAGE HEIGHT 'Ho'	76.2 mm	Wet Weight	130.3 gms	Wet Weight	gms	Time for consolidation	min
AVERAGE DIAMETER	38.1 mm	Moisture Content	%	Dry Weight	gms	Coefficient of consolidation (Cv =)	
VOLUME OF SAMPLE 'Vo'	86.87 Cu.c	Wet Density	1.50 Kg/c.m	Moisture	gms	Mv =	
		Dry Density	"	Moisture Content	%	K =	
		Weight of Porous plate	grm				

DATE	TIME	t (min)	σ_3 KN/Sq.m Guage No	Pore Pressure Base of Sample Gauge No Zero: Gauge (KN/Sq.m)	Diff	Dissi	Applied Pre TOP Gauge No (KN/Sq.m)	Applied Pre BASE Gauge No (KN/Sq.m)	B $\frac{\Delta u}{\Delta \sigma_3}$	Cell Gauge Readg	Cell Volume Cu.cm	Top Gauge Readg	Top Volume Cu.cm	Base Gauge Readg	Base Volu Cu.cm	Differential Head 'h' $i = \frac{h}{Ho}$ KN/m²	cm	Hydraulic Gradient	Quantity of flow (q) Cu.cm/Sec	K = q/iA cm/sec	Type of Test
16/4/84	16.00	0	300				0	250													
18/4/84	14.00		-	175			Closed														
			400	270	95				0.95												
			300																		
24/4/84		0	50				Closed					98.4									
		¼										98.2									
		1										98.2									
		2¼										98.2									
		4										98.2									
		6¼										98.2									
		9										98.2									
		12¼										98.2									
		16										98.2									
		25										98.2									
		36										98.2									
		49										98.2									
		64										98.2									
		81										98.2									
		100										98.2									
	8a.m											98.2	0.2								

Dv = 0.2cc

Vc = 86.87 − 0.2
= 86.67 cc

Hc = $7.62 \left(1 - \frac{.02}{86.87}\right)$
= 7.60 cm

Ac = $\frac{86.67}{7.60}$
= 11.40 cm²

Remarks

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CONSOLIDATED ~~UNDRAINED~~ / DRAINED TRIAXIAL COMPRESSION TEST.

JOB: OGUN RIVER SAND

SAMPLE NO: C | TEST NO: A | CELL NO: 7

INITIAL DIMENSIONS

Ave Height (Hc) 76.2 mm
Ave Diameter (Do) 38.1 mm
Volume (Vo) 86.87 c.cm
Wet Density 1.50 gm/c.cm

MOISTURE CONTENTS		INITIAL	FINAL
Wet Weight	(gm)	130.3	
Dry Weight	"		
Moisture	"		
Moisture Content	%		

DATE	TIME	P.W.P. GAUGE READING	VOLUMETRIC STRAIN: BURETTE READING	VOL CHANGE ΔV	ΔV/Vc	AXIAL STRAIN: STRAIN DIAL READING x	$E=\frac{\Delta h}{Hc}$	APPLIED LOAD: PR Rc 0.00178 KN/div FACTOR — DIAL READING	LOAD	CROSS SECTIONAL AREA: $100\pm\frac{\Delta V}{V}$	100−E%	C.S.A $Ac\frac{100\pm\Delta V}{100-E\%}$	$\sigma_1-\sigma_3$ Deviator Stress	σ_1' MAJOR PRIN'L STRESS	σ_3' MINOR PRIN'L STRESS
		KN/m^2	C.cm	C.cm	%	mm	%		KN	%	%	Sq.cm	KN/m^2	KN/m^2	KN/m^2
4/5/84	08.15	0	98.2	0	0	480	16.0	181	0.322	100	100	11.40	236.8		
"	09.30		98.0	-0.2	0.23	510	17.20	266	0.473	99.77	82.80	13.74	344.6		
	10.30		97.8	-0.4	0.47	540	18.21	348	0.619	99.53	81.79	13.87	446.4		
	11.30		97.4	-0.8	0.93	570	19.22	367	0.653	99.07	80.78	13.98	467.1		
	12.30		97.0	-1.2	1.40	600	20.23	393	0.699	98.60	79.77	14.09	496.3		
	13.30		96.8	-1.4	1.63	630	21.24	390	0.694	98.37	78.76	14.24	487.4		
	14.30		97.0	-1.2	1.40	660	22.25	380	0.676	98.60	77.75	14.46	467.7		

$\sigma_1-\sigma_3$ = 496.3 − 9.7 = 486.6 KN/M²

σ_3 = 200 − 0 = 200cc

σ_1 = 486.6 + 200 = 687 KN/M²

SATURATION STAGE

By Flooding
By Back Pressure
Assumed
B − Value %

CONSOLIDATION STAGE

Cell Pressure 200 kN/m²
Back Pressure − "
Cons Pressure 200 "
Drainage: Top/Base/Both
Filter Drains; Yes/No

SAMPLE DIMENSIONS AFTER CONSOLIDATION

Volume Change (ΔV) = 1.0cc
Final Volume (Vc) = 85.82cc
(Vo − ΔV) =
Final Height (Hc) = 75.2mm
Ho − (1−ΔV/3V) =
Final Area (Ac) = 11.4cm
(Vc/Hc) =

STRAIN = 0.0002 mm/sec

TEST CELL PRESSURE 100 (KN/m²)

C' = 0 (KN/m²)
Ø' = 34 degrees

4/5/84 off at 17.00 hrs.
5/5/84 on at 08.15 hrs.

TESTS A.B.C. A SATURATION & CONSOLIDATION OF SAMPLE IN TRIAXIAL CELL. B PERMEABILITY IN TRIAXIAL CELL C DISSIPATION TEST.

JOB: OGUN SARIVER SAND | SAMPLE No: C | TEST No: C | CELL No.: 7

INITIAL	INITIAL	FINAL	CONSOLIDATION
AVERAGE HEIGHT 'Ho' 76.2 mm	Wet Weight 130.3 gms	Wet Weight gms	Time for consolidation min
AVERAGE DIAMETER 38.1 mm	Moisture Content %	Dry Weight gms	Coefficient of consolidation (Cv =)
VOLUME OF SAMPLE 'Vo 86.87 Cu.cm	Wet Density Kg/c.m.	Moisture gms	Mv =
	Dry Density "	Moisture Content %	K =
	Weight of porous plate grm		

DATE	TIME	t (min)	σ_3 KN/Sq.m Gauge No	PORE PRESSURE BASE OF SAMPLE GAUGE No ZERO: Gauge (KN/Sq.m)	Diff	Dissi	Applied Pre TOP Gauge No (KN/Sq.m)	BASE Gauge No	B $\frac{\Delta u}{\Delta \sigma_3}$	VOLUME MEASUREMENTS CELL Gauge Readg	CELL Volume Cu.cm	TOP Gauge Readg	TOP Volume Cu.cm	BASE Gauge Readg	BASE Volu Cu.cm	PERMEABILITY COEFFICIENT K DIFFERENTIAL HEAD 'h' $i = \frac{h}{HO}$ KN/m^2	cm	Hydraulic Gradient	Quantity of flow (q) Cu.cm/Sec	K =q/iA cm/sec	Type of Test
1/5/84	08.20	0	200					closed				99.2									
3/5/84							open	closed				99.2				DV =	1.00cc				
												98.2									
												98.2	1.00			VC =	86.87	-	1.00		
																=	85.87cc				
																HC =	7.62 (1	-	$\frac{1.0}{86.87}$)		
																=	7.53cm				
																AC =	$\frac{85.87}{7.53}$				
																=	11.40cm^2				

Remarks

TRIAXIAL COMPRESSION (UNDRAINED)

5.0cm diameter, 10.0cm long,

black cotton soil sample.

Stress Dial 0.0001" (0.00254mm)	Strain Dial 0.001" (0.0254mm)	ΔL $x10^{-3}$m	Strain ϵ_1 $x10^{-2}$	Axial Stress σ_1 kN/m^2
10	1	0.025	0.025	17.5
20	3	0.075	0.075	34.99
30	6	0.15	0.15	53.95
40	9	0.225	0.225	69.89
50	12	0.30	0.30	87.29
60	16	0.40	0.40	104.65
70	24	0.60	0.60	119.36
80	32	0.80	0.80	138.97
90	43	1.075	1.075	155.91
100	80	2.00	2.00	171.60

Proving Ring Constant = 3.44 N/division.

A_o = 1.96 $x10^{-3}m^2$

Cell Pressure = 105 kN/m^2

Wet Weight = 329g

Moisture Content = 5.26%

Date: 26/10/83

TRIAXIAL COMPRESSION (UNDRAINED)

5.0cm diameter, 10.0cm long,

black cotton soil sample.

Stress Dial 0.0001" (0.00254mm)	Strain Dial 0.001" (0.0254mm)	ΔL $\times 10^{-3}$ m	Strain ϵ_1 $\times 10^{-2}$	Axial Stress σ_1 kN/m^2
10	5	0.125	0.125	17.49
20	11	0.275	0.275	34.92
30	22	0.450	0.450	52.30
35	55	2.825	2.825	68.07

Proving Ring Constant = 3.44 N/division.

A_o = 1.96 x10^{-3}m^2

Cell Pressure = 35 kN/m^2

Wet Weight = 323 g

Moisture Content = 5.26%

Date: 26/10/83

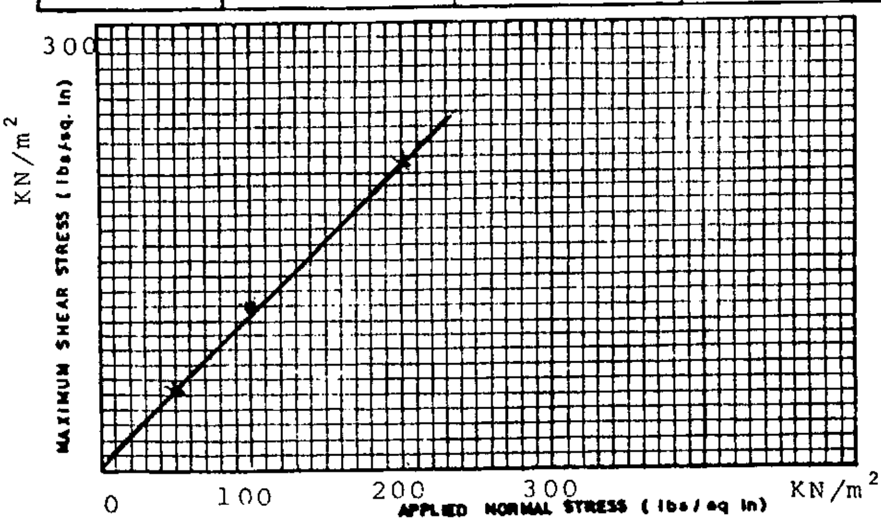
~~QUICK UN~~DRAINED SHEAR BOX TEST

Job. .... **Date** 30.4.84

Sample No. Beach Sand **Type** REMOULDED **Size** 6 sq cm x 2cm

Specimen No	A	B	C	D	Wet Weight (gms)				
Proving Ring No	7	4	8	6	Dry Weight (gms)	1	4	7.	6
Normal Stress KN/m² (psi)	50	100	200		Moisture Content (%)				
Rate Of Strain 0.0097 54 mm PER MINUTE					DRY Density (g/cc)	2	.	0	5

TIME (MIN)	STRAIN (%)	A VERTICAL	A LOAD DIAL	B VERTICAL	B LOAD DIAL	C VERTICAL	C LOAD DIAL	D VERTICAL	D LOAD DIAL
0			0		0		0		
1/4			18		18		40		
1/2			28		37		62		
3/4			35		53		86		
1			45		74		95		
1 1/2			53		83		119		
2			56		92		132		
2 1/2			58		98		147		
3			60		105		163		
3 1/2			61		110		175		
4			61		114		196		
4 1/2			60		116		205		
5					118		210		
5 1/2		61x0.34 x 98.07			119		215		
6		36			120		218		
6 1/2					120		220		
7		= 56.5 KN/m²		120 x 0.34 x 98.07			222		
7 1/2				36			224	225x0.34x98.07	
8				= 111.21KN/m²			225	36	
8 1/2							225	= 208.4KN/m²	
MAX. SHEAR LOAD			lbs = psi		lbs = psi		lbs = psi		lbs = psi



COHESION

C_s = 0 P.S.I.

ANGLE OF FRICTION

Ø = 47 DEGREES

~~QUICK~~ ~~UN~~DRAINED SHEAR BOX TEST

Job. .... Date 30.4.84

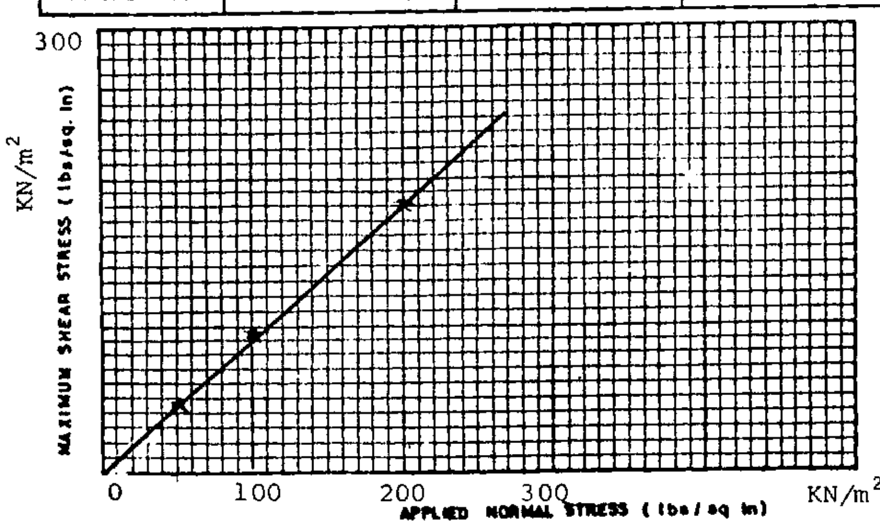
Sample No. Beach Sand Type REMOULDED Size 6sq. cm x 2cm

	A	B	C	D
Specimen No	A	B	C	D
Proving Ring No	7	4	8	6
Normal Stress (~~psi~~) kN/m²	50	100	200	

Rate Of Strain 0.009754 mm PER MINUTE

Wet Weight (gms)				
Dry Weight (gms)	1	3	7.	4
Moisture Content (%)				
DRY Density (g/cc)	1.	9	0	8

TIME (MIN)	STRAIN (%)	A VERTICAL	A LOAD DIAL	B VERTICAL	B LOAD DIAL	C VERTICAL	C LOAD DIAL	D VERTICAL	D LOAD DIAL
0			0		0		0		
¼			8		17		39		
½			15		30		57		
¾			23		40		86		
1			32		53		98		
1½			38		75		109		
2			44		82		128		
2½			47		88		139		
3			49		93		156		
3½			50		96		168		
4			51		98		175		
4½			51		99		180		
5			51		100		185		
5½		51x0.34x98.07			101		189		
6		36			101		192		
6½					101		194		
7		= 47.2 KN/m²			101x0.34x98.07		195	195x0.34x98.07	
7½							195	36	
8					93.6KN/m²		194	= 180.6KN/m²	
8½									
MAX. SHEAR LOAD		lbs = psi		lbs = psi		lbs = psi		lbs = psi	



COHESION

C = 0 P.S.I.

ANGLE OF FRICTION

Ø = 43 DEGREES

~~QUICK UN~~DRAINED SHEAR BOX TEST

Job. .... Date 30.4.84

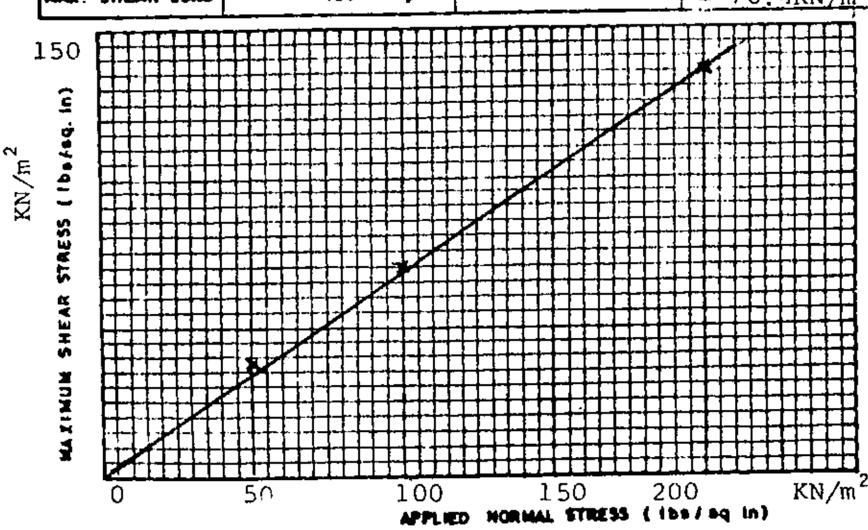
Sample No. Beach Sand Type REMOULDED Size 6 sq. cm x 2cm

Specimen No	A	B	C	D
Proving Ring No	7	4	8	6
Normal Stress (psi) KN/m²	50	100	200	

Wet Weight (gms)				
Dry Weight (gms)	1	1	5	.9
Moisture Content (%)				
Dry Density (g/cc)	1	.	6	1

Rate Of Strain 0.009754mm PER MINUTE

TIME (MIN)	STRAIN (%)	A VERTICAL	A LOAD DIAL	B VERTICAL	B LOAD DIAL	C VERTICAL	C LOAD DIAL	D VERTICAL	D LOAD DIAL
0			0		0		0		
1/4			14		13		17		
1/2			18		20		37		
3/4			22		28		49		
1			25		39		60		
1 1/2			27		50		73		
2			29		60		88		
2 1/2			30		66		98		
3			31		72		118		
3 1/2			33		76		125		
4			33		79		131		
4 1/2			34		81		138		
5			35		83		140		
5 1/2			35		84		142		
6			+5		85		143		
6 1/2		40x0.34x98.07 / 36			86		144		
7					86		145		
7 1/2			37.0KN/m²		86		145		
8					-10		145	144x0.34x98.07/36	
8 1/2					76x0.34x98.07/36			=134.3KN/m²	
MAX. SHEAR LOAD		lbs =	psi	lbs =	psi	= 70.4KN/m²		lbs =	psi



COHESION

C = 0 P.S.I.

ANGLE OF FRICTION

Ø = 34 DEGREES

UNSATURATED

~~QUICK~~ ~~UNDRAINED~~ SHEAR BOX TEST

Job. .... Date 30.4.84

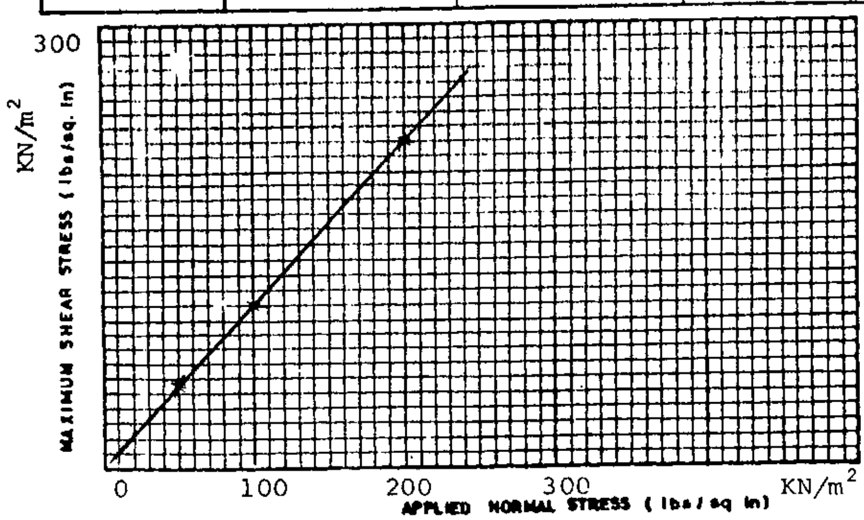
Sample No. BEACH SAND Type REMOULDED Size 6sq cm x 2cm

Specimen No	A	B	C	D
Proving Ring No	7	4	8	6
Normal Stress (~~psi~~) KN/m²	50	100	200	

Wet Weight (gms)				
Dry Weight (gms)	1	3	7.	4
Moisture Content (%)				
Dry Density g/cc	1.	9	0	8

Rate Of Strain 0.009754 mm PER MINUTE

TIME (MIN)	STRAIN (%)	A VERTICAL	A LOAD DIAL	B VERTICAL	B LOAD DIAL	C VERTICAL	C LOAD DIAL	D VERTICAL	D LOAD DIAL
0			0		0		0		
1/4			14		27		17		
1/2			24		42		47		
3/4			35		64		75		
1			45		81		92		
1 1/2			52		88		120		
2			55		95		140		
2 1/2			58		102		168		
3			59		110		188		
3 1/2			60		115		208		
4			61		118		220		
4 1/2			62		120		230		
5			62		121		235		
5 1/2			62		122		238		
6		62x0.34x98.07			122		240		
6 1/2		36			122		240		
7		= 57.4 KN/m²		122x0.34x98.07			240		
7 1/2				36			240 x	0.34 x 98.07	
8								36	
8 1/2				= 113.0 KN/m²			=	222.3 KN/m²	
MAX. SHEAR LOAD			lbs = psi		lbs = psi		lbs = psi		lbs = psi



COHESION

C = 0 P.S.I.

ANGLE OF FRICTION

Ø = 48 DEGREES

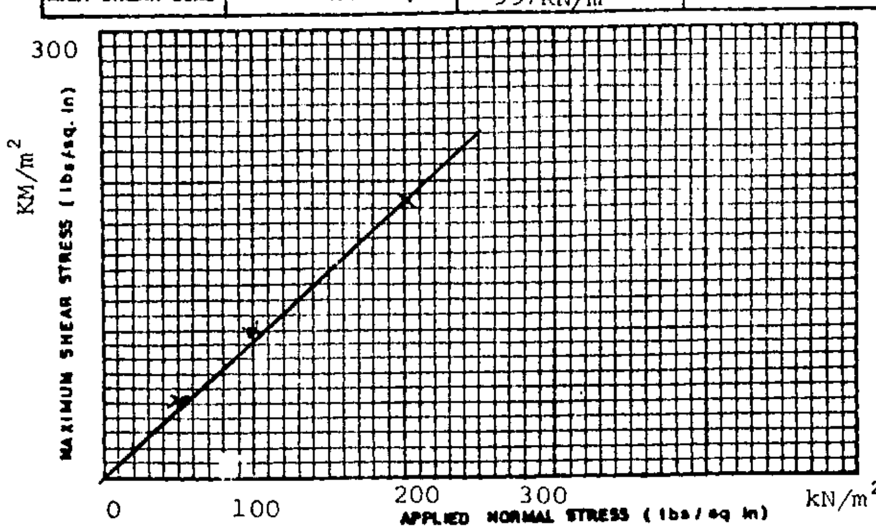
~~QUICK~~ UNDRAINED SHEAR BOX TEST

Job. .... Date. 3.5.84

Sample No. OGUN RIVER SAND Type. REMOULDED Size. 6sq cm x 2 cm

Specimen No	A	B	C	D	Wet Weight (gms)				
Proving Ring No	3	3	7	8	Dry Weight (gms)	1	4	3.	3
Normal Stress (psi) KN/m²	50	100	200		Moisture Content (%)				
Rate Of Strain 0.009754 mm PER MINUTE					Dry Density (g/cc)	1	.	9	9

TIME (MIN)	STRAIN (%)	A VERTICAL	A LOAD DIAL	B VERTICAL	B LOAD DIAL	C VERTICAL	C LOAD DIAL	D VERTICAL	D LOAD DIAL
0			0		0		0		
¼			2		8		17		
½			8		21		36		
¾			18		34		65		
1			25		43		80		
1½			30		56		114		
2			34		72		125		
2½			38		80		140		
3			41		88		151		
3½			44		96		175		
4			47		100		190		
4½			50		103		200		
5			53		166		207		
5½			56		110		212		
6			58		113		213		
6½			59		116		214	216x0.31x98.07	
7			60		117		214	36	
7½	61x0.37x98.07		61		118		213	= 182.4KN/m²	
8			61		118		+2		
8½	= 51.5KN/m²		61		118				
MAX. SHEAR LOAD		lbs = psi		99.7KN/m²		lbs = psi		lbs = psi	



COHESION

C = 0 P.S.I.

ANGLE OF FRICTION

Ø = 42 DEGREES

~~QUICK UN~~DRAINED SHEAR BOX TEST

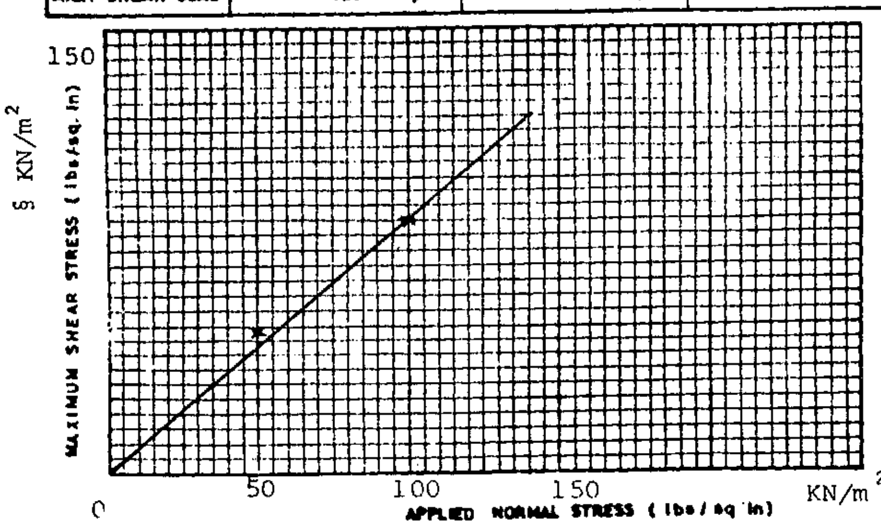
Job. .... Date. 3.5.84

Sample No. OGUN RIVER SAND Type. REMOULDED Size. 6sq cm x 2cm

	A	B	C	D
Specimen No	A	B	C	D
Proving Ring No	3	3	7	8
Normal Stress (psi) KN/m²	50	100	200	
Rate Of Strain 0.009754 mm PER MINUTE				

Wet Weight (gms)				
Dry Weight (gms)	1	3	9.	6
Moisture Content (%)				
Dry Density (g/cc)	1.	9	3	9

TIME (MIN)	STRAIN (%)	A VERTICAL	A LOAD DIAL	B VERTICAL	B LOAD DIAL	C VERTICAL	C LOAD DIAL	D VERTICAL	D LOAD DIAL
0			0		0		0		
¼			8		22		19		
½			16		33		35		
¾			24		43		45		
1			30		57		58		
1½			36		73		69		
2			40		80		80		
2½			44		86		94		
3			47		90		109		
3½			49		95		131		
4			50		98		148		
4½			53		99		159		
5			54		100		170		
5½			55		101		180		
6			55		101		186		
6½			53		100		190		
7		55x31x98.07			101x0.31x98.07		194		
7½		36			36		196	198x0.31x98.07	
8		= 46.5KN/m²			85.3KN/m²		198	36	
8½							198	= 167.2KN/m²	
MAX. SHEAR LOAD		lbs =	psi	lbs =	psi	lbs =	psi	lbs =	psi



COHESION

C = 0 P.S.I.

ANGLE OF FRICTION

Ø = 40 DEGREES

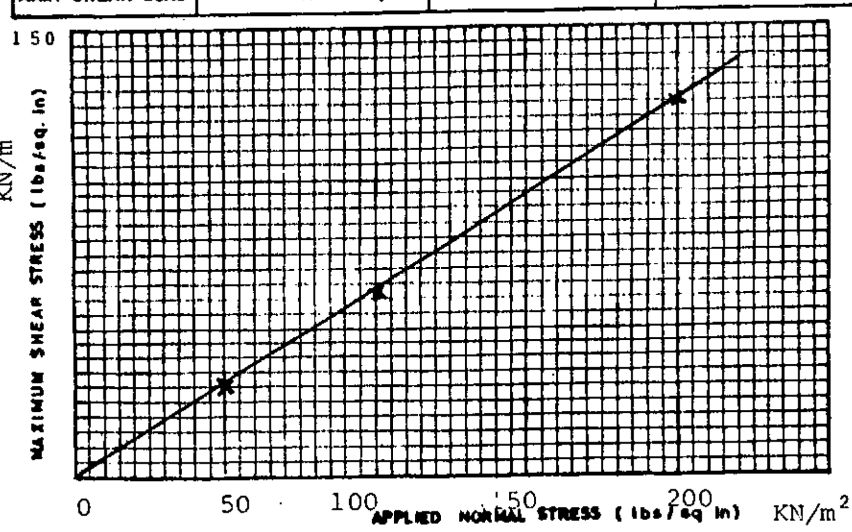
~~QUICK~~ ~~UN~~DRAINED SHEAR BOX TEST

Job.. Date 9.5.84

Sample No. OGUN RIVER SAND Type REMOULDED Size 6sq cm x 2 cm

Specimen No	A	B	C	D	Wet Weight (gms)				
Proving Ring No	3	3	7	8	Dry Weight (gms)	1	0	8	
Normal Stress KN/m²	50	100	200		Moisture Content (%)				
Rate Of Strain 0.009754 mm PER MINUTE					Dry Density g/cc	1	.	5	0

TIME (MIN)	STRAIN (%)	A VERTICAL	A LOAD DIAL	B VERTICAL	B LOAD DIAL	C VERTICAL	C LOAD DIAL	D VERTICAL	D LOAD DIAL
0			0		0		0		0
¼			77		14		30		
½			12		28		52		
¾			14		38		75		
1			17		50		90		
1½			22		59		105		
2			26		64		116		
2½			29		68		130		
3			31		70		136		
3½			33		72		139		
4			34		73		141		
4½			35		74		142		
5			36		75		143		
5½			36		76		144		
6			34		76		145		
6½		36x0.31x98.07			76		146		
7		36			76x0.31x98.07		146	746x0.31x98.7	
7½					36		145	36	
8		30.41 KN/m²			= 64.2KN/m²				
8½								= 123.3KN/m²	
MAX. SHEAR LOAD			lbs = psi		lbs = psi		lbs = psi		lbs = psi



COHESION

C = 0 P.S.I.

ANGLE OF FRICTION

Ø = 32 DEGREES

UNSATURATED

~~QUICK~~ ~~UN~~DRAINED SHEAR BOX TEST

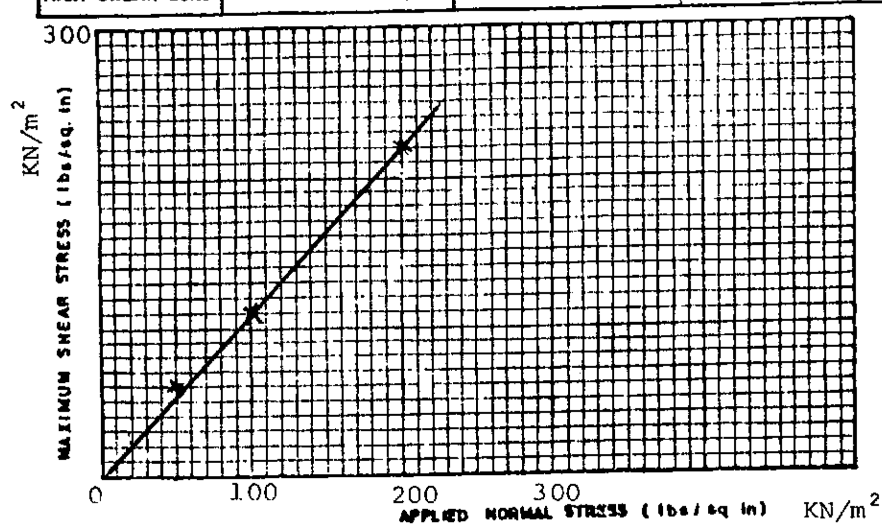
Job. .... Date 9.5.84

Sample No. OGUN RIVER SAND Type REMOULDED Size 6 sq. cm x 2 cm

Specimen No	A	B	C	D	Wet Weight (gms)				
Proving Ring No	3	3	7	8	Dry Weight (gms)	1	3	9	·6
Normal Stress (psi) kN/m^2	50	100	200		Moisture Content (%)				

Rate Of Strain 0.009754 mm PER MINUTE DRY Density (g/cc) 1.939

TIME (MIN)	STRAIN (%)	A VERTICAL	A LOAD DIAL	B VERTICAL	B LOAD DIAL	C VERTICAL	C LOAD DIAL	D VERTICAL	D LOAD DIAL
0			0		0		0		
1/4			16		22		37		
1/2			26		35		50		
3/4			42		58		84		
1			55		66		110		
1 1/2			60		80		138		
2			62		93		150		
2 1/2			63		110.		178		
3			64		122		190		
3 1/2			64		127		211		
4			64		130		228		
4 1/2					132		236		
5		64x0.3x98.07			133		246		
5 1/2		36			133		254		
6					133		259		
6 1/2		$= 54.2 KN/m^2$		133x0.31x98.07			263		
7				36			264	265x0.31x98.07	
7 1/2				$= 112.3 KN/m^2$			265	36	
8							265		
8 1/2							265	$= 223.8KN/m^2$	
MAX. SHEAR LOAD		lbs = psi		lbs = psi		lbs = psi		lbs = psi	



COHESION

C = 0 P.S.I.

ANGLE OF FRICTION

Ø = 48 DEGREES

APPENDIX B

Soil Cutting Tests.

OGUN RIVER SAND.

Date	H. Gauge	V. Gauge	Blade Width (mm)	β^o
22/10/83	4	3	100	30°
	5	4		
	7	4		
	11	4		
	13	3		
	9	3		
	8	3		
			f=20.5cm	
22/10/83	2	3	75	30°
	3	4		
	4	3.5		
	7	3		
	10	3		
	12	3		
	7	3		
			f=20.5cm	
22/10/83	1	3	50	30°
	3	3.5		
	5	3.5		
	7	3.5		
	3	3		
	3	1		
			f=20.5cm	

OGUN RIVER SAND.

Date	H. Gauge	V. Gauge	Blade Width (mm)	β°
22/10/83	3	3	100	45°
	3	3		
	5	4		
	5	4.5		
	5	3		
	6	3		
	7	3		
	6	3		
	5	3		
			f=19.5cm	
27/10/83	2	3	75	45°
	3	4		
	5	5		
	3	2		
	3	1.5		
	5	1.5		
	4	1		
			f=19.5cm	
27/11/83	2	2	50	45°
	2	3		
	2	3		
	3	3		
	3	2		
	3	2		
	4	2		
	4	1		
			f=19cm	

OGUN RIVER SAND.

Date	H. Gauge	V. Gauge	Blade Width (mm)	β°
27/10/83	4	2	100	60°
	4	4		
	4	2		
	5	1		
	5	1		
	5	1		
			f=15cm	
27/10/83	3	2	75	60°
	3	2.5		
	3	2		
	3	2		
	4	2		
	5	2		
	4	2		
			f=15cm	
27/10/83	2	1.5	50	60°
	2	2.5		
	2	2.5		
	2	2		
	3	2		
	2	1		
			f=14.5cm	

BEACH SAND

Date	H. Gauge	V. Gauge	Blade Width (mm)	β^{o}
28/10/83	3	4	100	30^{o}
	4	5		
	7	5		
	9	4.5		
	12	4		
	10	3		
			f=17cm	
5/11/83	2	4	75	30^{o}
	2	4.5		
	3	4		
	5	4		
	6	4		
	8	4		
	9	3.5		
	8	3		
			f=17cm	
5/11/83	3	2	50	30^{o}
	5	3		
	6	3		
	6	3		
	5	2		
	5	2		
			f=13.5cm	

BEACH SAND

Date	H. Gauge	V. Gauge	Blade Width (mm)	β^{o}
15/11/83	3	3	100	45°
	4	4		
	5	4		
	7	4		
	5	1		
	5	1		
			f=18.0cm	
15/11/83	3	2	75	45°
	3	3		
	4	3.5		
	5	4		
	6	3.5		
	6	3		
	5	2		
	5	2		
			f=16cm	
15/11/83	2	3	50	45°
	4	3.5		
	5	4		
	4	4		
	4	2		
	4	2		
			f=15cm	

BEACH SAND

Date	H. Gauge	V. Gauge	Blade Width (mm)	β^o
15/11/83	3	3	100	60^o
	3	3.5		
	3.5	4		
	5	3		
	4	2		
	4	2		
	3	1		
			f=17.5cm	
5/11/83	2	2.5	75	60^o
	2	3		
	3	3.5		
	3.5	3		
	4	2		
	3	1	50	
			f=15.5cm	
5/11/83	2	1		60^o
	2	2		
	3	2		
	3	2.5		
	3	2.5		
	3	2		
			f=15.5cm	

BLACK COTTON SOIL

Date	H. Gauge	V. Gauge	Blade Width (mm)	$\frac{\beta^{0}}{}$
24/11/83	4	2	100	30^{o}
	5	4		
	7	5		
	8	5		
	11	5.5		
	12.5	5.5		
	11	5		
	9	4.5	f=19cm	
24/11/83	3	3	75	30^{o}
	3	4		
	3	4.5		
	4	5		
	5	5		
	6	5		
	8	4		
	10	4		
	9	3		
			f=16.5cm	
24/11/83	2	2.5	50	30^{o}
	2	3		
	2	3		
	3	3		
	5	3		
	6	3		
	5	2	f=15cm	

BLACK COTTON SOIL.

Date	H. Gauge	V. Gauge	Blade Width (mm)	β^{o}
19/11/83	6	3	100	45^{o}
	8	6		
	10	6		
	11	6.5		
	8	6.5		
	8	5		
			f=16cm	
19/11/83	1	3.5	75	45^{o}
	2	4.5		
	4	5		
	6	5		
	7	5		
	4	4		
			f=15cm	
19/11/83	2	3	50	45^{o}
	3	4		
	4	5		
	6	5		
	6	5		
	6	4.5		
			f=15cm	

BLACK COTTON SOIL

Date	H. Gauge	V. Gauge	Blade Width (mm)	β°
24/11/83	3	4	100	60°
	4	6		
	4	7		
	5	7.5		
	5	6		
	6	6		
			f=13.5cm	
24/11/83	3	4	75	60°
	3	5.5		
	4	6		
	5	6		
	6	5.5		
	5	5.5		
			f=12.5cm	
24/11/83	3	3	50	60°
	4	4		
	4.5	5		
	4	5		
	4	4		
	3	4		
			f=13.5cm	

APPENDIX C

Derivations in the Boundary Energy Theory

1. Boundary Energy Theory

Boundary energy in soil cutting is defined as the product of the force and velocity along the boundary. The boundary forces are due to friction, cohesion, adhesion, surcharge and applied forces, acting on the boundary. The boundary in soil cutting is 0abc0, and is as shown in Figure C-1. The boundaries 0a, ab, bc and c0 are considered in the calculations using boundary energy theory.

2. Velocity V_s on Rupture Surface abc

From the geometry of soil cutting boundary in Figure C-1, the velocity diagram is as shown in Figure C-2. The velocity V_s on the rupture surface abc, is derived by the application of the sine rule to Figure C-2. If β is the inclination of blade to the vertical, V_o the horizontal velocity of the blade, V_b the velocity of the soil along the blade 0a, V_s the velocity of the soil along the slip line abc, then velocity V_s is as follows:

$$\frac{V_s}{\cos \beta} = \frac{V_o}{\cos\left(\frac{\pi}{4} - \left(\beta+\frac{\phi}{2}\right)\right)} \qquad \text{(C-1)}$$

3. Work dissipated along ab

Work done along ab is the product of cohesion C, velocity V, and the line element $rd\theta$, integrated

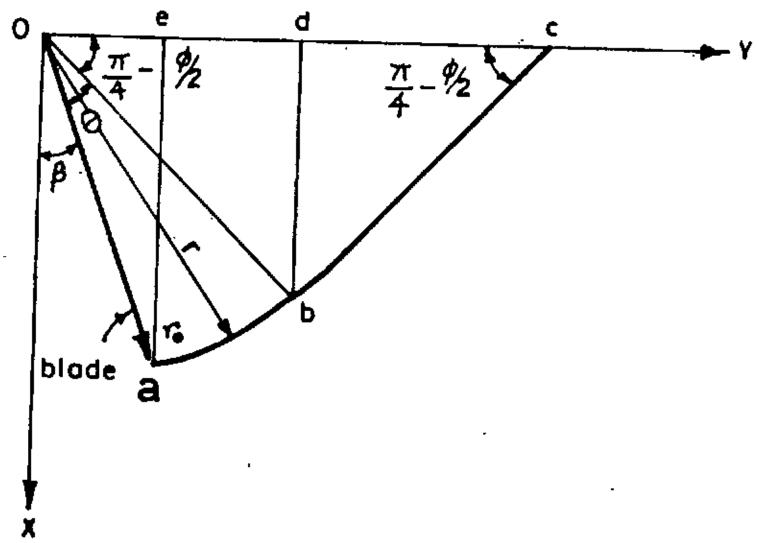


FIG. C-1 :-DIAGRAM FOR CALCULATING HORIZONTAL AND VERTICAL FORCES ON BLADE Oa, BY BOUNDARY ENERGY METHOD

V_o = Velocity of the blade in y direction

V_s = Velocity of the soil along the slip line abc

V_b = Velocity of the soil along the blade Oa

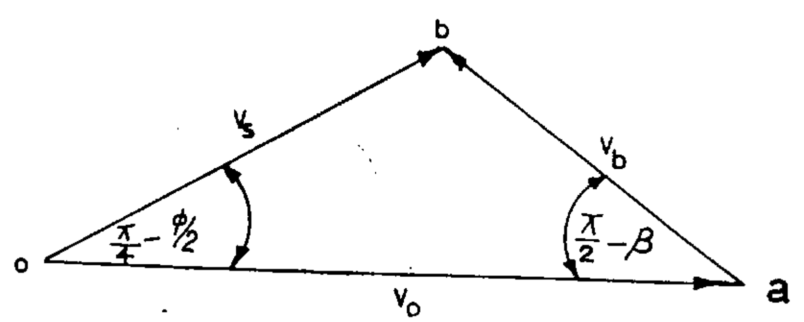


FIG. C-2 :-VELOCITY DIAGRAM OF THE KINEMATICS OF BLADE – SOIL MOTION AT FAILURE from the limits 0 and θ. Work done along ab is written as follows:

$$W_d = C \int_0^\theta r_0 \, e^{\theta \tan\phi} \, V_0 e^{\theta \tan\phi} \, d\theta \qquad \text{(C-2)}$$

Integrating equation (C-2) the following result is obtained

$$W_d = \frac{1}{2} \, C \, r_0 \, V_0 \, \cot\phi \, \left(e^{2\theta \tan\phi} - 1\right) \qquad \text{(C-3)}$$

The weight of the soil eabd is $(W_1 + \frac{1}{2} W_2 - W_3)$ since ab is a log-spiral, the component of this weight along ab is $(W_1 + \frac{1}{2} W_2 - W_3) \sin \phi$, where ϕ is the angle of the soil friction. The friction component of work done along ab, is the product of the weight component along ab and the velocity V_s along the slip line, and is written as follows:

$$W_{ab} = \left(W_1 + \frac{W_2}{2} - W_3\right) \frac{\sin\phi \, \cos \beta \, V_o}{\cos\left(\frac{\pi}{4} - \left(\beta + \frac{\phi}{2}\right)\right)} \qquad \text{(C-4)}$$

Equation (C-4), per unit V_o is the first term in Chapter 3 equation (3.17), for a unit width blade. Similarly equations (C-3) and (C-4), per unit V_o are the first and second terms in Chapter 3 equation (3.18) for unit width blade.

4. Work Dissipated along 0a

The velocity V_b along 0a, the blade interface is given by application of sine rule to Figure C-2 with the same procedure for determining V_s. The velocity V_b along 0a is expressed as follows:

$$V_b = V_o \frac{\sin(\frac{\pi}{4} - \phi/2)}{\cos(\frac{\pi}{4} - (\beta + \phi/2))} \qquad \text{(C-5)}$$

If H_{p_3} is the passive force on 0a, and acts at an angle δ^0 with the normal to the blade interface, then the component of H_{p_3} along the blade is H_{p_3} $\sin\delta$. The work done on 0a by H_{p_3} is the product of H_{p_3} $\sin\delta$ and velocity V_b along 0a, and it is expressed as follows:

$$W_{0ap} = \frac{H_{p_3} \sin\delta\ V_o \sin(\frac{\pi}{4} - \phi/2)}{\cos(\frac{\pi}{4} - (\beta + \phi/2))} \qquad \text{(C-6)}$$

The tangential component of force along 0a due to friction, by the wedge 0ae of weight W_3 is about $W_3 \tan\delta \cos(\frac{\pi}{4} - \frac{\phi}{2})$. The work dissipated along 0a due to friction, is the product of the tangential component of force due to friction and the velocity V_b along 0a, and is expressed as follows:

$$W_{0a} = \frac{W_3\ V_o \tan\delta \cos(\frac{\pi}{4} - \phi/2) \sin(\frac{\pi}{4} - \frac{\phi}{2})}{\cos(\frac{\pi}{4} - (\beta + \frac{\phi}{2}))} \qquad \text{(C-7)}$$

The work done along 0a due to adhesion is derived by multiplying the force due to adhesion c_a by the velocity V_b along the blade. This gives the following expression:

$$W_{0aa} = \frac{V_o c_a \sin(\frac{\pi}{4} - \phi/2)}{\cos(\frac{\pi}{4} - (\beta + \phi/2))} \qquad \text{(C-8)}$$

If H_{p_4} is the passive force on the blade 0a, inclined at angle $\beta°$ to the vertical, and if $\delta°$ is the friction angle between the blade and the soil, the horizontal component of passive force H_{p_4} is $H_{p_4} \cos(\beta-\delta)$ The work done is the product of the horizontal component of passive force and the blade horizontal velocity V_o. This work is expressed as follows:

$$W_{0bp} = H_{p_4} V_o \cos(\beta - \delta) \qquad \text{(C-9)}$$

The expression $\dfrac{\sin\delta \sin(\frac{\pi}{4} - \frac{\phi}{2})}{\cos(\frac{\pi}{4} - (\beta + \frac{\phi}{2}))}$ of equation (C-6)

is the first factor in the denominator of passive force H_{p_3} in equation (3.17). Equation (C-7) is the third term in equation (3.17) for a blade of unit width and velocity. Equations (C-7) and (C-8) are the fifth and sixth terms in equation (3.18), for a blade of unit width and velocity. The expression $\cos(\beta-\delta)$ of equation (C-9) is the first factor in the denominator of passive force H_{p_4} in equation (3.18)

5. <u>Work Dissipated Along bc</u>

The component of frictional force along bc due to weight $\frac{1}{2} W_2$ of wedge dbc is $\frac{1}{2} W_2 \cos$

$(\frac{\pi}{4} - \phi/2)$ tan ϕ. The friction component of work dissipated along bc is derived by multiply the frictional force along bc by the velocity V_s. The energy component per unit V_o on bc due to friction is written as follows:

$$W_{bc} = W_2 \cos(\frac{\pi}{4} - \phi/2) \frac{\tan\phi \cos\beta}{2\cos(\frac{\pi}{4} - (\beta + \phi/2))} \qquad \text{(C-10)}$$

In the passive Rankine zone 0abc0, 0b equals bc and the force on bc due to cohesion c is the product of c and length r and is written as follows:

$$cr = Cr_o \, e^{\theta \tan\phi} \qquad \text{(C-11)}$$

The energy component on bc due to cohesion is derived by multiplying cr in equation (C-11) by the velocity V_s on bc. Hence the cohesive component of energy per unit V_o on bc is written as follows:

$$W_{bcc} = \frac{r_o c \cos\beta \; e^{\theta \tan\phi}}{\cos(\frac{\pi}{4} - (\beta + \phi/2))} \qquad \text{(C-12)}$$

Equation (C-10) is the second term in equation (3.17) for a blade unit width. Equations (C-10) and (C-12) are the third and fourth terms in equation (3-18) for a blade unit width.

6. Recoverable Elastic and Irrecoverable Plastic Work in Soil Cutting

Consolidation and rebound equations are written respectively as follows (Terzaghi, 1947).

$$e = e_a + \lambda \log_e p \qquad \text{(C-13)}$$

$$e = e_a + \kappa \log_e p \qquad \text{(C-14)}$$

where e_a is the void ratio when the mean normal stress $p = 1$. Differentiating equations (C-13) and (C-14) the following expressions are derived:

$$de = \frac{\lambda dp}{p} \qquad \text{(C-15)}$$

$$de = \frac{\kappa dp}{p} \qquad \text{(C-16)}$$

The volumetric strain is

$$\frac{dv}{v} = \frac{de}{1+e} \qquad \text{(C-17)}$$

Substituting equation (C-17) into equations (C-15) and (C-16) respectively, the following expressions are derived

$$\frac{dv}{v} = \frac{\lambda}{1+e} \quad \frac{dp}{p} \qquad \text{(C-18)}$$

$$\frac{dv}{v} = \frac{\kappa}{1+e} \quad \frac{dp}{p} = dv^r \qquad \text{(C-19)}$$

where

dv^r = recoverable volumetric strain

The strain hardening of plastic strain, dv^p is derived by substracting equation (C-19) from equation (C-18). The following expression is derived (Wroth and Zyntynski, 1977).

$$\left(\frac{dv}{v} - \frac{dv^r}{v}\right) = dv^p = \frac{\lambda-\kappa}{1+e}\ \frac{dp}{p} \qquad \text{(C-20)}$$

The plastic strain energy per unit volume is the product of mean normal stress p and the plastic strain dv^p.

In soil cutting the volume of soil disturbed in unit time is bdV_o. Therefore the recoverable energy is the product of elastic strain energy and volume of soil disturbed. The elastic energy is written as follows:

$$E_r = \frac{bd\ V_o}{1+e}\ \kappa\ dp \qquad \text{(C-21)}$$

Similarly the plastic energy which is a product of disturbed volume and plastic strain energy is written as follows:

$$E_p = \frac{bd\ V_o}{1+e}\ (\lambda-\kappa)dp \qquad \text{(C-22)}$$

Since the side perspex glass of the soil bin is at rest, the mean stress perpendicular to surface 0ac0 is approximately ½ $K_o \gamma d$, where K_o is the coefficient of earth pressure at rest.

If the passive force H_p acts at angle $\delta°$ to the perpendicular on a blade inclined at angle β^0 to the vertical, then the passive horizontal force is $H_p \cos(\beta-\delta)$ an is assumed to be responsible for elastic work. In the calculation for internal energy dp is the average of stress increments acting on the soil boundary, in the direction of x, y, z coordinates. In the plastic work H_p is assumed to act horizontally. If the average stress acting on the soil-perspex glass is $\frac{1}{2}\gamma d K_o$, and if the surcharge pressure is P_q, then the mean stress dp is a third of the stresses in the soil cutting boundary. The mean stress dp is expressed as follows:

$$dp = \frac{H_p}{3bd} \cos(\beta-\delta) + \frac{1}{6}\gamma d K_o + \frac{P_q}{3} \qquad \text{(C-23)}$$

Substituting equation (C-23) into equation (C-21), the elastic energy is as follows:

$$E_r = \frac{H_p V_o \cos(\beta-\delta)\kappa}{3(1+e)} + \frac{\kappa\gamma b d^2 V_o K_o}{6(1+e)} + \frac{\kappa V_o bd P_q}{3(1+e)} \qquad \text{(C-24)}$$

Substituting $d = r_o \cos\beta$ into equation (C-24), the elastic energy is as follows:

$$E_r = \frac{H_p V_o \cos(\beta-\delta)\kappa}{3(1+e)} + \frac{\kappa\gamma b r_o^2 \cos^2\beta V_o K_o}{6(1+e)} + \frac{\kappa V_o b r_o \cos\beta P_q}{3(1+e)} \qquad \text{(C-25)}$$

The second and third terms in equation (C-25) for unit V_o are the fifth and seventh terms in equation (3.17) and the eight and tenth terms in equation (3.18). The first term factor, $\frac{\cos(\beta-\delta)}{3(1+e)}$ in equation (C-25) is the second term in the denominator of equations (3.17) and (3.18).

Similarly the mean stress dp for plastic work is expressed as follows:

$$dp = \frac{H_p}{3bd} + \frac{1}{6}\gamma dK_o + \frac{P_q}{3} \qquad (C-26)$$

Substituting equation (C-26) into equation (C-22), and noting that $d = r_o \cos\beta$, the plastic energy is as follows:

$$E_p = \frac{H_p V_o (\lambda-\kappa)}{3(1+e)} + \frac{(\lambda-\kappa)\gamma b r_o^2 \cos^2\beta \; V_o K_o}{6(1+e)}$$

$$+ \frac{(\lambda-\kappa)\; b\; r_o \cos\beta \, P_q V_o}{3(1+e)} \qquad (C-27)$$

The second and third terms in equation (C-27) for unit V_o are the sixth and eighth terms in equation (3.17) and the ninth and the eleventh terms in equation (3.18). The first term factor $\frac{\lambda - \kappa}{3(1+e)}$ in equation (C-27) is the third term in the denominator of equations (3.17) and (3.18).

7. Inertial Energy

The mass m of the soil accelerated in time t, is given from the volume of soil disturbed in time t, so that

$$m = \frac{\gamma}{g} bdV_o t \qquad \text{(C-28)}$$

The acceleration a is assumed to be the change in velocity V_s along the slip line, in time t, so that

$$a = \frac{V_s}{t} = \frac{V_o \cos \beta}{\cos \left(\frac{\pi}{4} - \left(\beta + \frac{\phi}{2}\right)\right) t} \qquad \text{(C-29)}$$

Newton's acceleration force F_a due to inertial effect is written as follows:

$$F_a = ma \qquad \text{(C-30)}$$

Substituting equations (C-28) and (C-29) into equation (C-30), the acceleration force is expressed as follows:

$$F_a = \frac{\gamma\, bd\, V_o^2 \cos \beta}{g \cos \left(\frac{\pi}{4} - \left(\beta + \frac{\phi}{2}\right)\right)} \qquad \text{(C-31)}$$

The energy due to inertial force is the product of F_a and velocity V_s, and noting that $d = r_o \cos \beta$, the inertial energy is expressed as follows:

$$W_{in} = \frac{b\gamma\, r_o V_o^3 \cos^3 \beta}{g \cos^2 (\frac{\pi}{4} - (\beta + \frac{\phi}{2}))} \qquad (C-32)$$

The inertial energy divided by V_o is the fourth term in equation (3.17) and the seventh term in equation (3.18).

APPENDIX D

Soil Cutting Equations by Previous Researchers

1. Equations by previous researchers

Soil cutting equations by previous researchers were based on three methods of analysis, namely static solution using plasticity techniques (Reece, 1965; Hettiaratchi et al., 1966; Hettiaratchi and Reece, 1974 and 1975), dimensional analysis (Wismer and Forth, 1969; Wismer and Luth, 1970) and limit equilibrium solution using method of characteristics (Yong et al., 1972). These equations were derived in terms of blade geometry, soil properties and imposed boundary conditions.

2. Plasticity solution

2.1 Reece and Hettiaratchi

In general the soil load P per unit width on a plane loaded interface can be expressed in terms of the variables (Osman, 1964).

$$P = f(\gamma, \phi, c, \delta, c_a, \alpha, z, q) \qquad \text{(D-1)}$$

Equation (D-1) can be written in terms of a set of dimensionless groups (Osman, 1964).

$$\frac{P}{\gamma z^2} = f\left(\frac{c}{\gamma z}, \frac{c_a}{\gamma z}, \frac{q}{\gamma z}, \phi, \delta, \alpha\right) \qquad \text{(D-2)}$$

Equation (D-2) can be written in form of additive equation (Reece et al., 1966).

$$P = \gamma z^2 N_\gamma + czN_c + c_a zN_a + qzN_q \quad (D-3)$$

The four terms in this equation represent the gravitational, cohesive, adhesive and surcharge components of the soil per unit width of interface respectively. The "N-factors" in the above equation represent pure numbers, which describe the shape of the soil failure surface and are thus functions of ϕ and δ and the geometry of the loaded interface. Values of N-factors are given by Reece et al. (1966). The interpolation relationship is written as follows (Reece et al., 1966).

$$N_\delta = N_{\delta=0} \left[\frac{N_{\delta=\phi}}{N_{\delta=0}} \right]^{\frac{\delta}{\phi}} \quad (D-4)$$

where N_δ is the required value of the appropriate N-factor (N_γ, N_c, N_a or N_q) and $N_{\delta=\phi}$ and $N_{\delta=0}$ are respectively the corresponding values of the N-factor at $\delta = \phi$ and $\delta = 0$.

The horizontal force is written as follows (Reece et al., 1966).

$$D = P \sin (\alpha + \delta) \quad (D-5)$$

For example from Figures D-1 to D-4, for black cotton soil, with friction angle $\phi = 16°$, density $\rho = 1.64$ Mg/m³, $\delta = 8°$, cohesion $c = 6.9$kN/m², surcharge $q = 0$, adhesion $c_a = 0$, and blade inclination $\beta = 30°$, the values of $N_\gamma = 0.8$ and $N_c = 1.8$. For a blade length and width of 100mm respectively, the horizontal force as derived from equation (D-3) and (D-5) gives

$$D = (1.64x9.807x0.8x\cos^2 30+69x\cos 30x1.8)$$
$$\sin 68 = 108.6N$$

3. Dimensional Analysis

3.1 Wismer and Forth

The horizontal component F_x of the draft force for cohesionless soil is given as follows (Wismer and Forth, 1969).

$$\frac{F_x}{\gamma b z^{0.5} \ell^{1.5}} = \alpha^{1.73}\left(\frac{z}{\ell \sin\alpha}\right)^{0.77} \left[1.05\left(\frac{z}{b}\right)^{1.1} + 1.26\frac{v^2}{g\ell} + 3.91\right] \quad \text{(D-6)}$$

For example for Ogun river sand with density, $\rho = 1.94 Mg/m^3$, blade angle $\alpha = 0.785$ radians, blade width $b = 100mm$, blade length $\ell = 100mm$ and blade velocity $v = 0.11cm/sec$, sustituted into equation (D-6) gives

$$\gamma b z^{0.5} \ell^{0.5} = 16.0$$

$$\alpha^{1.73} \left(\frac{z}{\ell \sin\alpha}\right)^{0.77} = 0.66$$

$$1.05\left(\frac{z}{b}\right)^{1.1} + 1.26\frac{v^2}{g\ell} + 3.91 = 4.64$$

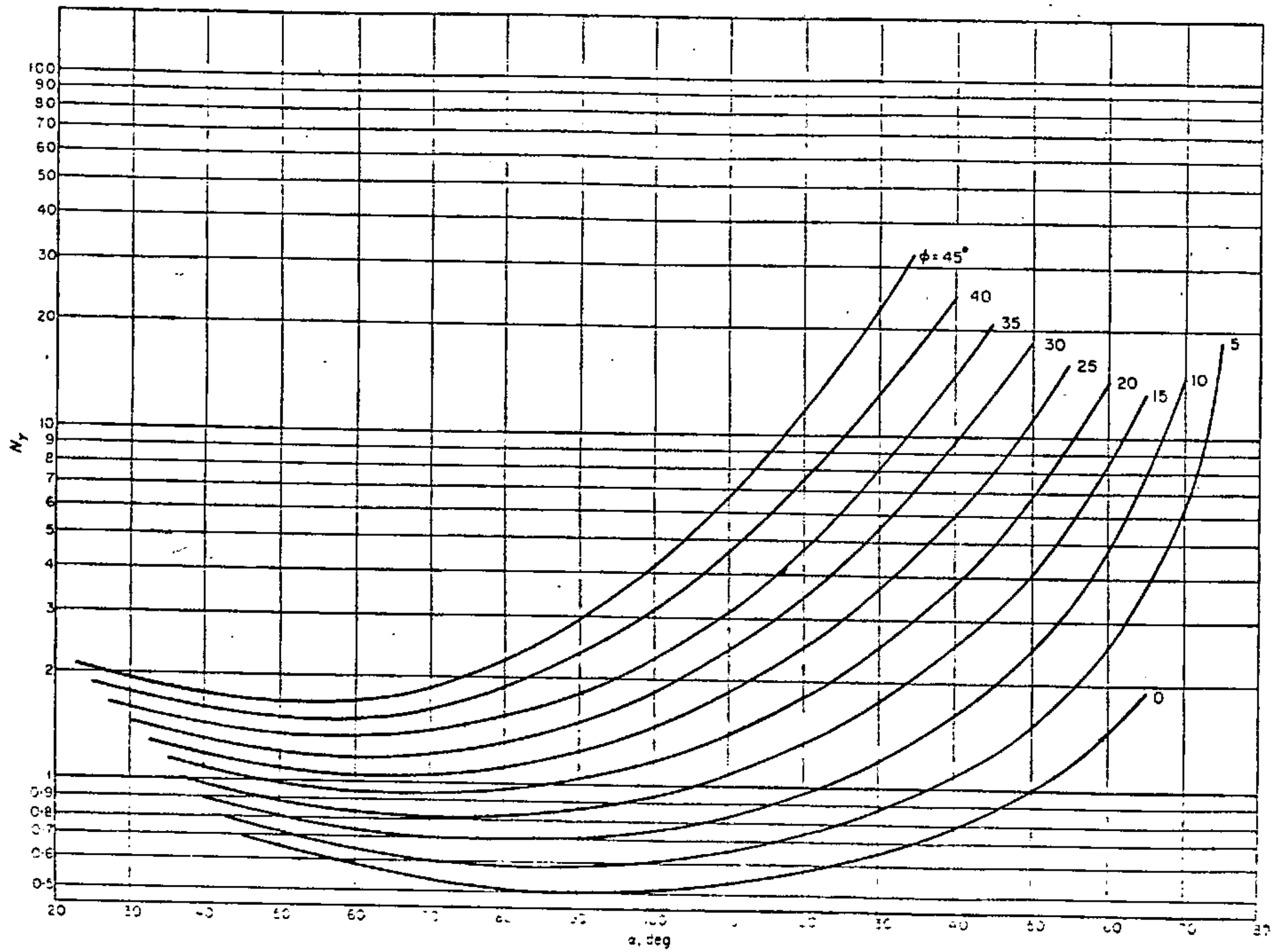


Fig D-1 *·Relationship between N_γ and α when δ = 0*

(After Reece et al.,1966)

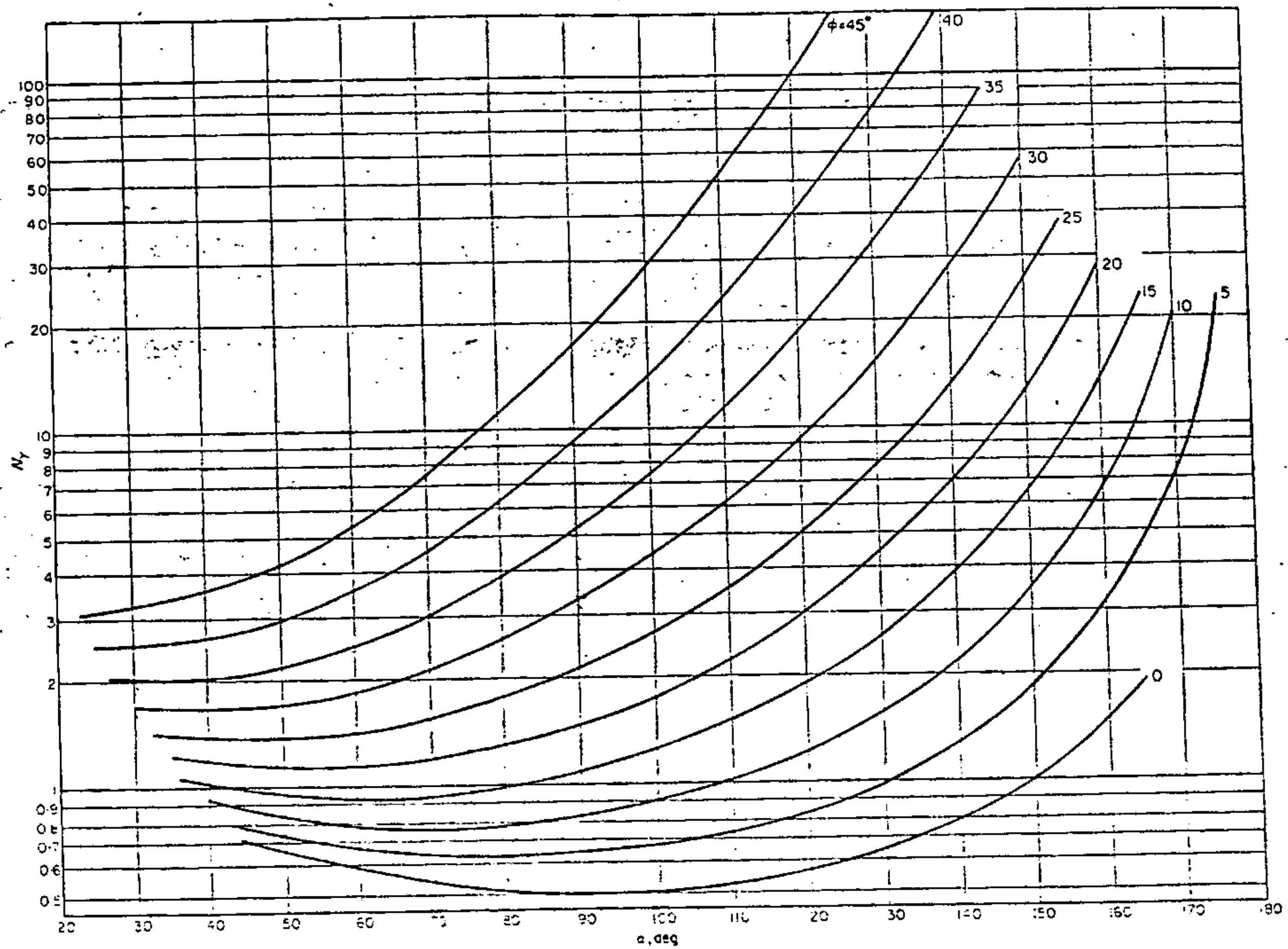


Fig. D-2: *Relationship between N_γ and α when δ = φ*

(After Reece et al, 1966)

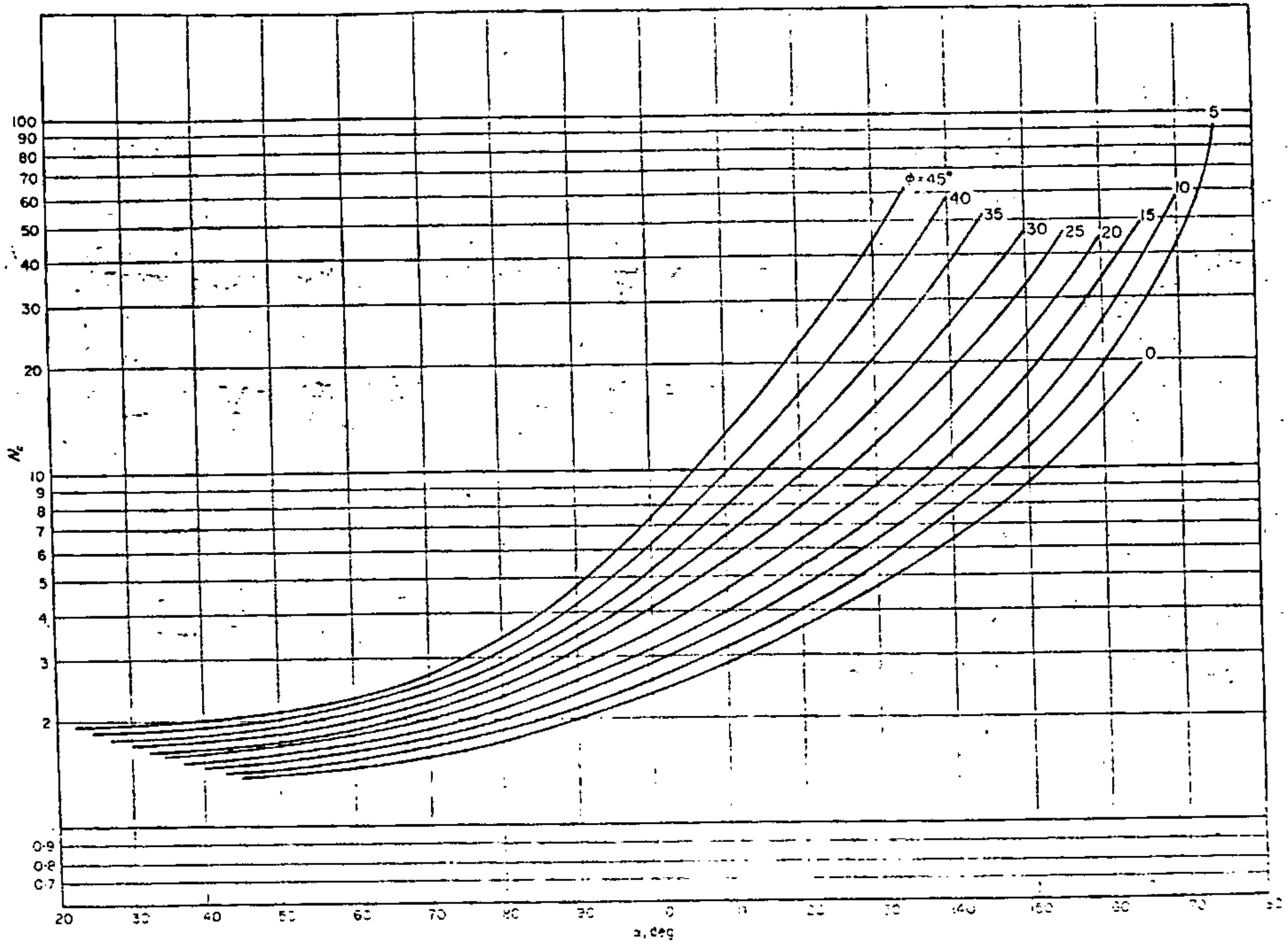


Fig. D-3: *Relationship between N_c and α when δ = 0*

(After Reece et al., 1966)

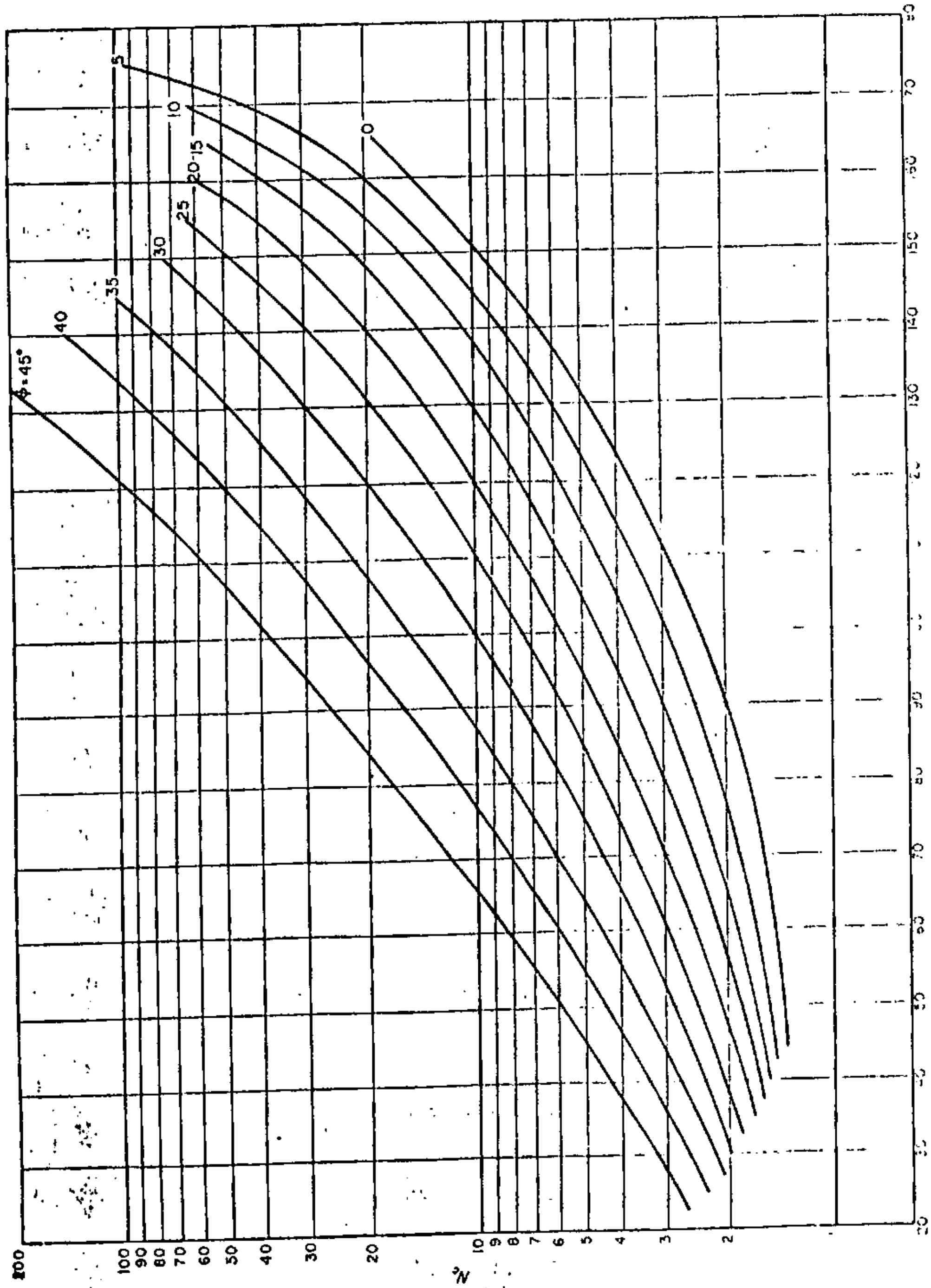


Fig. D-4: *Relationship between N_c and α when δ = φ*

(After Reece et al., 1966)

$$F_x = 16.0 \times 0.66 \times 4.64 = 49N.$$

3.2 Wismer and Luth

The horizontal prediction equation for cohesive soil is given as follows (Wismer and Luth, 1970);

$$\frac{F_x}{\gamma b z^{0.5} \ell^{1.5}} = \alpha^{1.15} \left(\frac{z}{\ell \sin\alpha}\right)^{1.21} \left[\left(\frac{CI}{\gamma z}\beta\right)^{1.21} \{0.055 \left(\frac{z}{b}\right)^{0.78} + 0.065\} + 0.64 \frac{v^2}{g\ell} \right] \quad \text{(D-7)}$$

CI is the cone index and is equal to 11.5c, β is the shear strength factor and is given as follows:

$$\beta = \left(0.667 \frac{v}{b}\right)^{0.1} \quad \text{(D-8)}$$

The vertical prediction equal is given as follows (Wismer and Luth, 1970)

$$\frac{F_z}{\gamma b z^{0.5} \ell^{1.5}} = \left[0.48 - (\alpha - 0.70)^3\right] \frac{z}{\ell \sin\alpha} \left[\left(\frac{CI}{\gamma z}\beta\right)^{0.41} \{9.2 \left(\frac{z}{b}\right)^{0.225} - 5\} + 0.24 \frac{v}{g\ell} \right] \quad \text{(D-9)}$$

For example for black cotton soil with density $\rho = 1.64$ Mg/m³, CI = 11.5c, blade inclination $\alpha = 0.785$ radians, blade width and length each of length 100mm, and blade velocity v = 0.11 cm/sec, substituted into equation (D-7) gives

$$\gamma b z^{0.5} \ell^{1.5} = 13.53$$

$$\alpha^{1.5} \left(\frac{z}{\ell \sin\alpha}\right)^{1.21} = 0.76$$

$$(\frac{CI}{\gamma z}\beta)^{1.21} \{0.055(\frac{z}{b})^{0.78} + 0.065\} + 0.64\frac{v^2}{g\ell} = 10.05$$

$$F_x = 13.53 \times 0.76 \times 10.05 = 103.34N$$

Similarly from equation (D-9)

$$\gamma b z^{0.5} \ell^{1.5} = 13.53$$

$$[0.48 - (\alpha - 0.7)^3]\frac{z}{\ell \sin\alpha} = 0.48$$

$$(\frac{CI}{\gamma z}\beta)^{0.41} \{9.2(\frac{z}{b})^{0.225} - 5\} + 0.24\frac{v^2}{g\ell} = 16.5$$

$$F_z = 13.53 \times 0.48 \times 16.5 = 107.2N$$

4. Limit equilibrium solution

4.1 Yong et al.

The stress acting in a cohesionless soil at the blade interface is as follows (Yong et al., 1972):

$$\sigma_r = \sigma(1 + \sin\phi \cos 2\psi') \qquad \text{(D-10)}$$

$$\sigma_\theta = \sigma(1 - \sin\phi \cos 2\psi') \qquad \text{(D-11)}$$

$$\tau_{r\theta} = \sigma \sin\phi \sin 2\psi' \qquad \text{(D-12)}$$

where

$$\sigma = \frac{\sigma_r + \sigma_\theta}{2} = \rho g r\, S(\theta) \qquad \text{(D-13)}$$

The differential equation in soil cutting is written as follows (Yong et al., 1972):

$$\frac{d\psi'}{d\theta} = \frac{\cos\theta - \sin\phi\cos(2\psi'+\theta) - S\cos^2\phi}{2(S\sin\phi + \frac{c}{\rho g r}\cos\phi)(\cos 2\psi' - \sin\phi)} - 1$$

(D-14)

$$\frac{dS}{d\theta} = \frac{S\ \mathrm{Sin}2\psi' - \sin(2\psi'+\theta)}{\mathrm{Cos}2\psi' - \mathrm{Sin}\ \phi} \quad \text{(D-15)}$$

where

$$S = \frac{\mathrm{Cos}\ \theta}{1 - \mathrm{Sin}\phi} \quad \text{(D-16)}$$

$$\psi' = \frac{\pi}{2} - \theta \quad \text{(D-17)}$$

$$\theta = \frac{\pi}{4} + \frac{\phi}{2} \quad \text{(D-18)}$$

At the blade, the boundary condition was given by the following relationship (Yong et al., 1972):

$$\psi' = 0.5(\pi - \delta - \text{arc sin}\ \frac{\sin\delta}{\sin\phi}) \quad \text{(D-19)}$$

For example for beach sand at the blade interface with $\phi = 31°$ and $\delta = \frac{\phi}{2}$, and from equation (D-19), ψ' equals 1.1627 radians. By applying the numerical solution of the 4th order Runge-Kutta method to equations (D-14) and (D-15), the stress function S at the blade interface of inclination $\beta = 30°$ is 1.7. Substituting equation (D-13) into equations (D-10), (D-11) and (D-12), with density $\rho = 1.91$ Mg/m^3, $\phi = 31°$, $\psi' = 66.62°$, r = 100mm and S = 1.7, the following is obtained

$$\sigma_r = 1.91x9.807x0.1x1.7x0.647 = 2.06kN \quad (D-20)$$

$$\sigma_\theta = 1.91x9.807x0.1x1.7x1.3524 = 4.31kN \quad (D-21)$$

$$\tau_{r\theta} = 1.91x9.807x0.1x1.7x0.375 = 1.19kN \quad (D-22)$$

The radial force F_r assuming linear stress distribution on the blade, is as follows:

$$F_r = \frac{br\,\sigma_r}{2} = \frac{0.1x0.1x2060}{2} = 10.3N \quad (D-23)$$

Similarly the tangential force F_θ is as follows:

$$F_\theta = \frac{br\,\sigma_\theta}{2} = \frac{0.1x0.1x4310}{2} = 21.55N \quad (D-24)$$

Similarly the shear force $F_{r\theta}$ is as follows:

$$F_{r\theta} = \frac{br\,\tau_{r\theta}}{2} = \frac{0.1x0.1x1190}{2} = 5.95N \quad (D-25)$$

since $\beta = 45°$, the horizontal force F_H is got by resolving all forces on the blade horizontally, and is obtained as follows:

$$F_H = F_r \sin 45 + F_\theta \cos 45 + F_{r\theta} \sin 45 \quad (D-26)$$

Substituting values of F_r, F_θ and $F_{r\theta}$ into equation (D-26), the horizontal force F_H is as follows:

$$F_H = 10.3 \sin 45 + 21.55 \cos 45 + 5.95 \sin 45$$
$$= 26.72N$$

APPENDIX E

Computer Programs of Soil Cutting

```
$JOB
      WRITE(3,10)
   10 FORMAT(24H BOUNDARY ENERGY THEORY )
   20 READ(1,30)              D,P,AL,V,R,G,X1,X2
   21 WRITE(3,22)
   22 FORMAT(//'B.ANGLE   PHI      CKN/M2      DEN.G/CC                HOR.F (N)
     *        VERT.F (N)')
   23 IF(D.LT.0.) GO TO 450
   30 FORMAT(8F6.2)
   40 READ(1,50) B,PP
   50 FORMAT(2F6.1)
   51 PI=3.141592654
   52 C=PI*P/180.
   60 E = C/2.
   70 F=PI*B/180.
   80 H=PI/4.+C/2.-F/2.
   90 AI=(R**2)*D*TAN(PI/2.-E)*0.25
  100 AJ=2.*H*TAN(C)
  110 AK=EXP(AJ)-1.
  120 W=AI*AK
  130 AX=(R**2)*D*COS(PI/4.-C/2.)*SIN(PI/4.-C/2.)*EXP(AJ)
  140 Y=(R**2)*D*COS(F)*SIN(F)*0.5
  150 AN=PI/4.-F-C/2.
  160 AM =AL*(W+AX/2.-Y)*SIN(C)*COS(F)/COS(AN)
  170 O=AL*AX/2.*COS(PI/4.-C/2.)*TAN(C)*COS(F)/COS(AN)
  180 PA=AL*Y*COS(PI/4.-C/2.)*SIN(PI/4.-C/2.)*TAN(C)/COS(AN)
  190 Q=(V**2)*R*AL*D*(COS(F)**3)/(COS(AN)**2*9.8)
  200 S=(AM+O+PA+Q)*COS(F-E)
  210 T=SIN(E)*SIN(PI/4.-C/2.)/(COS(AN)*COS(F-E))
  220 U=S/T
  230 Z=U*9.807/1000.
  240 A=Z*TAN(F-E)
  262 AX3=Z*T*1000./9.807
  270 WRITE(3,280) B,P,X1,D,Z,A
  280 FORMAT(2XF6.2,1X,F5.2,1X,F5.2,1X,F6.2,5X,F10.2,8X,F10.2)
  290 IF(PP-1.)40,300,440
  300 AN=PI/4.-F-C/2.
  310 AX8=0.5*AK*R*AL*TAN(PI/2.-E)*X1*100./9.807
  320 AJ=AJ/2.
  330 AX6=X1*R*AL*EXP(AJ)*100./9.807
  340 AX7=COS(F)/COS(AN)
  350 AX4=AX6*A''
  360 AX5=X2*R*AL*SIN(PI/4.-E)*10.196/COS(AN)
  370 U2=AX8*COS(F-E)+AX3+AX4+AX5
  380 Z2=U2*9.807/1000.
  390 A2=Z2*TAN(F-E)
  420 WRITE(3,430) B,P,X1,D,Z2,A2
  430 FORMAT(2XF6.2,1X,F5.2,1X,F5.2,1X,F6.2,5X,F10.2,8X,F10.2)
  431 GO TO 40
  440 GO TO 20
  450 STOP
      END
```

$ENTRY
BOUNDARY ENERGY THEORY

B.ANGLE	PHI	CKN/M2	DEN.G/CC	HOR.F (N)	VERT.F (N)
0.00	34.00	0.00	1.94	228.04	-69.72
15.00	34.00	0.00	1.94	189.42	-6.61

30.00	34.00	0.00	1.94	125.96	29.08
45.00	34.00	0.00	1.94	66.49	35.35
60.00	34.00	0.00	1.94	26.25	24.48
75.00	34.00	0.00	1.94	6.12	9.79
90.00	34.00	0.00	1.94	0.00	0.00
-15.00	34.00	0.00	1.94	216.12	-135.05
-30.00	34.00	0.00	1.94	153.36	-104.46
-45.00	34.00	0.00	1.94	71.44	-134.36
-60.00	34.00	0.00	1.94	13.81	-59.83
-75.00	34.00	0.00	1.94	0.20	5.84
-90.00	34.00	0.00	1.94	0.00	0.00
-90.00	34.00	0.00	1.94	0.00	0.00

.ANGLE	PHI	CKN/M2	DEN.G/CC	HOR.F (N)	VERT.F (N)
0.00	31.00	0.00	1.91	185.64	-51.48
15.00	31.00	0.00	1.91	153.42	-1.34
30.00	31.00	0.00	1.91	101.55	26.26
45.00	31.00	0.00	1.91	53.42	30.22
60.00	31.00	0.00	1.91	21.02	20.66
75.00	31.00	0.00	1.91	4.84	8.22
90.00	31.00	0.00	1.91	0.00	0.00
-15.00	31.00	0.00	1.91	176.94	-104.22
-30.00	31.00	0.00	1.91	126.73	-128.90
-45.00	31.00	0.00	1.91	60.48	-106.89
-60.00	31.00	0.00	1.91	12.92	-49.94
-75.00	31.00	0.00	1.91	0.01	1.06
-90.00	31.00	0.00	1.91	0.00	0.00
-90.00	31.00	0.00	1.91	0.00	0.00

.ANGLE	PHI	CKN/M2	DEN.G/CC	HOR.F (N)	VERT.F (N)
0.00	16.00	6.90	1.64	73.92	-10.39
0.00	16.00	6.90	1.64	210.93	-39.04
15.00	16.00	6.90	1.64	58.29	7.16
15.00	16.00	6.90	1.64	170.03	23.38
30.00	16.00	6.90	1.64	36.80	14.89
30.00	16.00	6.90	1.64	135.75	34.35
45.00	16.00	6.90	1.64	18.65	14.05
45.00	16.00	6.90	1.64	105.16	79.25
60.00	16.00	6.90	1.64	7.04	9.01
60.00	16.00	6.90	1.64	76.26	97.53
75.00	16.00	6.90	1.64	1.43	3.38
75.00	16.00	6.90	1.64	46.28	109.02
90.00	16.00	6.90	1.64	0.00	0.00
90.00	16.00	6.90	1.64	10.35	73.07
-15.00	16.00	6.90	1.64	73.83	-31.34
-15.00	16.00	6.90	1.64	264.67	-112.35
-30.00	16.00	6.90	1.64	55.96	-43.72
-30.00	16.00	6.90	1.64	354.96	-277.33
-45.00	16.00	6.90	1.64	29.63	-39.33
-45.00	16.00	6.90	1.64	686.10	-910.48
-60.00	16.00	6.90	1.64	8.76	-21.68
-60.00	16.00	6.90	1.64	-287.89	712.54
-75.00	16.00	6.90	1.64	0.51	-4.14
-75.00	16.00	6.90	1.64	105.55	-859.62
-90.00	16.00	6.90	1.64	0.00	0.00
-90.00	16.00	6.90	1.64	207.02	1473.05
-90.00	16.00	6.90	1.64	0.00	0.00

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C      BOUNDARY ENERGY THEORY
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    45.    0.
    60.    0.
    75.    0.
    90.    0.
   -15.    0.
   -30.    0.
   -45.    0.
   -60.    0.
   -75.    0.
   -90.    0.
   -90.    2.
   1.91 31.0  10.16   .11 10.16980.7   0.0   0.0
     0.    0.
    15.    0.
    30.    0.
    45.    0.
    60.    0.
    75.    0.
    90.    0.
   -15.    0.
   -30.    0.
   -45.    0.
   -60.    0.
   -75.    0.
   -90.    0.
   -90.    2.
   1.64 16.0  10.16   .11 10.16980.7   6.9   0.0
     0.    1.
    15.    1.
    30.    1.
    45.    1.
    60.    1.
    75.    1.
    90.    1.
   -15.    1.
   -30.    1.
   -45.    1.
   -60.    1.
   -75.    1.
   -90.    1.
   -90.    2.
  -1.64 16.0  10.16   .11 10.16980.7   6.9   0.0
  END OF DATA
PAGE  1
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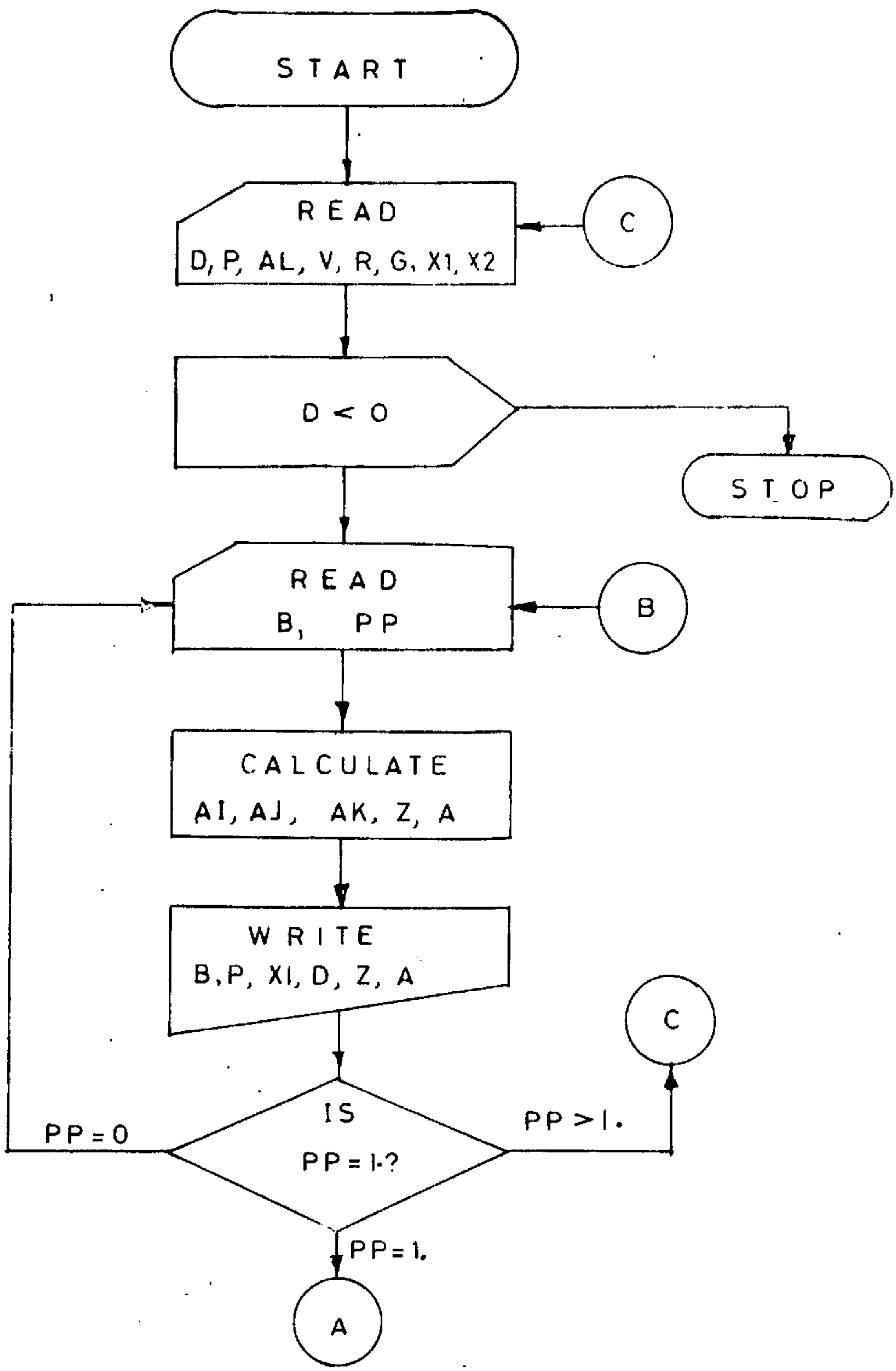
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C
D < O
STOP
READ
B, PP
B
CALCULATE
AI, AJ, AK, Z, A
WRITE
B, P, XI, D, Z, A
C
IS
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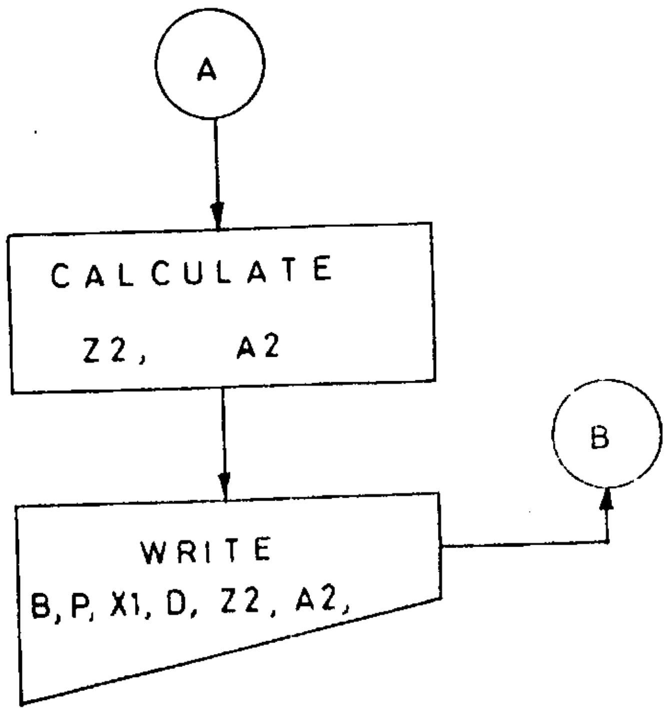
PP > 1.
PP = 1.
A


A
CALCULATE
Z2, A2
WRITE
B, P, X1, D, Z2, A2,
B