Bearing capacity of soils from cone penetration test

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SUMMARY: An equipment for progressive load application, with automatic recording device is developed. A relation between the applied load and penetration of a cone is proposed. Using this relation, it is possible to estimate the load carrying capacity of a plate, for a given settlement, if supplemented with the results of a single cone test. Extension of this method for larger areas is indicated.

Introduction

The bearing capacity of a soil is normally obtained with the help of various formulae developed by TERZAGHI [1943], MEYERHOF [1957], and others, or from a plate loading test at site or indirectly from a standard penetration test. Each one of them has some disadvantages. The theoretical methods make use of the shear parameters which are susceptible to variations due to the impossibility in getting truly undisturbed samples and on the methods of testing. The plate loading value represents the strength of the soil present only within a depth nearly twice the width of the plate. The test requires heavy dead loads or reactions and is not feasible at greater depths, time consuming, expensive and is associated with perimeter effects. The standard penetration test (SPT) [FLETCHER, 1965], gives unrealistic values because of its dynamic nature. Static cone test results have been used to estimate the point bearing value of piles empirically. No attempt appears to have been made to use these results for the determination of bearing capacity of soil.

In view of the above a new method of deducing the bearing capacity of the soil directly from the static cone test results is presented herein. It may be noted that at present the static cone tests are used only to obtain the bearing capacity of piles and that it is based on empirical method. A theoretical analysis is also presented which when supplemented with a single static cone test results, yields the required bearing capacity of the soil. The investigation is restricted to the analysis of remoulded soils. It may be further noted that the static cone test suffers from none of the disadvantages of the other methods and indirectly reflects the variation in soil formation at various levels. However the results of this laboratory investigation need to be correlated with field testing.

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Experimental set up

The tests were conducted on remoulded samples with cones of different vertex angles under gradually increasing loads. For this purpose an apparatus was designed and fabricated as shown in fig. 1 and fig. 2. A detailed description is presented below to explain the functions of all the six components of the apparatus.

i) Load supporting beam (fig. 1 - 1), provided with ball bearings at the masonry support, is designed to support the loads placed over the carriage and spans between the support and the loading spindle. It carries an adjustable hanger and a small sliding weight beyond the hinged support, for purposes of balancing the lever with the counter weights. A ball and groove adapter is used at the end of the lever to transfer the load vertically.

ii) The carriage (fig. 1 - 2), a hollow metallic box, carries the dead load and moves smoothly over the beam as the ball bearings provided act as wheels. Including the dead loads the centre of gravity of the assembly comes very near to the rolling surface; avoiding any eccentric pull on the loads and hence oscillations are avoided. The carriage is moved by a motor, through a flexible cable interconnecting them over a rolling disc.

iii) The load moving unit consists of a motor (0.5 hp) and a step-down pulley. The interconnections are shown in fig. 1 - 9, 19, 21, 22. With this arrangement the carriage can be moved at any desired rate. The carriage is brought backwards with the help of a reverse switch and a small dead weight connected to the carriage (fig. 1 - 17,6).

iv) Loading spindle (fig. 1 - 15) is the key piece of the apparatus to which various cones are attached at the bottom end. It is provided with a frictionless guide with unidirectional freedom to move up and down. The reaction on the loading

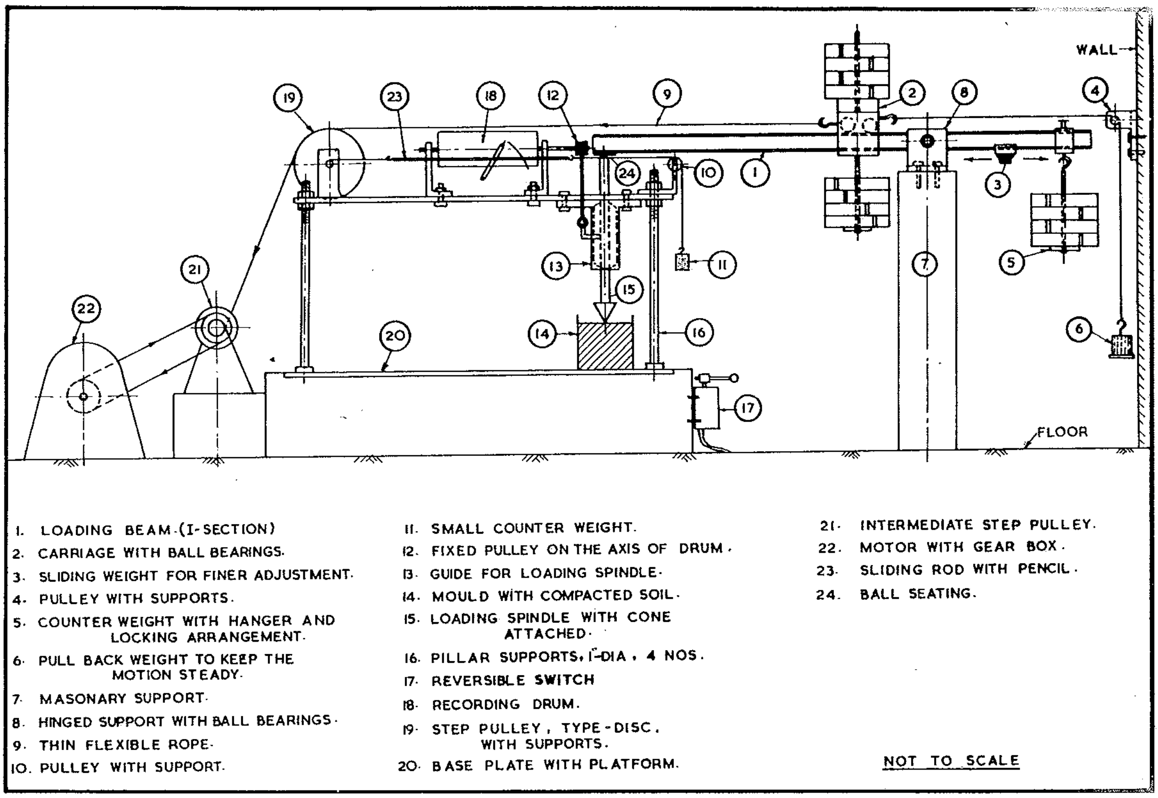

Fig. 1. — Illustration of test set up.

spindle of cones, increasing gradually from zero initially, to a definite magnitude P_c, is calculated as

$$P_c = W_L \frac{\text{Lenght of travel of carriage}}{\text{Lenght of lever arm}} \quad (1)$$

v) Recording unit (fig. 1 - 18) consists of a well machined drum free to rotate on its axis and properly supported by L-shaped legs. It is provided with a pencil holder, which can move along the axis of the drum. The movements of the spindle and the carriage are transfered to the drum and the pencil respectively through the thread connections as shown (fig. 1 - 12, 23).

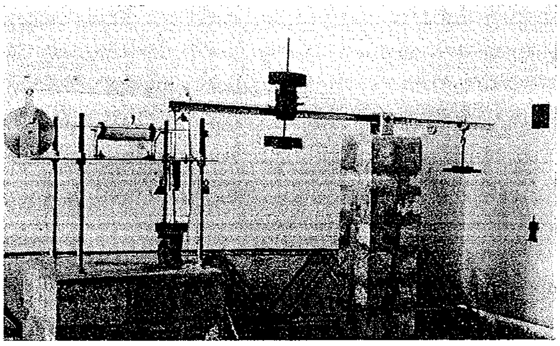

Fig. 2. — Apparatus for progressive load application (Photo).

The load penetration curve is directly obtained from the apparatus with the penetration shown to a magnified scale. The magnification ratio is 5.09 in all cases. Knowing the load on the cone as given by equation (1), and the actual length of the load axis on the graph, the scale factor along the load axis for the respective curves is obtained.

vi) The platform is mainly a base plate fixed at a convenient height for working. Four rods welded at the four corners of the base plate, support the top plate on which the recording device, rolling disc and guide for the loading spindle etc., are mounted. The elevation of the top plate is so adjusted that the top of the rolling disc and the carriage nose are at the same level so that no component of the pulling force comes on the spindle as the connecting cable is pulled. The platform mainly serves as a place to keep the soil mould below the loading spindle and the cone.

Soils used

In this study five soils from different locations were used. They are Hijli soil, Keshiary soil, Panskura soil, Ranchi soil and Rourkela soil. The index properties of the five soils are presented in Table 1 and their grain-size distributions are shown in fig. 3 and fig. 4.

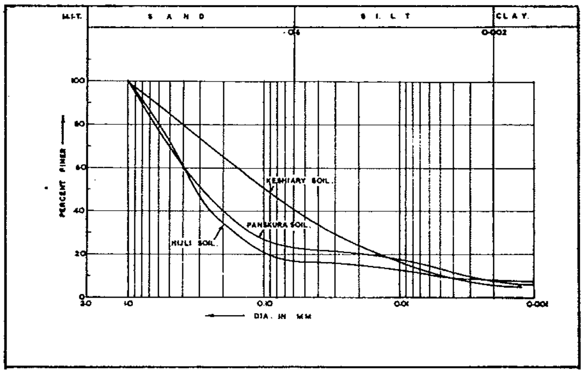

Fig. 3. — Grain size distributions.

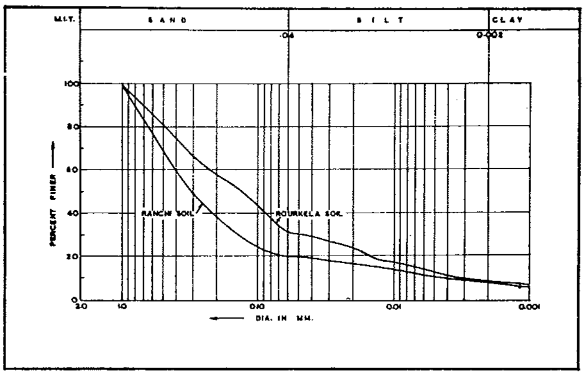

Fig. 4. — Grain size distributions.

Sample preparation

All the soils were air dried, powdered and sieved through B.S. No. 16 sieve and stored in wooden boxes. For all samples the required quantity of soil was mixed with the necessary quantity of water (optimum moisture content) and pressed between two pistons in a cylindrical mould of 12.70 cm (5 in.) inside diameter. The compacting force was increased uniformly to its final magnitude of 2.50 kg/q cm (35.5 psi) during a 10 minute period, and then held constant for another 5 minutes. The statically compacted samples had overall dimensions of 12.70 cm (5 in.) in diameter and 10.9 to 12.0 cm (4,3 to 4.75 inches) high. A few samples were checked for density variation along the height of the specimen by taking samples through a slit provided in the wall of the mould. The density was found to vary within 5 percent in the same specimen along the height. The average values of density and moisture content of test specimens of all five soils are presented in Table 1.

Test procedure

Static cone penetration tests were carried out on the remoulded samples with seven different 2 cm diameter brass cones on vertex angles of 30, 60, 90, 105, 120, 135, 150 degrees. The load on

TABLE 1. — *Index Properties of Soils Used*

Soil	Specific Gravity G	*Limits* LL (per cent)	PL (per cent)	O.M.C. (per cent)	*Average Values* Density at test γ (g/cm³)	Moisture w at test (per cent)	Cohesion C (kg/cm²)	Angle of internal friction Ø (degrees)	Half unconfined compressive strength ½ qu (kg/cm²)
Panskura	2.667	69.1	25.9	21.0	1.81	25	0.73	7.25	0.845
Hijli	2.65	41.5	15.65	14.75	2.05	17 to 18	0.421	3	0.423
Rourkela	2.64	33.85	15.2	18.75	1.82	18 to 19	0.674	16	0.873
Ranchi	2.69	55.6	22.0	22.0	1.81 to 1.89	21 to 22	0.477	7.5	0.535
Keshiary	2.695	31.6	21.6	14.75	1.73	15	0.477	17.3	0.660

the cones was increased in a time interval of 12 minutes to its maximum values to push the cone completely into the soil as the apparatus used is a stress controlled type. The rate of penetration for the various cones happens to be different. This is due to the fact that under the applied load the penetrations, of various cones are unequal, the angles of the cones being different. Thus the load penetration curves for the test in the five soils were obtained directly from the apparatus.

A brass plate of 2 cm (0.79 in.) diameter 0.95 cm (3/8 in.) thick was also loaded in the remoulded samples of the five soils, compacted in an identical manner and the load settlement curves were obtained (fig. 5).

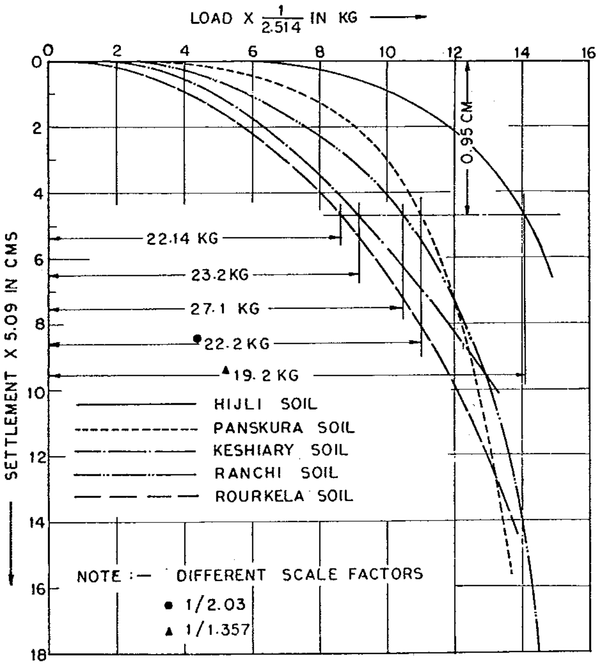

Fig. 5. — Load settlement curves.

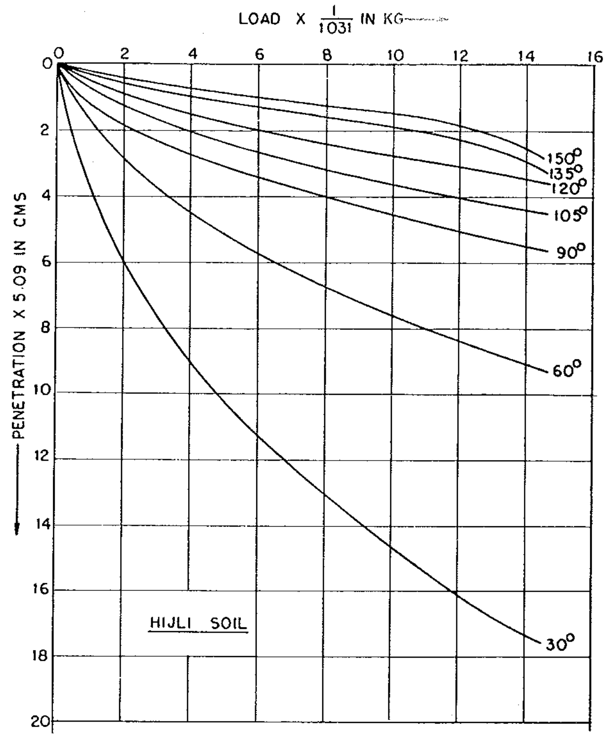

Fig. 6. — Load VS. penetration for static cone tests.

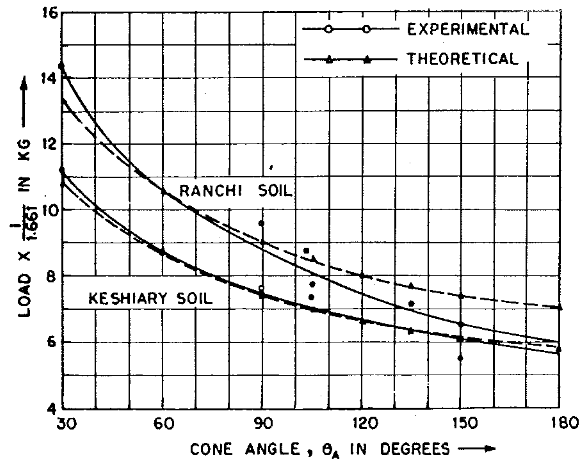

Fig. 7. — Cone angle VS. load compared at 2 cm base diameter.

Discussion of experimental results

The load penetration curves obtained in all the five soils for different cones are parabolic, similar to a typical one shown in fig. 6. At this stage it is necessary to define the resistance of soil for the penetration of cone which we may call as cone resistance. The cone resistance is the load just enough to push completely the conical part of the penetrometer into the soil. For different angled cones the cone resistance of a soil is read from the respective load penetration curves. These values of cone resistance are plotted against vertex angle of the cones in figs. 7, 8 and 9. The cone resistance was found to diminish with increasing values of vertex angle and reached asymptotically a definite value as the vertex angle approached 180°. This value corresponds to that of a plate at the verge of sinking and it forms a part of the bearing capacity of a plate of equal diameter as that of the cone.

The load carrying capacity of a plate may be considered to be composed of two parts. The first part P_1 is the load necessary to cause the possible elastic strain under the plate and the second part P_2 is the load required to push the plate to a given settlement displacing the soil. The first part is obtained as explained in the above para.

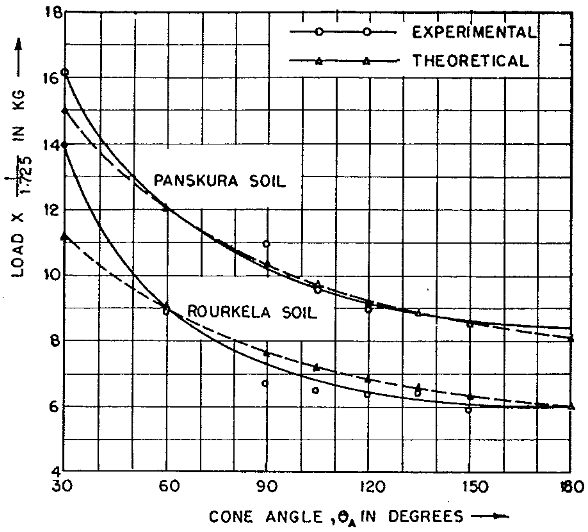

Fig. 8. — Cone angle VS. load compared at 2 cm base diameter.

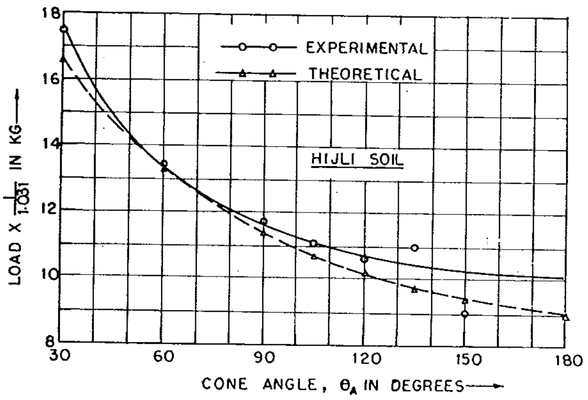

Fig. 9. — Cone angle VS. load compared at 2 cm base diameter.

The second part, P_2 of the load is obtained from the latter portion of the load penetration curves as follows. Beyond the penetration of conical part, i.e. for the penetration of the cylindrical portion the load penetration curves are parallel and drooping down for all the cones as shown in fig. 10. It means that the soil resistance for the various cones of equal diameter to penetrate beyond the base by a given amount of penetration is constant and is independent of vertex angle of cones. A plate can be assumed to be a cone of 180 degrees vertex angle. Hence the extra load required for the plate (diameter same as that of cone) to sink to a given settlement is read from the latter portion of the load penetration curve of any cone, keeping the settlement of the plate as equal to the penetration of the cone beyond its base (fig. 11).

Thus the load carrying capacity of a plate for a given settlement is the sum of the above two

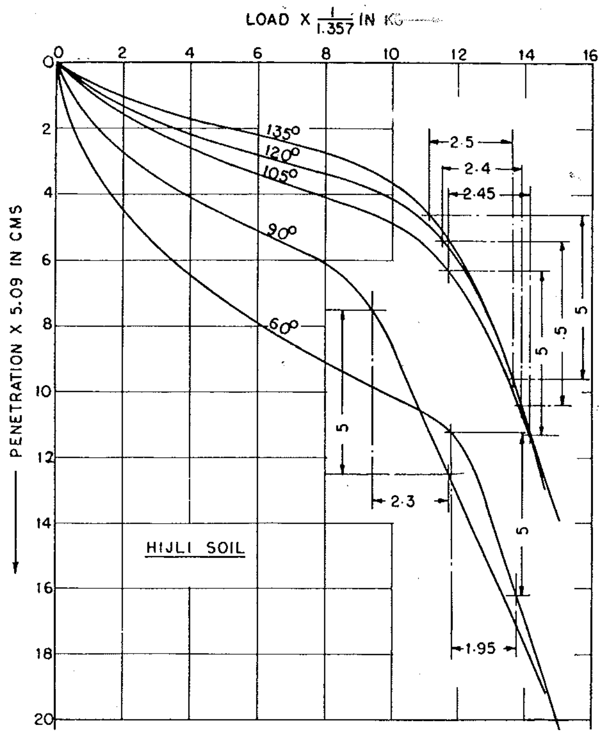

Fig. 10. — Load penetration curves.

parts if the diameters of plate and cone are equal.

But to obtain the first part of the load P_1 one has to conduct cone tests with different vertex angles, which is not advisable in practice. Hence, the authors have derived an analytical expression to estimate the load P_1, which makes use of the

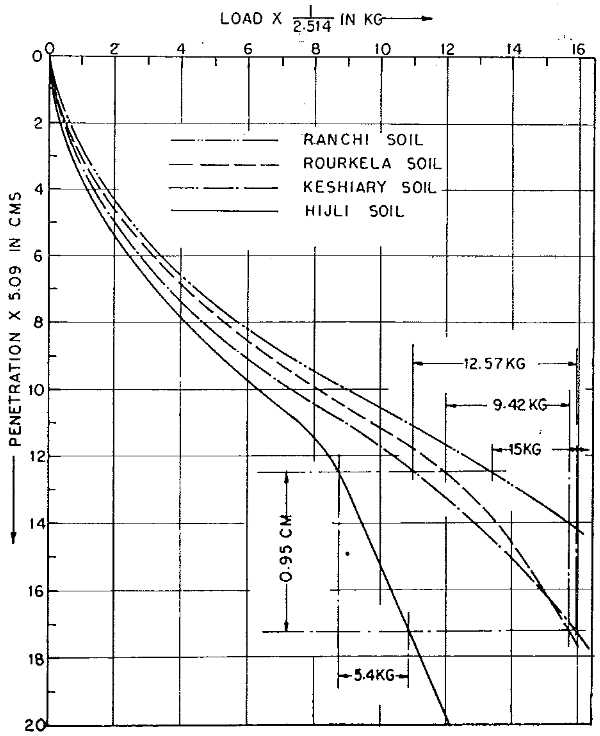

Fig. 11. — Load VS. penetration.

results of a single test performed at the site. From the same test results the second part of the load, P_2 can be obtained as already explained.

Theoretical analysis

A relation between the applied load P_c and depth of penetration Z_1 of any cone of semi-vertex angle θ which is obtained by considering the equilibrium of forces acting on an imaginary hemisphere through the soil mass is presented below.

Assumptions:

1) The soil is elastic, homogeneous and Hooke's law is valid.
2) The weight of the soil within the hemisphere is negligible.
3) The radius of hemisphere is large enough so that it is well beyond the plastic deformation of the soil around the cone.
4) On the surface of the hemisphere the shearing stresses are negligible in comparison with the normal stress σ_R.
5) The cone is considered to be rigid in comparison with the soil.

In fig. 12 on the two hemispheres with radii R and R + dR consider two points N (R, β) and N′ (R + dR, β). When a certain load is applied on the cone it is known that the points N and N′ will be displaced due to the radially distributed stress in the soil and the farther the points lie, the less they are displaced. Moreover, it is obvious that the displacement « s » of the point « N » diminishes as β increases and that the displacement of point N approaches zero when β = 90°.

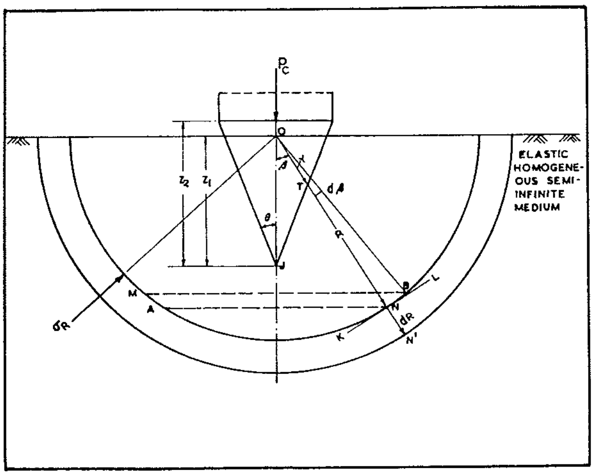

Fig. 12. — Definition sketch for analysis.

In view of the foregoing, the displacements s and s′ of N and N′ are respectively given by

$$s = \frac{\alpha \cos \beta}{R} \qquad (2)$$

$$s' = \frac{\alpha \cos \beta}{R + dR} \qquad (3)$$

where α is a coefficient of proportionality.

The radial strain ϵ of the soil at the surface of the hemispherical bowl may be defined as

$$\epsilon = \frac{s - s'}{dR} = \frac{\alpha \cos \beta}{R^2 + R \cdot dR} \qquad (4)$$

with the help of direction cosines of points N and N′ we get from the triangle OJT the solid portion « Y » of the cone (see fig. 12) as

$$\frac{Y}{\sin \theta} = \frac{Z_1}{\sin(\theta + \beta)} \qquad (5)$$

Changing R to its effective valume, namely (R — Y), and substituting in equation 4, we get

$$\epsilon = \frac{\alpha \cos \beta}{(R - Y)^2 + (R - Y)\, dR} \qquad (6)$$

Neglecting the second terms in the denominator which is very small, the expression for the radial compressive stress σ_R is obtained as

$$\sigma_R = \frac{\alpha E \cos \beta}{(R - Y)^2} \qquad (7)$$

where E = Young's modulus.

The equation of equilibrium of forces on the soil mass in the hemispherical bowl is

$$P_c = \int_0^A \sigma_R \cos \beta \, dA \qquad (8)$$

where P_c = applied load on the cone and

$$dA = 2 \pi R^2 \sin \beta \, d\beta, \qquad (9)$$

being the area of the curved surface of the hemispherical zone bounded by two parallel horizontal planes (MB and AN in fig. 12).

Substituting the values of σ_R, dA, and Y in equation 11,

$$P_c = 2\pi\alpha E \int_0^{\pi/2} \frac{\cos^2\beta \sin\beta \sin^2(\theta + \beta)\, d\beta}{\left[\sin(\theta + \beta) - \dfrac{Z_1 \sin \theta}{R}\right]^2} \qquad (10)$$

$$\text{Substituting } \theta + \beta = x, \quad \frac{Z_1 \sin \theta}{R} = k \qquad (11)$$

in equation 10 one gets on simplification

$$P_e = 2\pi\alpha E \int_0^{\pi/2+\theta} (b_1 \cos x \sin^2 x + b_2 \sin^3 x + b_3 \cos x \sin^4 x + b_4 \sin^5 x) \frac{dx}{(\sin x - k)^2} \qquad (12)$$

where

$$\begin{aligned} b_1 &= -\sin\theta\cos^2\theta \\ b_2 &= \cos^3\theta - 2\sin^2\theta\cos\theta \\ b_3 &= 3\sin\theta\cos^2\theta - \sin^3\theta \\ b_4 &= 3\sin^2\theta\cos\theta - \cos^3\theta \end{aligned} \qquad (13)$$

On integrating equation (12) [GRANDSHTEYN, RYZHIK, 1965] the value of P_e is obtained as

$$P_e = 2\pi\alpha E\, [I]_\theta^{\pi/2+\theta} \qquad (14)$$

with

$$I = \sum_{J=1}^{J=8} A_J \qquad (14a)$$

where, with $t = (\sin x - k)$,

$$A_1 = b_1 \left(-\frac{k^4}{t} + 2k \ln t + t \right)$$

$$A_2 = b_3 \left(-\frac{k^4}{t} + 4k^3 \ln t + 6k^2 t + 4k\frac{t^2}{2} + \frac{t^3}{3} \right)$$

$$A_3 = b_4 \left[\left(\frac{1}{3}\cos^3 x - \cos x \right) - 3k \left(\frac{1}{2} x - \frac{1}{2} \sin x \cos x \right) - 3k^2 \cos x - k^3 x \right]$$

$$A_4 = 5k \cdot b_4 \left[\frac{x}{2} - \frac{1}{2} \sin x \cos x + 2k \cos x + k^2 x \right]$$

$$A_5 = (10k^2 \cdot b_4 + b_2)\, [-\cos x - kx]$$

$$A_6 = (10k^3 \cdot b_4 + 3k \cdot b_2)\, [x]$$

$$A_7 = (5 \cdot k^4 \cdot b_4 + 3k^2 \cdot b_2) \cdot \left[\frac{1}{\sqrt{1-k^2}} \ln \frac{-k \tan\frac{x}{2} + 1 - \sqrt{1-k^2}}{-k \tan\frac{x}{2} + 1 + \sqrt{1-k^2}} \right]$$

$$A_8 = \frac{(k^5 \cdot b_4 + k^3 \cdot b_2)}{k^2 - 1} \cdot \left[\frac{\cos x}{(\sin x - k)} - \frac{k}{\sqrt{1-k^2}} \ln \frac{-k \tan\frac{x}{2} + 1 - \sqrt{1-k^2}}{-k \tan\frac{x}{2} + 1 + \sqrt{1-k^2}} \right]$$

and b_1 to b_4 are as defined by equation 13.

For evaluating I in equation 14, the radius of the hemispherical bowl is taken as five times the depth of penetration of the 30 degrees cone so that it would be much beyond the plastic deformation of the soil around the cone.

The value of the product (α E) in equation 14 is quite different as calculated from different cone test results in the same soil, as it is proportional to P_e which is variable. The coefficient of proportionality (α) may also depend on the amount of displaced soil due to the penetration of the cone. It is observed that the magnitude of (α E) is varying in direct proportion with the surface area of the cone and inversely with the perimeter of the vertical cross section of the cone portion that has penetrated into the soil. Hence the product (α E) is replaced as

$$\alpha E = (\alpha' E')\, R_H \qquad (15)$$

where

$$R_H = \frac{\text{Surface area}}{\text{Perimeter of vertical section}} \qquad (16)$$

of the cone portion that has penetrated into the soil. The final semi-empirical relation (SER) proposed is

$$P_c = 2 (\alpha' E') (I) R_H \quad (17)$$

with (α'E') modified coefficient.

The magnitude of (α'E') is found to be practically constant (Table 2) for a given soil which is an essential requirement if it is to be used as a material parameter for evaluating the values of loads on different cones. Wherever it is required, the value of (α'E') should be evaluated from a penetration test conducted under actual conditions of soil.

In equation 17, the value of α'E' is calculated from a single test result of 60° cone for a given soil. This value of α'E' is used as a material parameter and cone resistance (i.e. values of P'_c when the cone just penetrates to its full depth, but not beyond the base) for different angled cones are estimated from the same equation 17. These values along with the corresponding experimental results are graphically represented against the cone angle in the figs. 7, 8 and there is close agreement between the two. Both theoretical and experimental values tend to a particular magnitude, as the cone angle approaches 180 degree (plate). This is part P_1 of the bearing capacity of a plate of diameter equal to that of the cone necessary to cause possible elastic strain under the plate. The metod of obtaining the remaining part P_2 is already explained.

The load carrying capacity of a 2 cm diameter plate for a settlement of 0.95 cm (equal to the thickness of plate tested), was arrived at by the above procedure for the said five soils and compared with experimentally obtained values (fig. 5) as well as with the calculated values from Terzaghi's theory (Table 3). The values obtained by the author's procedure are closer to the experimental ones in all the five soils used in this investigation. These values when expressed per unit area give the bearing capacities of the soils for a settlement of 0.95 cm.

TABLE 2. — *Values of Modified Coefficient* α'E' in Eq 17; $P_c = 2\pi (\alpha' E')\ I \cdot R_H$

Cone angle degrees	$\frac{R}{Z_1}$	*Kesiary Soil* Load on the cone (experimental)	α'E'	*Ranchi Soil* Load on the cone (experimental)	α'E'
30	5.00	12.10	5.06	15.33	6.40
60	10.78	9.98	5.18	11.50	5.97
90	18.66	8.96	5.45	9.22	5.60
105	24.32	8.68	5.62	8.47	5.48
120	32.32	8.52	5.80	7.98	5.43
135	45.05	8.38	5.96	7.60	5.40
150	69.64	8.28	6.08	7.36	5.41
180 / Plate	∞	8.00	6.20	7.14	5.52

Extension to large areas

As the load penetration curves of cones are parabolic in shape, from a smaller cone the resistance to penetration of the bigger cone can be estimated in proportion to the square of the ratio of depth of their penetrations (θ being same). By testing a 60 degree cone of 4.9 cm diameter the resistance so estimated from 2.5 cm (1 in.) to 3.75 cm (1.5 in.) penetration was found to be within 10 percent. Now the load carrying capa-

TABLE 3. — *Particulars of Load Carrying Capacity of 2 cm dia. Plate*

Soil brought from	P_1 Load required to overcome elastic settlement in kg.	P_2 Load required for sinking, 3/8" (0.95 cm) in kg.	$(P_1 + P_2)$ Load estimated in kg.	Experimental value in kg.	Calculated from Terzaghi's theory in kg.
Hijli	8.77	5.40	14.17	19.2	6.88
Keshiary	9.718	12.57	22.29	23.2	13.005
Panskura	14.08	8.57	22.65	22.2	13.9
Rourkela	10.429	9.42	19.85	22.14	17.4
Ranchi	11.82	15.0	26.82	27.1	10.2

city of a plate of diameter equal to that of big cone can be estimated as explained above. The only difference is to increase the second part, P_2 of load proportionately with the perimeter. However, this needs further investigation.

Illustrative Example

Let it be required to estimate the load carrying capacity of 2 cm diameter plate (equal to the diameter of the cones tested) in Hi li soil.

The load penetration curve of 60° cone (diameter 2 cm depth of cone Z_2 = 1.732 cm) may be obtained as shown in figure 11.

From fig. 11, P'_c = 13.10 kg (corresponding to a penetration of 1.732 cm).

Using I = 0.3721 (for 60° cone from eq. 14a) and

$R_H = \frac{\pi}{3}$ (for 60° cone from eq. 16) in eq. 17

$$\text{Soil parameter} \quad \alpha' E' = \frac{P'_c}{2\pi I R_H}$$

$$= \frac{13.10}{2\pi\, 0.3721 \frac{\pi}{3}} = 5.335$$

Using (I) = 0.3333 from eq. 14a and

(R_H) plate $= \frac{\pi}{4}$ from eq. 16, for the plate in eq. 17 first part of the load, (on the plate)

$$P_e = 2\pi \times 5.333 \times 0.3333 \frac{\pi}{4} = 8.77 \text{ kg}$$

Second part of the load, P_2, is read from the load penetration curve. From fig. 11, the load required to penetrate the cone by the thickness of the plate (0.95 cm), P_2, = 5.40 kg.

So $P_1 + P_2 = 8.77 + 5.40 = 14.17$ kg.

Estimated load on the plate = 14.17 kg.
(for a penetration of 0.95 cm).

Conclusions

1. A semi-empirical relation, relating applied load and depth of penetration of the cone, useful for any angled cone is proposed.
2. Load carrying capacity of a plate for a given penetration is estimated for five soils from cone penetration results and are found to be in close agreement with the experimentally obtained results.
3. A method of estimating load carrying capacity of larger plates, from the test results of a small cone is suggested.

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NOTATION

C	=	cohesion
E	=	modulus of elasticity
G	=	specific gravity
I	=	integral
L_L	=	liquid limit
OMC	=	optimum moisture content

P_c	=	load on the cone at any instant
P'_c	=	load necessary to push completely the conical part
P_L	=	plastic limit
q_u	=	unconfined compressive strength
R	=	radius
R_H	=	ratio
S.E.R.	=	semi-empirical relation proposed
SPT	=	standard penetration test
s	=	displacement
w	=	water content
W_L	=	dead load applied on the lever
y	=	length
Z_1	=	depth of penetration of cone under the load P_c
Z_2	=	depth of cone
α	=	coefficient of proportionality
β	=	angle
γ	=	unit weight
ϵ	=	unit strain
ϕ	=	angle of internal friction
ϑ	=	semi-vertical angle of cone
ϑ_A	=	vertex angle of cone
σ_R	=	radial stress

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SOMMARIO

Valutazione della capacità portante da prove di penetrazione statica

Tutti i metodi usualmente impiegati per la valutazione del carico limite presentano limitazioni.

Le formule teoriche (Terzaghi, Meyerhof, etc.) fanno riferimento a parametri di valutazione incerta per le difficoltà connesse con il campionamento e per gli errori sperimentali di laboratorio; le prove di carico con piastra interessano il terreno per uno spessore limitato a circa due volte il diametro della piastra; i dati forniti dalla prova di penetrazione dinamica non sono del tutto trasferibili al campo statico.

Per superare gli inconvenienti segnalati, gli AA. propongono un metodo basato sui risultati di prove penetrometriche statiche.

Ad esso si è pervenuti con una serie di esperienze condotte, in laboratorio, su provini di terre artificialmente rimaneggiate e ricompattate, per mezzo di un apparecchio a velocità di carico controllata munito di dispositivo per la registrazione automatica della curva carico-penetrazione.

I provini sono contenuti in un recipiente cilindrico del diametro di 12,70 cm.

Le prove sono state eseguite con sette coni aventi angolo al vertice ϑ_A di 30°, 60°, 90°, 105°, 120°, 135°, 150°, e diametro della base di cm 2, e con una piastra dello stesso diametro e di spessore pari a circa 1 cm.

La velocità di applicazione del carico varia da prova a prova: il carico è stato incrementato in un intervallo di 12 minuti, fino al valore, definito « resistenza conica », necessario per la completa infissione della punta del penetrometro.

Sono stati esaminati cinque tipi di terreno dei quali nelle figg. 3 e 4 si riportano le curve granulometriche e nella tabella 1 le proprietà indici.

I risultati delle prove sono esposti nelle figg. 5, 6, 7, 8 e 9.

I diagrammi delle figg. 7, 8 e 9, in cui la « resistenza conica » è rappresentata in funzione dell'angolo al vertice, mostrano che al tendere dell'angolo a 180° la « resistenza conica » tende a un valore definito, coincidente con il carico P_1 che può applicarsi ad una piastra, di diametro uguale a quello dei coni, senza che avvenga la penetrazione nel campione.

Il carico P_1 costituisce la prima parte di cui può considerarsi composta la capacità portante del complesso piastra-terreno.

La seconda parte P_2 è il carico corrispondente ad una data penetrazione della piastra nel campione e può ottenersi da una qualunque delle curve di fig. 10 (tutte relative a un determinato terreno).

Tutte le curve, infatti, raggiunto il carico che determina l'infissione completa della punta conica, dopo un breve tratto, divengono rette fra loro parallele: ciò vuol dire che la resistenza opposta dal terreno alla penetrazione, a partire da quel punto, è indipendente dall'angolo al vertice e che le curve rappresentano il comportamento di una piastra avente diametro uguale a quello dei coni. P_2 rappresenta l'incremento di carico che determina la prefissata penetrazione e si desume dall'ultimo tratto rettilineo del diagramma (fig. 11).

In definitiva, per determinare P_2 è necessario disporre di una sola curva carico-penetrazione ottenuta con una punta conica di apertura arbitraria; la determinazione di P_1 richiederebbe invece una serie di prove eseguite con coni di apertura diversa.

Gli AA., a questo punto, considerando l'equilibrio delle forze agenti su una porzione emisferica del terreno attorno alla punta conica, derivano una relazione semiempirica tra carico applicato P_c e penetrazione Z_1 del cono (v. fig. 12), che consente di ricavare P_1 disponendo di una sola curva carico-penetrazione.

Le ipotesi poste a base della trattazione sono quelle di terreno omogeneo e linearmente elastico; il peso proprio del terreno viene trascurato; il raggio R dell'emisfero si assume tanto grande da poter trascurare l'effetto della zona plasticizzata intorno al cono; la tensione tangenziale sulla superficie emisferica si ritiene trascurabile in confronto, alla tensione radiale σ_R; il cono si suppone rigido.

Assunta valida la (2) per lo spostamento dei punti del terreno all'esterno dell'emisfero la deformazione ϵ e

la tensione σ_R sono fornite dalla (6) e (7) rispettivamente.

L'equilibrio alla traslazione verticale dà luogo alla equazione (8) che, fatte le posizioni (11) e (14a) può trascriversi nella forma (14): il carico P_c risulta pari al prodotto della costante 2π per il termine I dipendente dalla geometria del sistema e per αE, essendo α il coefficiente di proporzionalità già introdotto nella (2), E il modulo di elasticità del terreno.

Il valore di αE si ricava da prove penetrometriche misurando P_c, e risulta dipendente dall'apertura del cono usato.

Con la posizione (15), in cui R_H è pari al rapporto tra la superficie laterale e il perimetro della sezione verticale, entrambi riferiti alla parte del cono penetrata, si riscontra, sulla scorta dei risultati sperimentali ottenuti, che $\alpha'E'$ si mantiene pressoché costante (v. tab. 2) indipendentemente dal cono usato e può pertanto assumersi a caratterizzare il terreno.

L'equazione (17) consente di calcolare la « resistenza conica »: i risultati del calcolo sono confrontati con i valori sperimentali nelle figg. 7, 8 e 9.

L'accordo è soddisfacente; per $\vartheta_A = 60°$ esso è completo, in quanto si è fatto riferimento, per ricavare $\alpha'E'$, proprio alle esperienze con cono di 60°. P_1 si ottiene direttamente dalla (17) per ϑ_A tendente a 180°.

I risultati ottenuti col metodo proposto, per piastra con diametro di 2 cm., e per penetrazione di 0,95 cm. sono in ottimo accordo con i valori sperimentali (tab. 3).

Gli AA., pur rilevando la necessità di ulteriori ricerche, propongono l'estensione del metodo a piastre di grande diametro partendo dai risultati delle prove eseguite con coni di piccolo diametro.

La resistenza alla penetrazione del cono di maggiore diametro potrebbe ottenersi moltiplicando quella corrispondente relativa al cono piccolo per il quadrato del rapporto tra le penetrazioni dei due coni. Il valore di P_2 si otterrebbe moltiplicando il valore relativo alle piastre di piccolo diametro per il rapporto tra la circonferenza della piastra maggiore e la circonferenza di quella minore.

Le prime ricerche, in numero limitato, sembrano confermare la validità dell'estensione del metodo proposto.