Computer-Aided Data for Machinery Foundation Analysis and Design

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Abstract: Data on soil properties and characteristics are essential for proper analysis and design of machinery foundations. Most of the data are available in the form of tables or graphical charts which are not suitable for computer-aided analysis and design. The paper collects some of the important soil data which are required to analyze and design foundations for machinery support. The date is molded in a curve fitting form suitable for computer-aided analysis and design of those foundations. The models used are in the form of polynomials, power models or complex 16-parameters models of multi-parameters models. The assigned models facilitate the optimal design of foundations for multiple purposes such as production machinery and turbo-machinery support and have multiple correlation coefficient ≥ 0.989.

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Introduction

The first step in any scientific work leading to analysis or design is data collection. In the field of foundation engineering, most of the data are available in a graphic or tabular form. There is a lot of such data in the work of Bishop and Henkel [1], Vesic [2], Peck et.al. [3], Tavenas and et.al. [4], Tarzaghi and others [5], Murthy [6], Das [7], B. Fellenius [8] and Verriujt [9].

The effect of temperature on water properties affecting the soil mechanics is studied by Zwolinski and Eicher [10] and Kestin and others [11].

The classification of soils for engineering purposes is defined by the American standard D2487-6 [12].

The limits of the foundation vibration as affected by vibration frequency is given graphically by Murthy [6] and Rao [35].

Some of the important properties and parameters affecting the analysis and design of foundations and piles are presented with the appropriate mathematic model.

1. Variation of water density with temperature

Water content in the soil affects its characteristics. Water properties are affected by its temperature. Table 1 shows the effect of temperature on water density for temperature in the range: - 8.28 to 40 ^{o}C [10,11].

Table 1: Temperature effect on water density and viscosity [11].

Temp. t °C	Density ratio $\rho(t)/\rho(20\ °C)$	Viscosity ratio $\mu(t)/\mu(20\ °C)$
−8. 280	1. 00027	2. 4508
−6. 647	1. 00065	2. 2920
−4. 534	1. 00110	2. 1103
−1. 108	1. 00152	1. 8596
0	1. 00161	1. 7886
5	1. 00173	1. 5161
10	1. 00150	1. 3042
15	1. 00090	1. 1359
20	1. 00000	1. 0000
25	0. 99884	0. 8884
30	0. 99744	0. 7957
35	0. 99582	0. 7178
40	0. 99400	0. 6516

Using MATLAB, a suitable model defining the water density data is a third order polynomial of the form:

$$\rho/\rho_{20} = 1.00158318043032 + 0.00007652123877\ T - 0.00000884390406\ T^2 + 0.00000005521743\ T^3 \quad (1)$$

where T is the water temperature in ^{o}C, ρ is its density and ρ_{20} is its reference density at 20 ^{o}C.
Correlation coefficient: R^2 = 0.9998

2. Variation of water viscosity with temperature

The viscosity variation of water with temperature is also given in Table 1 [10,11]. The data are used to fit the following third order polynomial model:

μ/μ_{20} = 1.79870762003608 - 0.06368511808356T + 0.00147563028345 T^2 -0.00001517001871 T^3 (2)
where μ is its viscosity and μ_{20} is its reference viscosity at 20 °C.
Correlation coefficient: R^2 = 0.9997

3. Percent finer P % against grain diameter for sand

The percent passing of soil against soil particle size is shown in Fig.1 [12].

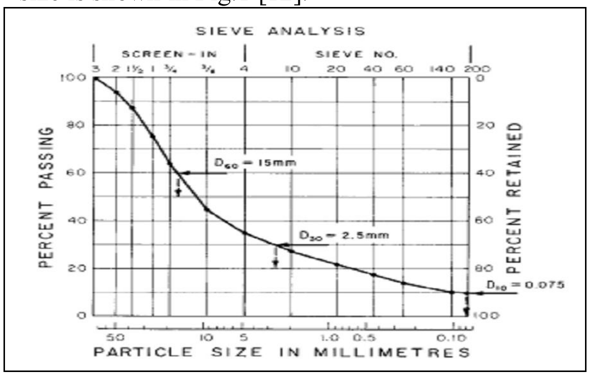

Fig.1: Percent Finer P%

The model defining the percentage passing, %P as function of the particle diameter , D (in mm) is a fifth order polynomial of the form:
%P = 11.60330326203972 + 9.13146418499006 D - 1.07916041156282 D^2 + 0.06295890920736 D^3 - 0.00151348586545 D^4 + 0.00001251888372 D^5 (3)
Correlation coefficient: R^2 = 0.9976

4. Plasticity Index

The plasticity index of the soil (PI) is defined as the difference between the liquid limit and the plastic limit of the soil. It is a useful measure of the possibility to process the clay [9].
The plasticity index I_p for activity A = 0.75 & 1.4 is shown graphically in Fig.2 [13].

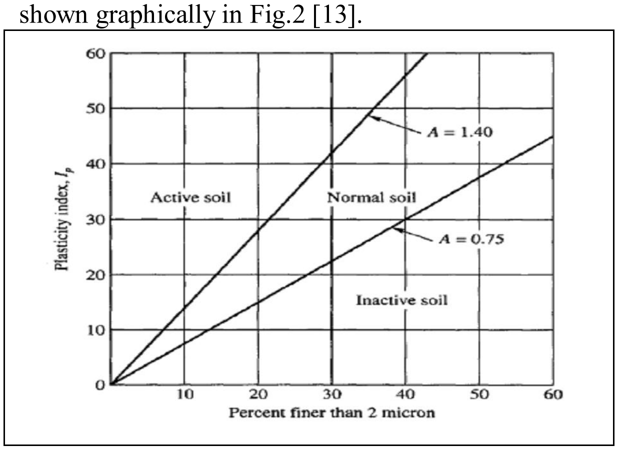

Fig.2: Plasticity Index I_p

The data in Fig.2 is well represented by a first order polynomial of the form:

$$I_p = a_0 + a_1X$$

Where X = percent finer than 2 micron
For A = 0.75:
Model: I_p = - 0.247148349881 + 0.756714463234 X (4)
Correlation coefficient: R^2 = 0.9999
For A = 1.4:
Model: I_p = - 0.140000000596 + 1.399500012398 X (5)
Correlation coefficient: R^2 = 0.9997

5. Approximate methods for calculating soil stress under square strip load

The stress in the soil is function of the type of loading and the depth of the soil. The variation of the soil stress σ_z as function of the dimensionless depth z/B where B is the strip width is shown in Fig.3 for exact method and point load method as stated by Murthy [14].

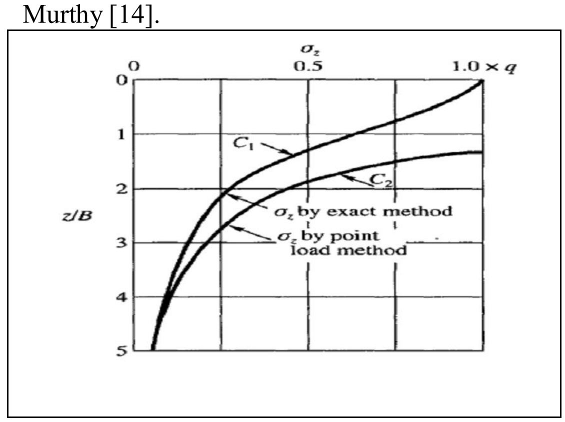

Fig.3: Soil Stress σ_z

For the exact method:
Let X = z/B
The model defining the dimensionless soil stress is a 5th order polynomial of the form:
σ_z/q = 1.00298426573427 - 0.08163886946387 X - 0.52253350815851 X^2 + 0.29431759906760 X^3 - 0.06063519813520 X^4 + 0.00436410256410 X^5 (6)
where q is the load per unit area ($q = Q/B^2$).
Correlation coefficient: R^2 = 0.9990

For a point load method:
The model representing the data is:
σ_z/q = 6.38789030999244 - 8.51052696393012 X + 4.88351494078893 X^2 -1.42194538479060 X^3 + 0.20543492443599 X^4 - 0.01168622398898 X^5 (7)
Correlation coefficient: R^2 = 0.9998

6. Undrained shear strength, C_u

The variation of the dimensionless shear strength, C_u/p' (where p' is the effective overburden pressure) against the soil plasticity, I_p is shown in Fig.4 as given by Murthy [15] based on the work of Tavenus et.al. [4].

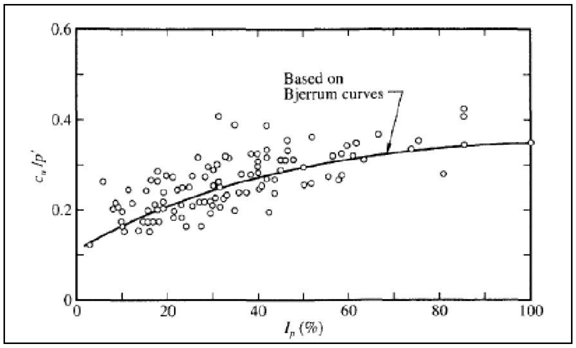

Fig.4: Shear Strength against soil plasticity

C_u/p' is related to the plasticity index I_p through the 2nd order model fitted using MATLAB:

$C_u/p' = 0.121268533170 + 0.004718809389\ I_p - 0.000024708454\ I_p^2$ (8)

Correlation coefficient: $R^2 = 0.9983$

7. Correction factor μ for shear strength correction:

According to Bjerrum [16], the measured shear strength using the vane apparatus is greater than that in compression tests. The correction factor μ depends on the plasticity index I_p as shown in Fig.5 [16].

The correction factor is used as given in Eq.9.

$$C_{u,field} = \mu\ C_{u,vanetest} \quad (9)$$

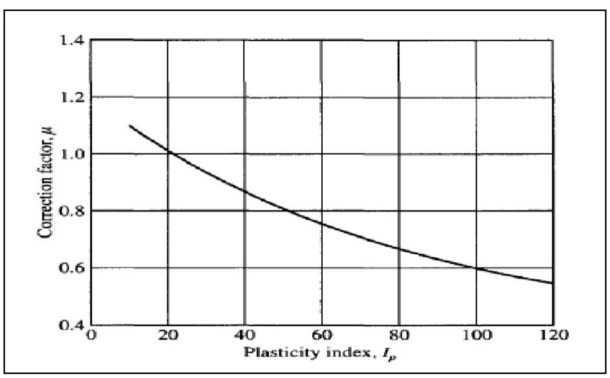

Fig.5: correction Factor μ

μ is related to the plasticity index I_p through the second order polynomial model:

$\mu = 1.179999351501 - 0.008994471282 I_p + 0.000031318403\ I_p^2$ (10)

Correlation coefficient: $R^2 = 0.9988$

8. Clay shear strength:

The Un-drained shear strength of two types of clay as function of soil depth under ground is shown in Fig.6 [17].

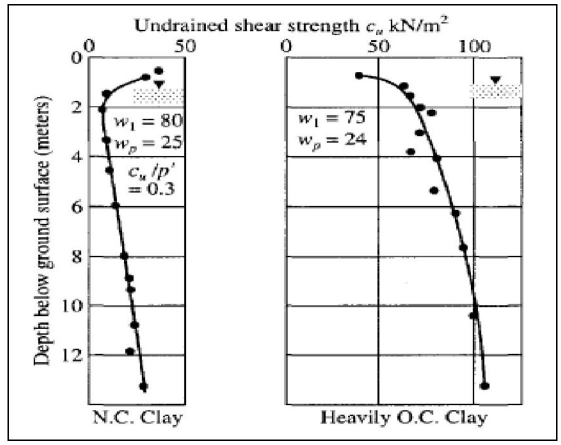

Fig.6: Un-drained Shear strength of Soil

For N.C. clay:

C_u (in kN/m^2) is related to the depth of cut, X (in m) through the 5th order polynomial:

$C_u = 59.59405517578 - 51.37217712402\ X + 17.48160552978\ X^2 - 2.57330775261\ X^3 + 0.17492927611\ X^4 - 0.00446781144 X^5$ (11)

Correlation coefficient: $R^2 = 0.9909$

For Heavy O.C. clay:

The same model of Eq.10 is used and it has the form:

$C_u = 12.04870414734 + 57.63009643555X - 19.06491470337\ X^2 + 3.04352760315\ X^3 - 0.22288510203X^4 + 0.00605789432\ X^5$ (12)

Correlation coefficient: $R^2 = 0.9873$

9 . Un-drained shear strength- liquidity index

The un-drained shear strength of soft clays as function of the liquidity index I_p is shown graphically in Fig.7 [18,19].

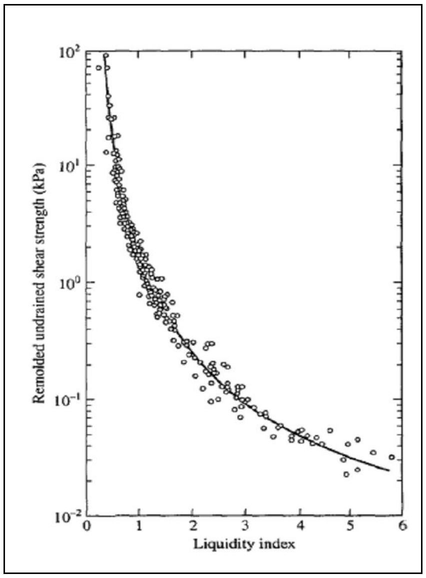

Fig.7: Un-drained Shear Strength of Soft Clays

Let C_u = un-drained shear strength (kN/m^2):
In this range of I_p ($0.3 \le I_p \le 5.7$), the un-drained shear strength is well defined by a power model of the form:

$$C_u = 1.512761116027832\ I_p^{-2.475059747695923} \quad (13)$$

Correlation coefficient: $R^2 = 0.9992$

10. Stress distribution due to surface load (strip loads)

Stress in the soil depends on the shape of the load , the soil depth and the radial location. Fig.8 shows the soil dimensionless stress distribution for soil loading using a strip of length 2b[20].

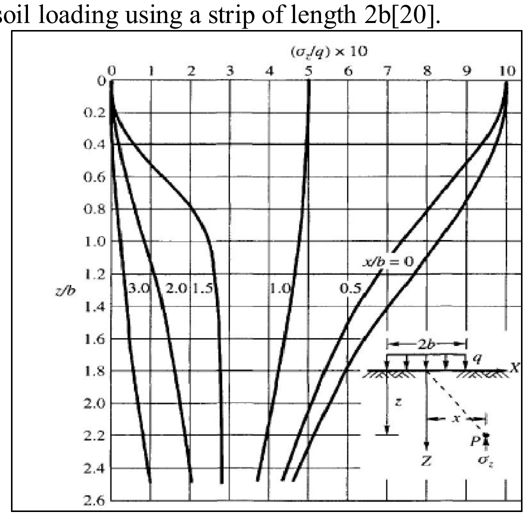

Fig.8: Soil Stress Distribution

q in Fig.8 is the load/unit surface area of the strip.
Only the curve corresponding to x/b = 0 is used, i.e. when P is on the vertical axis.

For x/b = 0 ; the data are well represented by the fourth order polynomial model:

$$\sigma_z/q = 0.995286107063 + 0.012137694284\ (z/b) - 0.286908298731\ (z/b)^2 + 0.104408301413\ (z/b)^3 - 0.010142614134\ (z/b)^4 \quad (14)$$

Correlation coefficient: $R^2 = 0.9994$

11. Pore pressure coefficients A & B

Clay soils usually contain water in its pores, and loading the soil may give rise to the development of additional pore pressures [21]. Pore pressure parameters A and B are used to express the response of the pore pressure to changes in total stress under un-drained conditions [22]. The pore pressure coefficients A and B are shown graphically in Fig.9 as given by Murthy [23].

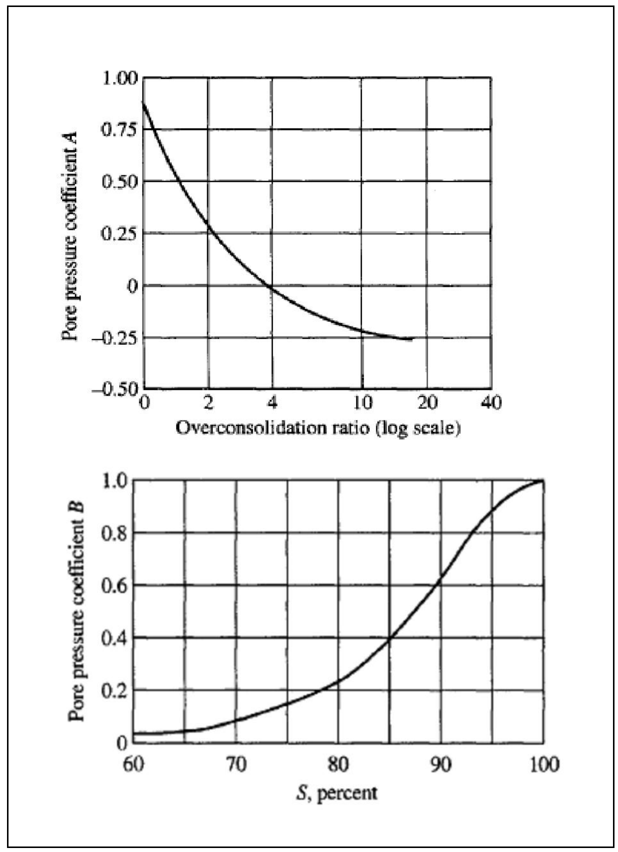

Fig.9: Pore Pressure Coefficients

For pore coefficient A:
Let X = over-consolidation ratio
The graph is presented by a fourth order polynomial of the form:

$$A = 0.888375878334 - 0.369547337294X + 0.043617967516\ X^2 - 0.002058588900X^3 + 0.000028900962\ X^4 \quad (15)$$

Correlation coefficient: $R^2 = 0.9980$

For pore coefficient B:
Let S = Saturation
The graph is presented by a fifth order polynomial of the form:

$$B = 228.002772564440 - 15.400664606503S + 0.413586655865S^2 - 0.005517782023S^3 + 0.000036541516\ S^4 - 0.000000095918\ S^5 \quad (16)$$

12. Soil internal friction angle

According to the work of the department of army and the air force (USA) [24], and the work of Dewoolkar and Hazjack [25], the internal friction angle of the soil is function of the soil plasticity index. Fig.10 illustrates this relation [24]. There is a range of values at each plasticity index. An average curve is drawn which is used to fit a mathematical model for this relation.

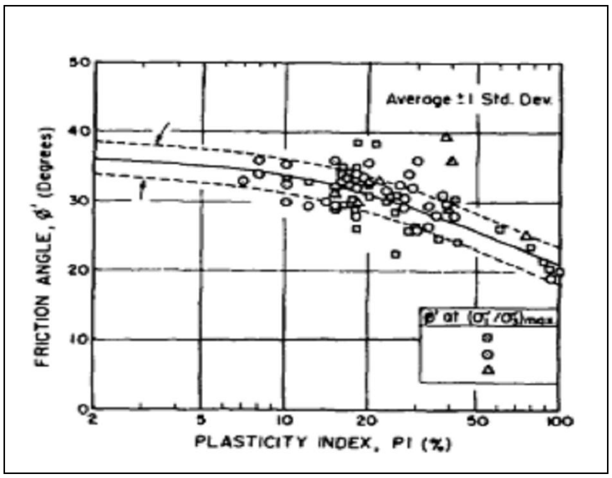

Fig.10: The Friction Angle of Soil and Soil Plasticity Index.

A third order polynomial model is fitted relation the friction angle, φ and the plasticity index, I_p of the soil in the form:

$$\varphi = 35.956314086914 - 0.269176721573\ I_p + 0.001345862867\ I_p^2 - 0.000002350898\ I_p^3 \quad (17)$$

Correlation coefficient: $R^2 = 0.9987$

13 . Soil void ratio

The soil void ratio is function of its water content. Fig.11 shows the variation of the soil void ratio, e with the water content, WC in the range: $6 \le WC \le 60$ [26].

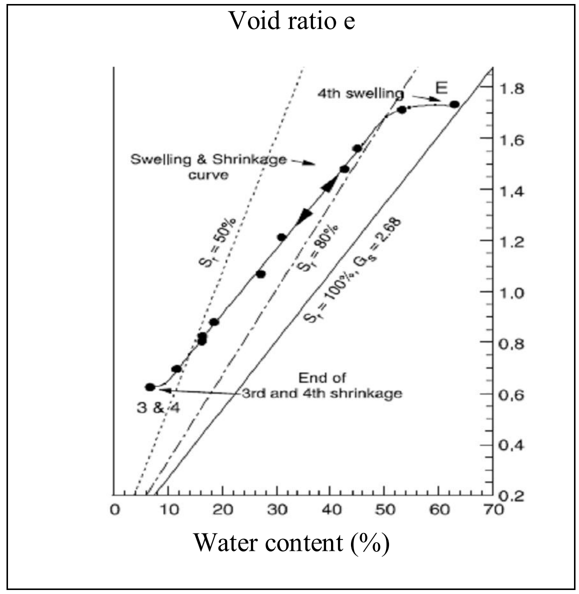

Fig.11: Soil Void Ratio (e)

The following 6th order polynomial is fitted to the data in Fig.11:

$$e = 0.962967017971123 - 0.128158892941511\ WC + 0.014742752230574\ WC^2 - 0.000668282644297\ WC^3 + 0.000015551088541\ WC^4 - 0.000000178597336\ WC^5 + 0.000000000794398\ WC^6 \quad (18)$$

Correlation coefficient: $R^2 = 0.9987$

14. Soil Matric suction

The soil Matric suction is function of the soil water content depending on the soil type. Fig. 12 shows the Matric suction for 3 types of soils [27].

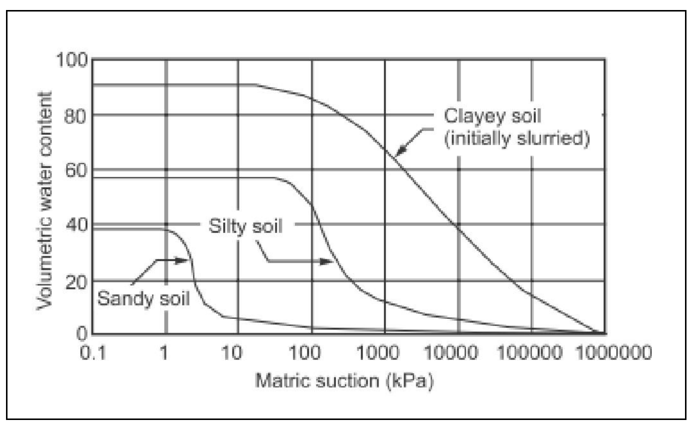

Fig.12: Matric Suction for 3 Types of Soils

For a clayey soil:
The following 6th order polynomial is fitted to the data in Fig.12 for water content (%) and Matric suction (kPa):

$s = 1.013451836122844\text{x}10^6 - 0.119976257496594 \text{x}10^6 \text{ WC} + 0.005837105261077\text{x}10^6 \text{ WC}^2 - 0.000145917031476\text{x}10^6 \text{ WC}^3 + 0.000001966516747\text{x}10^6 \text{ WC}^4 - 0.013568802 \text{ WC}^5 + 0.000037589 \text{ WC}^6$ (19)

Correlation coefficient: $R^2 = 0.9989$

For a silty soil:

The following 10^{th} order polynomial is fitted to the data in Fig.12:

$s=2.743215123902390\text{x}10^5 1.621260968537128\text{x}10^5 \text{ WC} +0.412695527128262\text{x}10^5\text{WC}^2- 0.058159983819816\text{x}10^5 \text{ WC}^3 + 0.005000773619034\text{x}10^5 \text{ WC}^4 - 27.4850595156 \text{ WC}^5 + 0.9831458993 \text{ WC}^6 – 0.0227363495\text{WC}^7 + 0.0003272577 \text{ WC}^8 - 0.0000026618 \text{ WC}^9 + 0.0000000093 \text{ WC}^{10}$ (20)

Correlation coefficient: $R^2 = 0.9995$

For a sandy soil:

For a good correlation, the water content range is divided to 2 sub-ranges:

Range 1: $0.1 \leq \text{WC} \leq 1.7$

Range 2: $3 \leq \text{WC} \leq 38$

For Range 1: $0.1 \leq \text{WC} \leq 1.7$: A 4^{th} order polynomial of unit correlation coefficient represents the data as follows:

$s=1.482367187499999\text{x}10^6 - 5.524780133928551\text{x}10^6 \text{ WC} + 7.427837053571373 \text{ x}10^6 \text{ WC}^2 - 4.255558035714237\text{x}10^6 \text{ WC}^3 + 0.880133928571416\text{x}10^6 \text{ WC}^4$ (21)a

For Range 2: $3 \leq \text{WC} \leq 38$: A 7^{th} order polynomial of 0.9994 correlation coefficient represents the data as follows:

$s = 158.5096749019764 - 64.9057288171960 \text{ WC} + 10.9666875630567 \text{ WC}^2 - 0.9677311181482 \text{ WC}^3 + 0.0483435575978 \text{ WC}^4 - 0.0013760790337 \text{ WC}^5 + 0.0000207992293 \text{ WC}^6 – 0.0000001295267 \text{ WC}^7$ (21)b

1. Soil effective vertical stress

According to Nuth and Laloui, the soil effective vertical stress, p' is function of void ratio, e and Matric suction, s [28]. The relation between p' and e for 4 levels of s is shown graphically in Fig.13 [28].

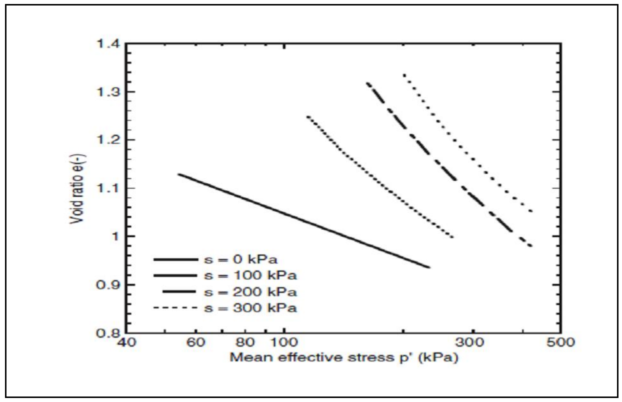

Fig.13: Relation Between p' and e for 4 levels of s

A second order polynomial multiple regression model is fitted to the data of Fig.13 having the form:

$p' = 2920.58544921+ 3.29155206680s – 4649.81152343750e – 0.0007531451s^2 + 1869.84313964844e^2 – 1.90608596802se$ (22)

where:

Correlation coefficient: $R^2 = 0.9978$

2.Bearing capacity factors taking care of mixed state of local and general shear failures in sand

According to Peck, Hanson and Thornburn, the capacity factors N_c, N_q and N_γ as function of the angle of internal friction φ of the soil and for taking care of mixed state of local and general shear failures in sand is shown graphically in Fig.14 [29].

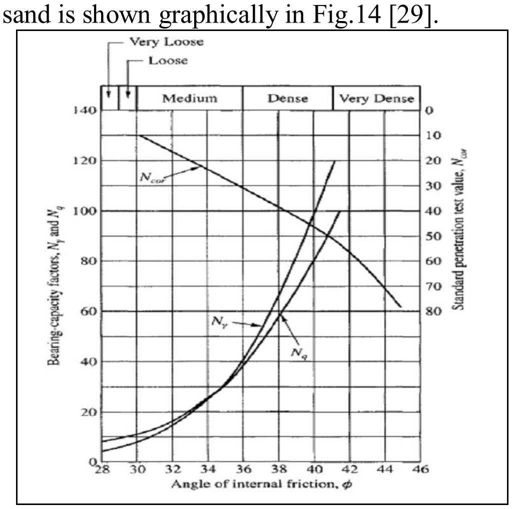

Fig.14: Relation between Capacity Factors N_c, N_q and N_γ , and Angle of Internal friction φ of the soil.

For N_γ:

$N_\gamma = -7718.67968101048 + 865.29961107015\varphi - 34.91846009470 \varphi^2 + 0.56763435513\varphi^3 - 0.00201299288 \varphi^4 - 0.00002049525 \varphi^5$ (23)

For N_q:

N_q = 22951.8294289856 - 3467.3605713658 φ + 208.9594652514 φ^2 -6.2757649085 φ^3 + .0938438677 φ^4 - 0.0005576555 φ^5 (24)

For N_c:

N_c = -1913.87242930531 + 272.64866454596 φ - 13.86944472924 φ^2 + 0.33677634532 φ^3 - 0.00387974098 φ^4 + 0.00001631578 φ^5 (25)

The correlation coefficient for the models in equations 23 – 25 is greater than 0.999.

2.Skempton bearing capacity factor N_c for clay soils

According to Murthy , the Skempton bearing capacity factor N_c for clay soils is function of the foundation type (circular or square, strip or rectangular) and the relative depth D_f/B [30] . This relation is shown graphically in Fig.15[30].

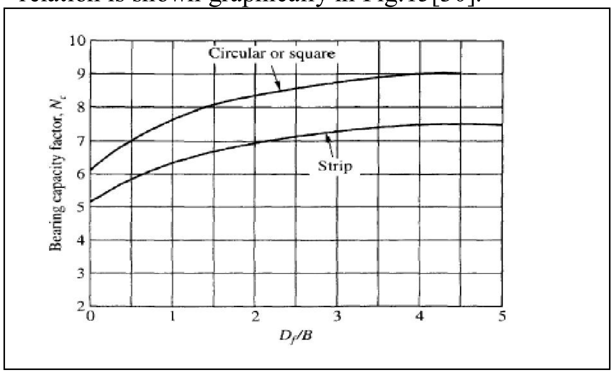

Fig.15: Relation between Skempton bearing capacity factor N_c , foundation type relative depth D_f/B [6]

For strip foundation:

N_c = 5.19720279720280 + 1.33701631701634 (D_f/B) - 0.20909090909094 $(D_f/B)^2$ -0.04452214452213 $(D_f/B)^3$ + 0.02051282051282 $(D_f/B)^4$ - 0.00205128205128 $(D_f/B)^5$ (26)

Correlation coefficient: $R^2 = 0.9995$

Circular or square foundation:

N_c = 5.99944055944057 + 2.46317482517480 (D_f/B) - 1.04522144522143 $(D_f/B)^2$ + 0.27242424242424 $(D_f/B)^3$ - 0.03878787878788 $(D_f/B)^4$ + 0.00225641025641 $(D_f/B)^5$ (27)

Correlation coefficient: $R^2 = 0.9998$

18. Theoretical compressibility factors

Murthy studied the effect of soil compressibility on the soil bearing capacity based on the work of Vesic and Murthy [2, 31]. Vesic used compressibility factors functions of the soil rigidity index, I_r and the angle of shearing resistance, φ for different types of foundations as shown in Fig.16 [2].

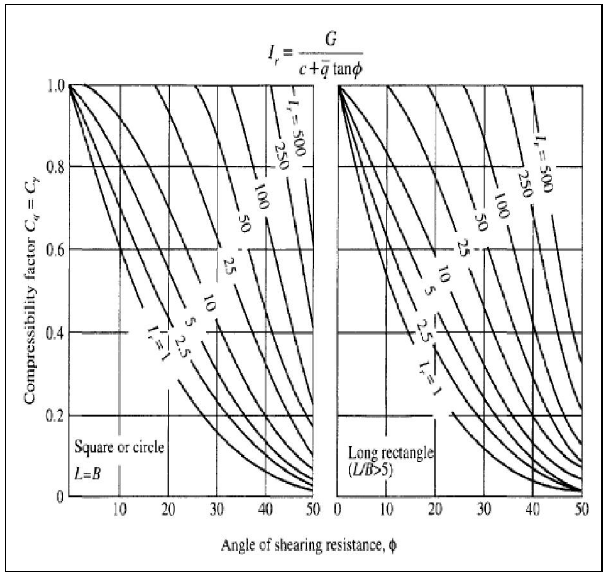

Fig.16: Soil Rigidity Index, I_r and the angle of shearing resistance, φ

For Square & Circular Foundations:

The compressibility factor C_q (= C_γ) is function of I_r and φ. A 16 parameters model is used to identify the data of Fig.16 using a code prepared by Prof. Galal Hassaan based on optimization techniques. The model has the form:

C_q = 1.06005465984 – 0.06648942828 φ – 0.05125475302 I_r + 0.00145848258 φ^2 + 0.01179346535 I_r^2 + 0.01987789199 φI_r + 0.00010395483 $(\varphi I_r)^2$ – 0.00280426652 φI_r^2 – 0.00075457187 $\varphi^2 I_r$ – 0.00001119525 φ^3 – 0.00069307291 I_r^3 + 0.00013407799 φI_r^3 – 0.00000478832 $\varphi^2 I_r^3$ + 0.00000789103 $\varphi^3 I_r$ – 0.00000111904 $\varphi^3 I_r^2$ + 0.00000005183$(\varphi I_r)^3$ (28)

Correlation coefficient: $R^2 = 0.9892$

For long rectangular foundations L/B > 5:

The model using the data of Fig.16 has the form:

C_q = 1.04221749306 – 0.08545932919 φ – 0.04875162244 I_r + 0.00247926032 φ^2 + 0.01241779234 I_r^2 + 0.02945883572 φI_r + 0.00024841732 $(\varphi I_r)^2$ – 0.00528917834 φI_r^2 – 0.001342112768 $\varphi^2 I_r$ – 0.00002407614 φ^3 – 0.00079491240 I_r^3 + 0.00030897983 φI_r^3 – 0.00001463081 $\varphi^2 I_r^3$ + 0.00001586905 $\varphi^3 I_r$ – 0.00000305017 $\varphi^3 I_r^2$ + 0.00000018174$(\varphi I_r)^3$ (29)

Correlation coefficient: $R^2 = 0.9994$

19. Soil cohesion

Hamdani tabulated a numerical values for the cohesion (in psi) as function of the internal friction angle of the soil [32]. A 6th order polynomial model is fitted to Hamdani data having an 0.9880 correlation coefficient relating the cohesion c (kPa) to the phase angle φ (degrees):

$c = -3303.570198728455 + 1638.575481456941\ \varphi - 324.370920840790\ \varphi^2 + 33.175709179842\varphi^3 - 1.846874663295\ \varphi^4 + 0.053170042966\ \varphi^5 - 0.000619669123\ \varphi^6$ (30)

20. Soil stiffness in the vertical and horizontal directions

Gazetus has given the soil stiffness in the vertical and horizontal directions as [33]:

$k_z = 4GRC_z(L/B) / (1 - v)$ and $k_x = 8GRC_x(L/B) / (2 - v)$

where: G = soil rigidity modulus, R = equivalend circular radius of the rectangular foundation, C_z = correction factor in the vertical direction, C_x = correction factor in the horizontal direction, v = Poisson's ratio of the soil, L = foundation length, B = foundation width.

The correction factors C_z and C_x are given by Barken as in Table 2 [34]:

Table 2: Correction factors C_z and C_x

L/B	1	2	4	6	8	10
C_z	0.953	0.975	1.077	1.152	1.196	1.250
C_x	0.993	0.983	1.000	1.055	1.132	1.191

The following models is fitted for C_z and C_x:

$C_z = 0.968339145184 - 0.044979844242\ (L/B) + 0.033221840858\ (L/B)^2 - 0.004676759709\ (L/B)^3 + 0.000208628044\ (L/B)^4$ (31)

With 0.99980 correlation coefficient.

$C_x = 1.026129841805 - 0.04249420017\ (L/B) + 0.011028882116\ (L/B)^2 - 0.000512405066\ (L/B)^3$ (32)

With 0.99977 correlation coefficient.

21. Vibration limits

Rao has given the vibration limits in graphical form for some important applications such as: machine foundations, structures, persons as function of the vibration frequency. Those limits are shown in Fig.17 [35].

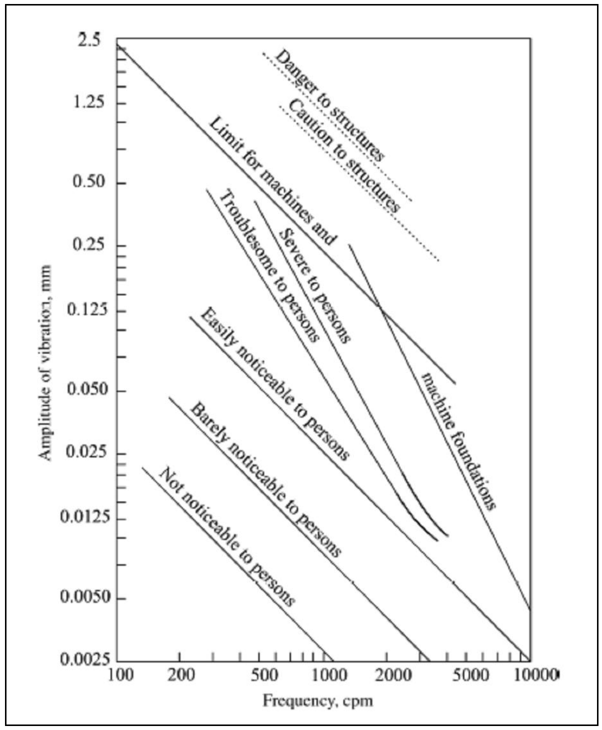

Fig.17: Machine Foundations, Structures, Persons as Function of the Vibration Frequency.

For machine foundations:

The data of Fig.17 is well represented by a power model given by:

$A_v = 112.429489135742\ f^{1.969963312149}$ (33)

Where f is the vibration frequency in cycle/min and A_v is the peak vibration amplitude in mm.

Correlation coefficient: $R^2 = 0.9994$

Models applications:

A MATLAB code is written using most of the models generated in this work to help soil mechanics and foundation design engineers in their research and application work. The code is available from Prof. Galal Hassaan free of charge through his electronic mail: galalalihassaan@yahoo.com

Discussions:

The work presented in this paper covered data required for the analysis and design of different types of foundations. The graphical and tabulated date are moulded into mathematical models compatible with requirements of computer-aided anaysis and design of foundations.

The generated models took the form of:

- Polynomial models with orders 1 to 10.
- 16 parameters complex model.
- Second order polynomial multiple regression model.

- Power model.

The accuracy of the fitted models was measured by the correlation coefficient, R^2. It was in the range:

- Polynomial models: $0.9873 \leq R^2 \leq 1.0$.
- 16 parameters complex model: $0.9892 \leq R^2 \leq 0.9994$.
- Second order polynomial multiple regression model:0.9978
- Power model: 0.9994.

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