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SETTLEMENT OF STRIP FOOTINGS ON RECENTLY DEPOSITED TROPICAL COASTAL LOWLANDS

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ABSTRACT: Many coastal lowlands are recently deposited. That is the soil layer consists of a thick layer of normally consolidated clay, silty clay, clayey silt or a combination thereof. In certain areas the deposit is so soft at the grade level that it can not support the slightest of loads. In other areas, perhaps a few kilometers away from the shore-line, the surficial soils have become over-consolidated by desiccation and can support some load. These localities are, more often than not, of very gentle slope and carry scant vegetation. The layer supporting the crust (the desiccated soil) is still normally consolidated, highly compressible and its water content often exceeds the LL. Construction on such a formation obviously presents a serious problem and certain guidelines may be of value. It is the aim of the present paper to provide some such information. The discussions are limited to the performance of strip footings for low cost single story housing units.

INTRODUCTION

In many region of the world the coastal lowlands consist of a layer of fine grained soils which are the results of outwash from the highlands. These lowlands are flat in topography, have a very gentle slope (almost horizontal) and more often then not, sustain scant vegetation. The water table is quite near the surface and a typical element within the soil layer is normally consolidated having experienced only the submerged weight of the soil column above it. Thus near the grade, where little pressure is exerted, the elements have very low strength and stiffness. It is in fact very difficult, if not impossible, to walk over these formations. These lowlands exist, for example, in the south-eastern part of Iran where they are locally known as "khors". At a distant away from the sea shore the characteristics of the land may change. Here the soil at grade elevation is quite hard. That is, a layer (crust) of overconsolidated stiff clay covers the region. The overconsolidation is caused by desiccation and although the soil is almost saturated yet both its strength and stiffness are of considerable magnitude.

Naturally construction in such regions is a challenge. Major structures must be supported on deep foundations or improved soil layers or be floated in the soil. For low cost single story housing units such measures are out of question considering the costs involved. Since the magnitude of the loads exerted are not very high, these buildings can be supported on strip footings that rest directly on the top of the hard crust. That is the site preparation consists of a surface scraping to merely remove the little existing vegetation. Care must, of course, be taken to scrape as little as possible of the crust layer. Such a scheme, obviously, is only feasible where ground freezing is not an issue. That is, tropical regions of the world.

Every foundation must satisfy two basic requirements. First it must not break into the ground (experience bearing capacity failure). Second it must not settle "excessively"; i.e. the settlements experienced must not jeopardize the integrity of structure it is supporting. It is this second issue that is addressed in the present paper. Specifically it provides an analysis to

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Note: Discussion on this paper is open until December 25, 2001.

evaluate the magnitude of settlement of a row of strip footings with a given spacing between them. In the analysis the ID numerical technique is employed since the conventional technique based on an estimation of the stress field (using the Boussinesq's or Wesregaard's equations) are not adequate.

The paper is written in the following sequence. First an account is given of the soil profile under consideration. Next the ID technique, as it pertains to the present situation, is outlined. This is followed by a presentation of certain results from the analysis and finally two design charts are provided.

THE SOIL PROFILE

Figure 1 shows the variation of the deformation modulus (DM) of the soil layer with depth assuming a maximum crustal value of 10 MPa. This is within the range of values proposed for hard clays, see for example Das (1990). Other values used in this study are DM_0 = 2 MPa, a value suggested for soft clays, and DM_0 = 5 MPa corresponding to a medium hard clay. Below the desiccated zone, shown by h_{des} in Fig. 1, the stiffness of the soil layer increases linearly with depth consistent with the assumption that the soil has consolidated under its own weight. In this figure the rate of increase of DM with depth (denoted α by in this paper) is taken to be 100 kN/m^3. This value corresponds to a compression index of about 0.25 or a LL of about 40% using the equation proposed by Nagaraj and Murty (1985) for evaluation of C_c. The Poisson's ratio used at all levels is taken to be 0.1 and the water table is assumed to be at the grade level. The lateral deformation of the soil layer under the application of the footing load is assumed to be negligible. In this way the results from the one-dimensional consolidation tests are directly applicable. Thus putting all the above conditions together, the soil layer is assumed to act as a Gibson-Westergaard foundation supporting a hard crust.

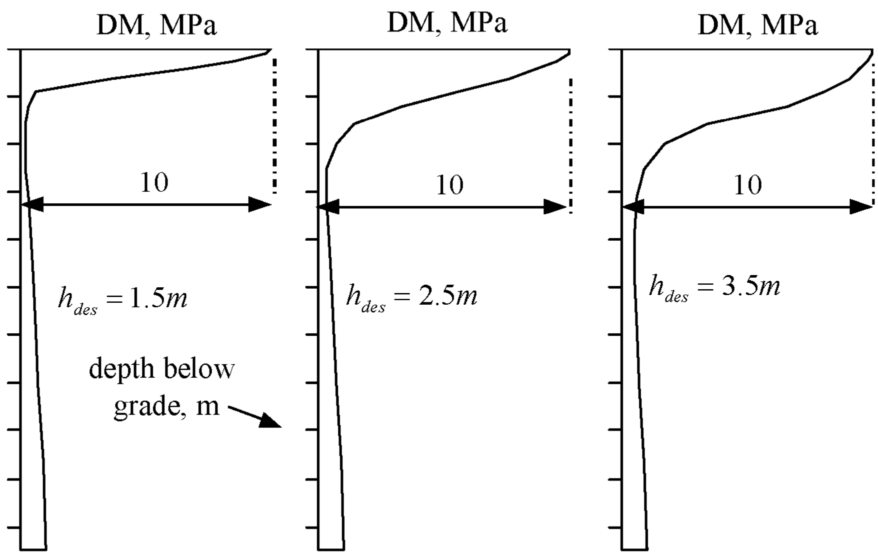

Fig. 1 Variation of soil stiffness with depth for a typical recently deposited soil formation

ANALYSIS

The numerical approach used in this study is the ID technique developed by the Author, Professor Miura and his student, see Poorooshasb, Alamgir and Miura (1996). A brief outline of the technique, as it pertains to problem at hand, is presented here.

Referring to Fig. 2, the solution region is represented by a series of nodal points as shown.

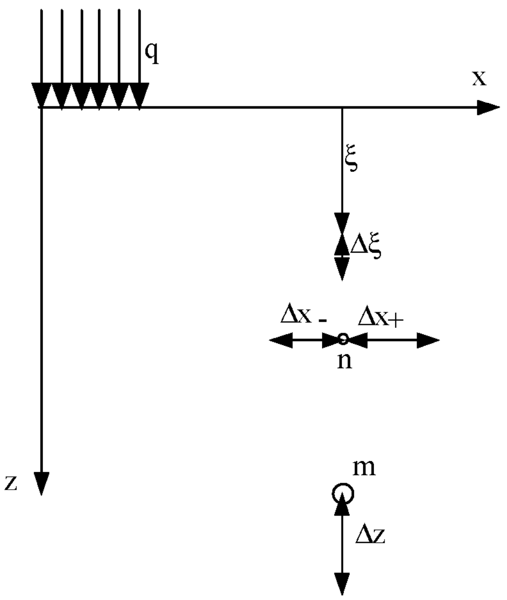

Fig. 2 Nodal points within the solution region

Consider the element at a typical location. The incremental equation of equilibrium in the vertical direction is:

$$\frac{\partial \sigma_{zz}}{\partial z} + \frac{\partial \sigma_{xz}}{\partial x} = 0 \tag{1}$$

If the above equation is integrated with respect to ξ between the limits of 0 and z one obtains the equation:

$$\sigma_z + \int_0^z \frac{\partial \sigma_{\xi x}}{\partial x} d\xi = 0 \tag{2}$$

But $\sigma(x,\xi) = G(\xi)\frac{\partial u(\xi)}{\partial x}$ (Westergaard's condition) and $\sigma_z = E(z)\frac{\partial u(z)}{\partial z}$. Thus Eq.(2) reduces to the form:

$$\frac{\partial u(z)}{\partial z} + \int_0^z \frac{G(\xi)}{E(z)} \frac{\partial^2 u(\xi)}{\partial x^2} d\xi = 0 \tag{3}$$

The last equation may be rewritten in a form suitable for numerical manipulation. The result is:

$$u(z+\Delta z) - u(z) - \frac{\Delta z}{E(z)} . \sum_0^{iz} G(\xi) * \lambda(x,\xi)\Delta\xi = 0 \tag{4}$$

where,

$$\lambda(x,\xi) = 2*[f_1*(u^+ + u^- - 2u) - f_2*(u^+ - u^-)];$$

$$f_1 = \frac{1}{\Delta x_+^2 + \Delta x_-^2};$$

$$f_2 = f_1 \frac{\Delta x_+^2 - \Delta x_-^2}{\Delta x_+^2 + \Delta x_-^2}$$

Of course at nodal points directly below the base of the footing (loaded area in Fig. 2) the right hand side of Eq.(4) must be replaced by the value $p*\Delta z/E(z)$. This completes a brief account of the ID technique. For a more detailed discussion see the above reference.

RESULTS OF THE ANALYSIS

Figure 3 shows two typical results obtained from the above analysis. The figure on the right hand side shows a flexible strip footing of 1 meter width exerting a uniformly distributed load (UDL) of 50 kPa. Both these values represent about the maximum permissible values that may be used for the type of land formation under consideration. The spacing between the footings (center line to center line) is about 5.3 m indicating a practical span for a housing unit.

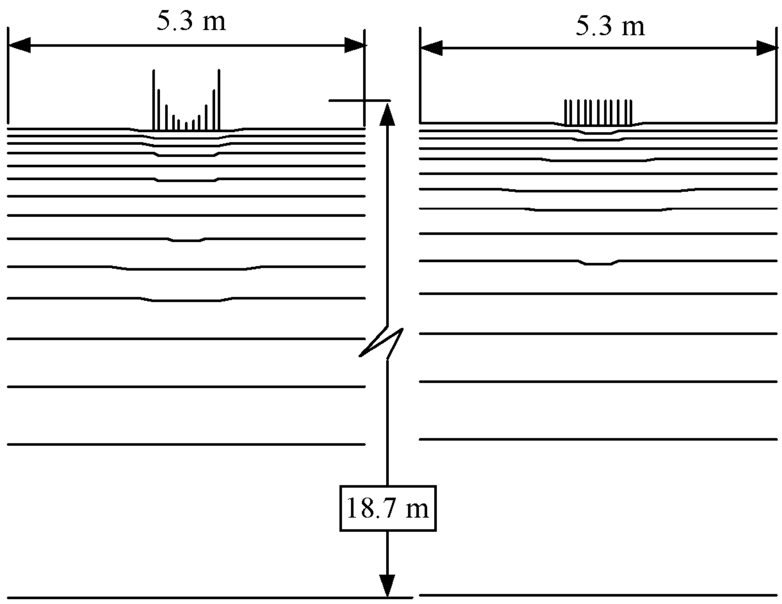

Fig 3 Performance of a rigid footing (LHS) and flexible footing (RHS) supported by a 18.7 m thick layer. Depth of hard crust =2.5 m, DM_0= 10 MPa. UDL= 50 kPa, Footing width=1 m, Spacing=5.3 m

The dots shown in the figure are the position of the nodal points before the footing is constructed while the continuous curves indicate the ground profile a long period after the construction of the footing. The footing load results in a moderate settlement of about 40 mm at the centerline, which is quite acceptable considering the type of the building to be erected and the supporting soil formation.

The situation shown on the left hand side of Fig. 3 corresponds to a similar but rigid footing. Here the exerted load is not uniform but as may be noted has maximum values at the two extremities of the loaded zone. The evaluated maximum settlement differs from the previous figure by a value less than 5% and the pattern of ground deformation is almost identical to the previous case. Thus in all the subsequent analysis the footing was considered to be flexible exerting a UDL of 50 kPa.

To investigate the influence of the depth of the hardened crust and the magnitude of DM_0 on the value of the resulting settlements several test were performed with results shown in Figs. 4 to 6 inclusive. In all these figures the depth of the soft layer is assumed to be about 9 m.

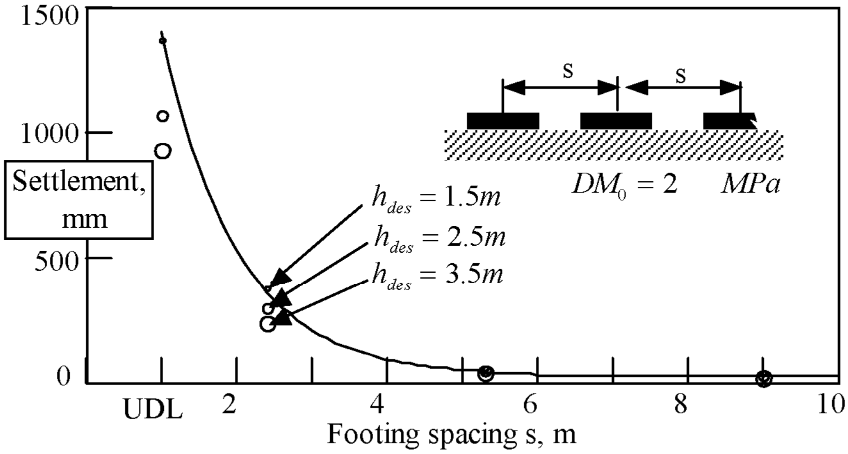

Fig. 4 Influence of spacing on the magnitude of settlement for a 1 m wide footing supporting a UDL of 50 kPa, MD_0=2 MPa, depth of layer=9 m

Note that a spacing of 1 m indicates that the surface is subjected to a UDL of 50 kPa extended over a large area of the ground.

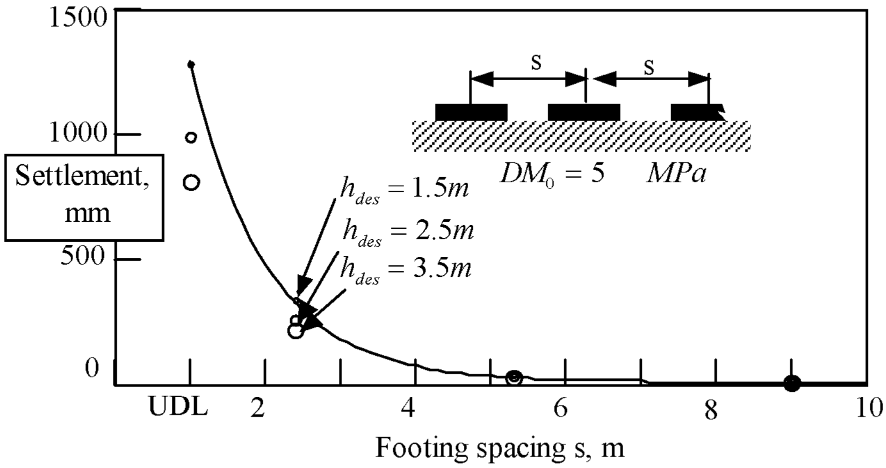

Fig. 5 Influence of spacing on the magnitude of settlement for a 1 m wide footing supporting a UDL of 50 kPa, DM_0=5 MPa, depth of layer = 9 m

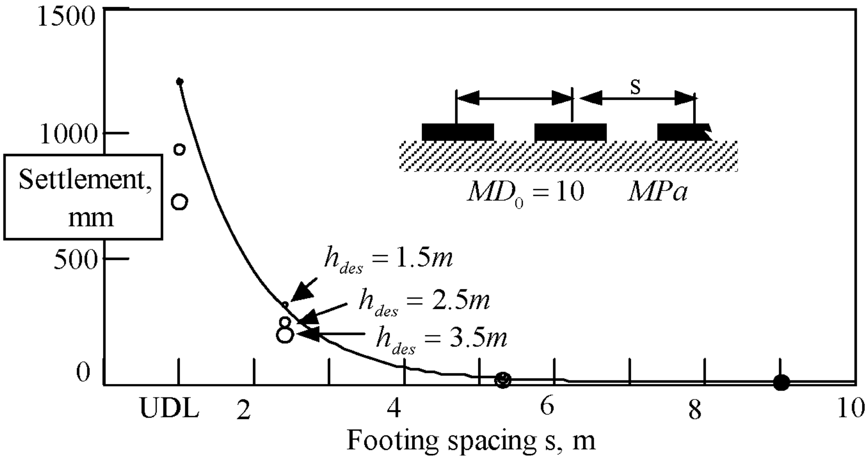

Fig. 6 Influence of spacing on the magnitude of settlement for a 1 m wide footing supporting a UDL of 50 kPa, MD_0= 10 MPa, depth of layer = 9 m

A comparison of the results shown in the last three figures tend to indicate that the value of DM_0, the stiffness of the crust at the grade level has very little influence on the performance of the system. To examine the truth, or otherwise, of this observation the portion of the "envelope curves" of Figs. 4 to 6 are reproduced in Fig. 7 using a much larger scale and for a spacing of 3 to 6 m. The envelope curves correspond to a crustal thickness of 1.5 m and as such represent the worst scenario cases. [Note: Fig. 7 may also be used as a design chart as will be seen later on]

Based on the results obtained it was concluded that for MD_0 values larger than 10 MPa the hardness of the crust does not contribute to a reduction of settlement. In the lower range (MD_0 =2 MPa) it (i.e. hardness of the crust) plays a fairly significant role. For intermediate values a linear interpolation is acceptable.

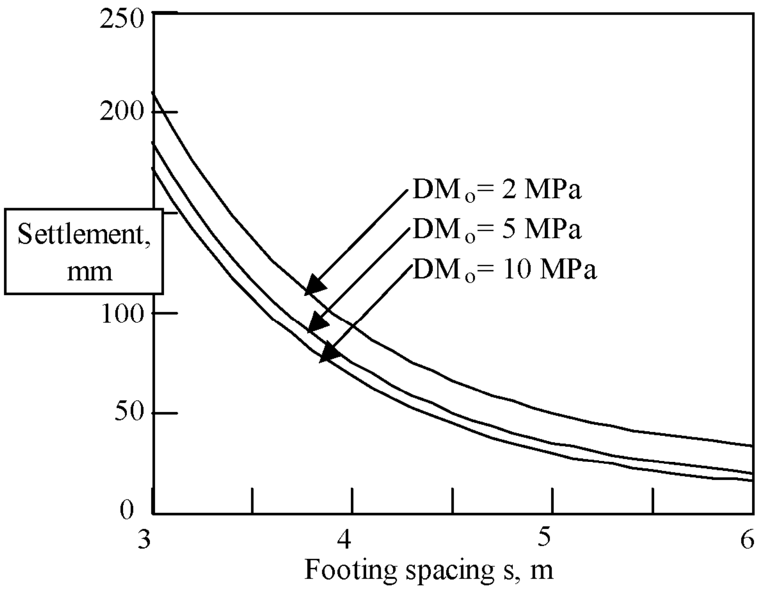

Fig. 7 Guide design chart for a layer of about 10 m deep

Figure 8 shows the results of several tests carried out on an 18.7 m thick layer with a crust of 1.5 m thick. The moduli of deformation varied between 2 to 10 MPa.

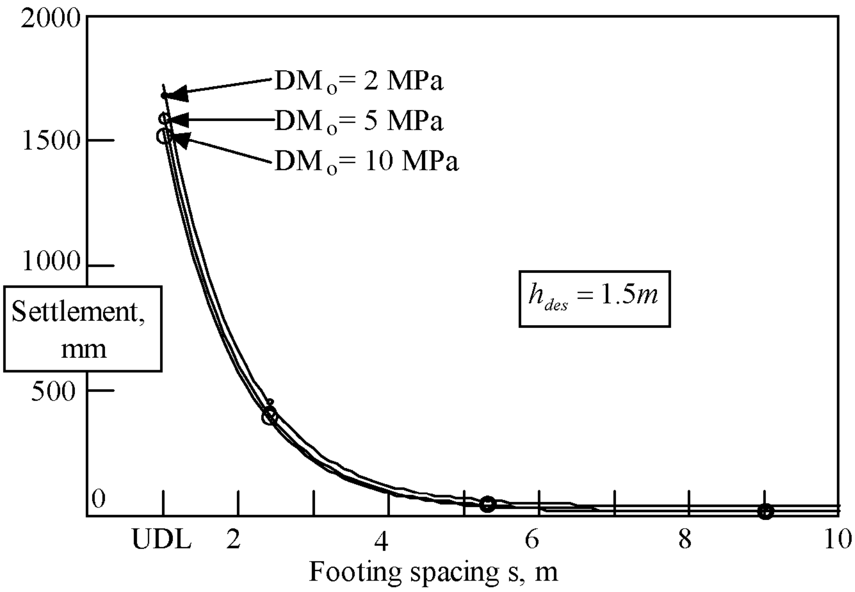

Fig. 8 Influence of DM_o on the performance. Depth of layer 18.7 m, crust = 1.5 m

A scaled up version of Fig. 8 is shown in Fig. 9, which may also be used as a design chart.

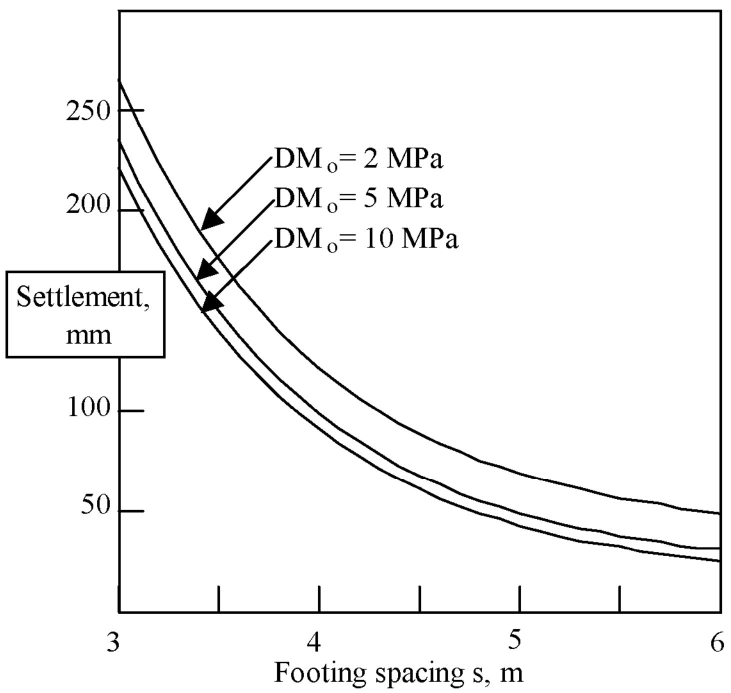

Fig. 9 Guide design chart for a layer of about 20 m deep

Another factor which needs to be investigated is the effect of the rate of increase with depth of the deformation modulus, α, on the observed performance of the system. As noted before in all the above examples the value of α was taken to be equal to 100 kN/m^3. In Fig. 10 the influence of this parameter for a footing spacing of 5.3 m is shown as a ratio of settlement for a given α to that of α=100. The points present the ratios for depth =9 m and depth =18.7 m. For all practical purposes the single curve passing through the average of the points may be used in evaluations.

Finally the effect of width of the footing on the calculated settlements was investigated. Figure 11 shows the ratio $\frac{set(B)}{set(1)}$ as a function of the spacing ratio defined as the ratio of spacing between footings (C.L. to C.L.) to the breadth of the footings. The curves show the situation assuming a DM_o=2 MPa, a crustal depth of 1.5 m and a layer depth of about 9 m. It is proposed to use this set of curves for all situations as the represent about the most conservative case.

EXAMPLE

The following example is used to demonstrate the application of the design charts.

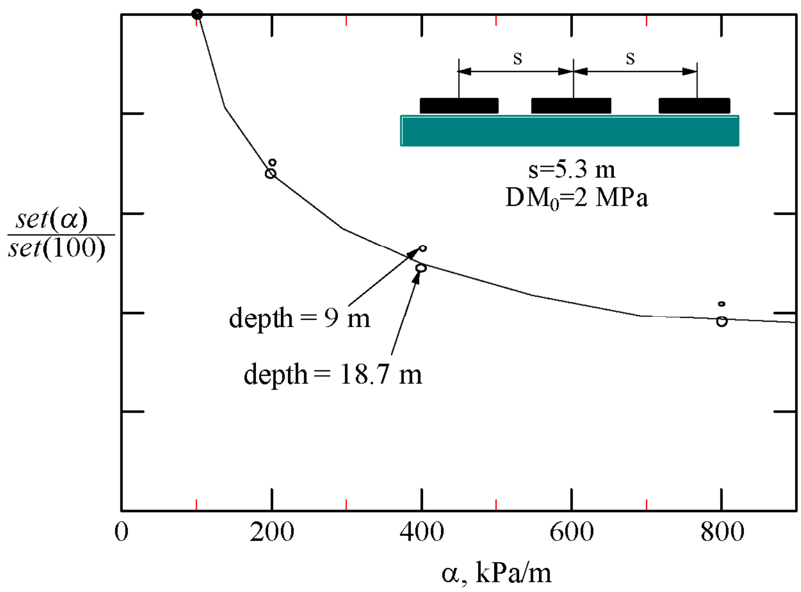

Fig. 10 The influence of α on the settlement of the footings. Spacing = 5.3 m

It is proposed to construct a number of strip footings to support light one-story buildings. Each footing is 0.7 m wide and carries a UDL of 60 kPa. The footings are placed at 4.5 m center line to center line. The supporting soil layer is a soft clay deposit having an estimated modulus of deformation of 2.5 MPa at a depth of 10 m. The clay layer is supported by a strong layer of old mud, which is considered to be very competent, at a depth of about 17 to 18 m. The crust is about 2.8 m thick and has a maximum modulus of deformation of 6 MPa at the grade level. Evaluate the expected long-term settlement of each footing.

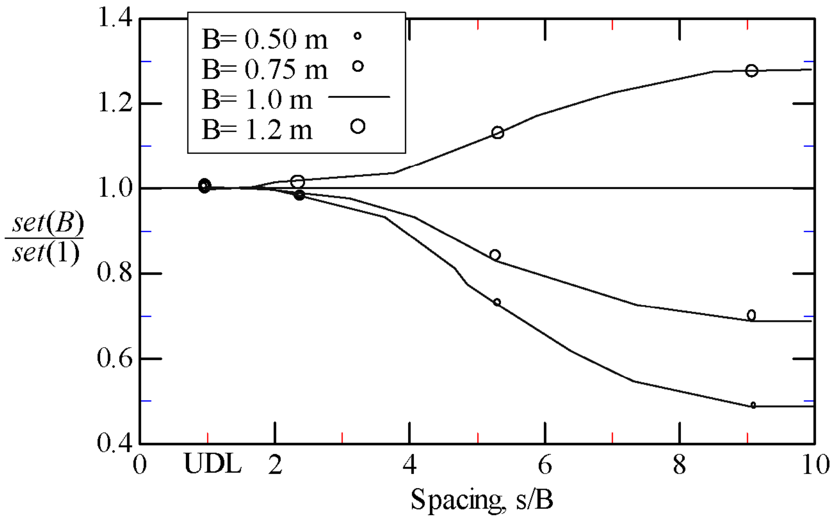

Fig. 11 Influence of the width of footings on the settlements

Assume depth of clay layer equal to 20 m and use Fig. 9. For the value of DM $_o$ = 6 MPa provided the middle curve of Fig. 9 indicates a settlement of 70 mm for a UDL of 50 kPa and spacing of 4.5 m. Thus for a UDL of 60 kPa the resulting value is 60×70/50= 84 mm. And for a spacing/breadth ratio of 4.5/0.7 (s/B=6.4) this figure reduces to 0.8×84=67.2 mm.

Since at depth of 10 m the modulus of deformation of the soil is estimated to be 2500 kPa then the value of α is estimated to be 250 assuming an average submerged unit weight of the soil equal to 10 kN/m^3. Thus from Fig. 10 the value of set(α)/set(100) is estimated to be 0.58. The final evaluated settlement is, therefor, equal to 0.58×67 or 38.9 mm, say 40 mm, which is quite acceptable.

CONCLUSIONS

In tropical coastal lowlands often the recently deposited clays and silty clay layers are capped with a hard crust. Major structures must be founded on deep foundations or else a suitable scheme of soil improvement technique must be employed.

For minor buildings, for example low cost single story housing units, such measures are out of question mainly due to the high costs involved. In such cases it is recommended to place the shallow footings directly on the top of the hard crust. That is, to scrape the ground at the surface and build directly on the grade.

Of course such a scheme is only feasible if the danger of ground freezing or washing away of the soil particles due to erosion is not an issue. Another condition that must be safeguarded against is the punching of the footing through the hard crust which would lead to breaking of the footing into the ground. This condition can happen if the depth of the hard crust is too small compared to the width of the footing.

The above analysis establishes the influence of various factors on the magnitude of the settlement. The most important design factor appears to be the proximity of the footings relative to one another: The magnitude of settlement increases *exponentially* as the footings get closer to each other.

The analysis leads to the development of certain design charts which can be used in estimating the expected settlement of a system of spread footings carrying loads of low to moderate magnitude.

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