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Bearing Capacity of Foundation: Review

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ABSTRACT – Bearing capacity is the most important aspect of the geotechnical engineering. The foremost requirement of any structure is safety and stability with achieving economy. So, to design any structure estimation of bearing capacity is compulsory. Several research works have been done in the last few decades for the estimation of ultimate bearing capacity of shallow foundations in cohesionless as well as cohesive soils through experimental studies on model footings and theoretical analyses. The objective of this paper is to present some of the rigorous works carried out so far using the above methods and to bring out the limitations of them.

Keywords: bearing, foundation.,raft

I. INTRODUCTION

All civil engineering structures whether they are buildings, dams, bridges etc. are built on soils. A foundation is required to transmit the load of the structure on a large area of soil. The foundation of the structure should be so designed that the soil below does not fail in shear nor there is the excessive settlement of the structure. The conventional method of foundation design is based on the concept of bearing capacity. Soil when stressed due to loading, tend to deform. The resistance to deformation of the soil depends upon factors like water content, bulk density, angle of internal friction and the manner in which load is applied on the soil. The maximum load per unit area which the soil or rock can carry without yielding or displacement is termed as the bearing capacity of soils. Soil properties like shear strength, density, permeability etc., affect the bearing capacity of soil. Dense sand will have more bearing capacity than loose sand as unit weight of dense sand is more than loose sand. If the bearing capacity of soil at shallow depth is sufficient to safely take the load of the structure, a shallow foundation is provided. Isolated footing, combined footing or strip footing are the option for the shallow foundation. Deep foundations are provided when soil immediately below the structure does not have the adequate bearing capacity. pile, piers or well are the options for deep foundations.

Foundation is the lower most hidden but very important part of any structure whether it is onshore or offshore structure. It is the part which receive huge amount of load from superstructure and distribute it to ground. So, the foundation should be strong enough to sustain the load of superstructure. The performance of a structure mostly depends on the performance of foundation. Since it is a very important part, so it should be designed properly. Design of foundation consists of two different parts: one is the ultimate bearing capacity of soil below foundation and second is the acceptable settlement that a footing can undergo without any adverse effect on superstructure. Ultimate bearing capacity means the load that the soil under the foundation can sustain before shear failure; while, settlement consideration involves estimation of the settlement caused by load from super structure which should not exceed the limiting value for the stability and function of the superstructure. Ultimate bearing capacity problem can be solved with the help of either analytical solution or experimental study. Bearing capacity of soil is simply strength of soil, technically it is defined as the capacity of soil to support the load applied to the ground. The bearing capacity of soil is the maximum average contact pressure between the foundation and soil which should not be produced shear failure in the soil. In geotechnical engineering, bearing capacity is the capacity of soil to support the loads applied to the ground. The bearing capacity of soil is the maximum average contact pressure between the foundation and the soil which should not produce shear failure in the soil. Ultimate bearing capacity is the theoretical maximum pressure which can be supported without failure; allowable bearing capacity is the ultimate bearing capacity divided by a factor of safety. Sometimes, on soft soil sites, large settlements may occur under loaded foundations without actual shear failure occurring; in such cases, the allowable bearing capacity is based on the maximum allowable settlement. A foundation is the part of a structure which transmits the weight of the structure to the ground. All structures constructed on land are supported on foundations. A foundation is a connecting link between the structure proper and the ground which supports it. All civil engineering structures whether they are buildings, dams, bridges etc. are built on soils. A foundation is required to transmit the load of the structure on a large area of soil. The foundation of the structure should be so designed that the soil below does not fail in shear nor there is the excessive settlement of the structure. The conventional method of foundation design is based on the concept of bearing capacity.

Soil when stressed due to loading, tend to deform. The resistance to deformation of the soil depends upon factors like water content, bulk density, angle of internal friction and the manner in which load is applied on the soil. The maximum load per unit area which the soil or rock can carry without yielding or displacement is termed as the bearing capacity of soils.

Soil properties like shear strength, density, permeability etc., affect the bearing capacity of soil. Dense sand will have more bearing capacity than loose sand as unit weight of dense sand is more than loose sand.

Research on the ultimate bearing capacity problems can be carried out using either analytical solutions or experimental investigations. The former could be studied through theory of plasticity or finite element analysis, while the latter is achieved through conducting prototype, model and full-scale tests. A satisfactory solution is found only when theoretical results agree with those obtained experimentally. A literature survey on the subject shows that the majority of the bearing capacity theories

involve homogeneous soils under the foundations. Soil properties were assumed to remain constant for the bearing capacity analysis, and therefore analytical solutions, like Terzaghi's bearing capacity theory, matched with the experimental results. However, in cases where the soil properties vary with depth, most of these theories cannot be implemented, and the analytical solutions that take into consideration the non-homogeneity of the soils are approximations, and hence the results are inaccurate.
In the literature, over the last four decades, several reports can be found dealing with the problem of foundations resting on layered soils. At first, researchers based their studies on the results of prototype laboratory model testing in order to develop empirical formulae to predict the ultimate bearing capacity of these footings. In this chapter a brief review of some of these reports followed by discussions are presented in chronological order.

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(i) Messe–Torhaus, Frankfurt, Germany (1983-85)[1].

2.1 Terzaghi [1]

An analysis of the condition of complete bearing capacity failure, usually term general shear failure, can be made by assuming that the soil behaves like an ideally plastic material.The concept was first developed by Prandtl, and later extended by terzaghi`s, Meyerhof and others terzaghi derived a general bearing capacity equation from a modification of equation proposed by Prandtl

$qf=cNc+\sigma Nq+0.5YBNY$ (1)

for circular footing,

$qf=1.3cNc+\sigma Nq+0.4YBNY$ (2)

for square footing,

$qf=1.3cNc+\sigma Nq+0.4YBNY$ (3)

for rectangular footing,

$qf=cNc(1+0.3B/L)+\sigma Nq+0.4YBNY$ (4)

The analysis was done between the previous SPT to the SPT perform in the hilla city of Iraq.In this total 110 bore holes were studied in which 105 bore holes already present and 5 new bore holes were erected for study purpose. The city was divided into two parts for study purpose.The study was done at 10m,12m,15m and 20m depth.In this analysis it was found that the value of N varies with depth compare to previous analysis work. During analysis it was found that the value of N increases upto 5m then it start decreasing upto 8m and again it start increasing.The variation in value of N is due to the different types of hammer used during the test .The GPS coordinate system was to find the same number of N in different bore holes.

2.2 Meyerhof C.G.[2]

He investigated the case of sand layer overlying clay: dense sand on soft clay and loose sand on stiff clay. The analyses of different modes of failure were compared with the results of model test results on circular and strip footings and field data. In the case of dense sand overlying a soft clay deposit, the failure mechanism was assumed as an approximately truncated pyramidal shape, pushed into the clay so that, in the case of general shear failure, the friction angle ϕ of the sand and the un drained cohesion c of the clay are mobilized in the combined failure zones. Based on this theory, semi-empirical formulae were developed to calculate the bearing capacity of strip, and circular footings resting on dense sand overlying soft clay. He conducted model tests on strip and circular footings on the surface and at shallow depths in the dense sand layer overlying clay. The results of these tests, and the field observations were found to agree with the theory developed. In the case of loose sand on stiff clay, the sand mass beneath the footing failed laterally by squeezing at an ultimate load. Formulae for the ultimate bearing capacity of strip and circular footings were developed. Model tests were carried out on strip and circular footings, and the results also agreed with the theory developed. Theory and test results showed that the influence of the sand layer thickness beneath the footing depends mainly on the bearing capacity ratio of the clay to the sand, the friction angle (ϕ) of the sand, the shape and depth of the foundation. This paper is limited to vertically loaded footings, and does not include eccentric or inclined loads, it is also limited to sand over clay, and has no solution for clay over sand. In the case of dense sand on soft clay, the theory considers simultaneous failure of the sand layer by punching, and general shear failure in the clay layer, which is not always the case.

2.2 Button

He analyzed the bearing capacity of a strip footing resting on two layers of clay. He assumed that the cohesive soils in both layers are consolidated approximately to the same degree. In order to determine the ultimate bearing capacity of the foundation, he assumed that the failure surface at the ultimate load is cylindrical, where the curve lies at the edge of the footing. The bearing capacity factor used depends on the upper soil layer and on the ratio of the cohesions of the lower/upper clay layers

2.3 Aggour,M.S.and Radding

The analysis was done between the previous SPT to the SPT perform in the hilla city of Iraq.In this total 110 bore holes were studied in which 105 bore holes already present and 5 new bore holes were erected for study purpose. The city was divided into two parts for study purpose.The study was done at 10m,12m,15m and 20m depth.In this analysis it was found that the value of N varies with depth compare to previous analysis work. During analysis it was found that the value of N increases upto 5m then it start decreasing upto 8m and again it start increasing.The variation in value of N is due to the different types of hammer used during the test .The GPS coordinate system was to find the same number of N in different bore holes.

2.4 Reddy and Srinivasan

They extended the work of Button to include the effect of the non-homogeneity and anisotropy of soil with respect to the shear strength. The basic assumptions involved in determining the ultimate bearing capacity are: the failure surface is cylindrical, the coefficient of anisotropy is the same at all points in the foundation medium, the soil in each layer is either homogeneous with respect to the shear strength or the shear strength in each layer varies linearly with depth. In both papers, the assumption of cylindrical potential failure surface led to values of Nc is 7% higher than the values obtained by the Prandtl solution in the case of homogeneous subsoil. In the case of an-isotropic and non-homogeneous subsoil, the values are even higher and the error increases with increasing non-homogeneity of the two layers.

2.5 Musa Alhassan

Bearing capacity of the soil helps in deciding various factors such as shape of footing and dimension.Foundations are of two types one is shallow and other is deep. The study is done mostly for the shallow foundation. Square, rectangular and circular footing are commonly use in shallow foundation. Till now foundation use in consruction varied along horizontal section or by plan. The interaction of foundation with soil base is mostly studied using load settlement relationship. Wooden models of different shape with same width but different in vertical section were consider for the study. Which were studied on a sub soil, placed in a rectangular container. Clay soil is taken for study on which wooden models are placed and load is applied in three direction on each model and observation were observed by using dail gauges and relationship for load settlement was developed for models.

2.6. Brown and Meyerhof (1969)

They investigated foundations resting on a stiff clay layer overlying a soft clay layer deposit, and the case of a soft layer overlying a stiff layer. They assumed that the footing fails by punching through the top layer for the first case, and with full development of the bearing capacity of the lower layer in the second case. Equations and charts giving the appropriate modified bearing capacity factors were given, derived from the empirical relationships obtained based on the experimental results. The results of the investigation are summarized in charts, which may be used in evaluating the bearing capacity of layered clay foundations, but these results are essentially experimental, and therefore are strongly affected by the characteristics of the clay tested. The purpose of this paper is to present the results of a series of model footing tests carried out on two-layered clay soils, and the models have many limitations. First, they are limited to one type of clay, although the strength of the clay was varied, the deformation properties remained constant. Second, studies were limited to surface loading only, using rigid strip and circular footings with rough bases. Third, all studies were made in terms of the undrained shear strength of the clay, using the $\phi = 0$ analyses. They also conducted a series of tests on footings in homogeneous clay. They observed that the pattern of failure beneath a footing is a function of the physical mode of rupture of the clay, which is strongly dependent on the structure of the clay. The failure mechanism of the structure of the clay is not adequately defined by conventional Mohr-coulomb concepts of cohesion and friction.

2.6 Meyerhof and Hanna (1978)

They considered the case of footings resting in a strong layer overlying weak deposit and a weak layer overlying strong deposit. The analyses of different soil failure were compared with the results of model tests on circular and strip footings on layered sand and clay. They developed theories to predict the bearing capacity of layered soils under vertical load and inclined loading conditions. In the case of a strong layer overlying a weak deposit, considering the failure as an inverted uplift problem, an approximate theory of the ultimate bearing capacity was developed, at failure, a soil mass, roughly shaped like a truncated pyramid, of the upper layer is pushed into the underlying deposit in the approximate direction of the applied load. The forces developed on the actual punching failure surface in the upper layer are the total adhesion force and a total passive earth pressure inclined at an average angle Ƨ acting upwards~ on an assumed plane inclined at an angle α on to the vertical. The analysis for strip footings was extended to circular and rectangular footings, and approximate formulae for the bearing capacity of strip, rectangular, and circular footings were deve1oped, taking into consideration the case of eccentric and inclined loading as well. Model tests on rough strip and circular footings under central inclined loads at varying angles on were made on the surface and at shallow depth in different cases of two layered soils of sand and clay, where good agreement was found between the theoretical and experimental results. In the case of a weak layer overlying a strong deposit, considering that the weak soil mass beneath the footing may fail laterally by squeezing, which is the same theory as from the previous paper developed the theory of the ultimate bearing capacity. The bearing capacity can be estimated by the approximate semi-empirical formula. Model tests were also carried out on strip and circular footings under vertical and inclined loads, and the results of the tests were compared to the theoretical ones. The authors concluded that the ultimate bearing capacity of footings on a dense layer overlying a weak layer can be expressed by inclination factors in conjunction with punching shear coefficients, which depend on the shear strength parameters and bearing capacity ratio of the layers under vertical loads.

This paper is a development of the previous theory (Meyerhof 1974), taking into consideration all possible cases of two different layers of subsoil, and also including the effect of inclined and eccentric loading on the ultimate bearing capacity of strip, rectangular, and circular footings. This theory and the failure mechanism considered are approximations of the real failure mechanism, which depends on many factors.

2.6 Hanna and Meyerhof (1979)

They extended their previous theory of the ultimate bearing capacity of two- layer soils to the case of three-layer soils. The analysis compared well with the results of model tests of strip and circular footings on a three-layer soil. Only one case was considered in this paper, that for footings subjected to vertical loads and resting on subsoil consisting of two strong layers overlying a weak deposit. The same theoretical failure mechanism was assumed by considering a soil mass of the upper two layers is pushed into the lower layer, and the same forces acting on the failure surface was assumed as well. Formulas and charts were developed and can be used in designing foundations having the same conditions. Model tests on rough strip and circular footings under central vertical loads were made on the surface of three- layer sand consisting of two dense upper layers and a loose lower one. By comparing the results of the model tests with the results of the punching theory, good agreement was found. Briefly, this paper is an extension of the previous theory in order to include the case of the three-layer soil. But, it is restricted to only one case of three-layer soil, and it needs more development to include all possible cases of three-layer soils.

2.6.5 Hanna and Meyerhof (1980) They extended the previous theory to cover the case of footings resting on subsoil consisting of a dense layer of sand overlying a soft clay deposit, and they presented the results of this analysis in the form of design charts. It is a kind of revision of the assumptions previously used in the punching theory of the previous papers in order to reduce their effects on the analysis. Thus, in the previous theory of punching, the bearing capacity formula depends to a large extent on the value of the average mobilized angle of shearing resistance Ƨ on the assumed failure planes, which was previously estimated as $2\phi/3$. The exact value of Ƨ is difficult to calculate, and approximate value will affect the results of the calculation of the bearing capacity. However, these difficulties may be overcome by expressing the angle Ƨ in the dimensionless form ($Ƨ/\phi_1$), where ϕ_1 is the friction angle of the upper sand layer. The design charts presented in this paper, together with the punching theory previously developed by the authors, can be utilized to predict the ultimate bearing capacity of footings on a dense sand layer overlying a soft clay deposit. These charts give more accurate results than the previous formulas and charts, but still estimation of the real bearing capacity since they are based on experimental results, the properties of sand and clay and the method used to model the tests can affect the charts and therefore the results.

2.6.6 Hanna

He extended his previous theory to cover the case of footings resting on subsoil consisting of a strong sand layer overlying a weak sand deposit. Applying the same theory that at ultimate load, a soil mass of the upper layer is pushed to the lower sand layer, and by calculating the forces on the assumed vertical punching failure surface, the ultimate bearing capacity can be calculated theoretically. Charts are presented in this paper and can be used in the design of footings. In order to verify the theory presented, model tests on strip and circular footings resting on dense sand layer overlying loose sand layer were done, and the results of the tests agreed well with the theory presented.

2.7.1 Pfeifle and Das

They presented laboratory model tests results for the case of rough rectangular footings in sand with a rigid rough base located at a limited depth. The results were compared to the predicted results of Mandel and Salencon (1972) and Meyerhof (1974). The authors concluded that the critical depth of location of the rough rigid base beyond which it has no effect on the value of the ultimate bearing capacity is about 50%-75% higher than that predicted by the theory. And the previous theories do not predict correctly the bearing capacity for the case when the rigid base is located at shallow depth. This experimental investigation is very limited to one case of layered soils, and the friction angle ϕ of the sand used varies in a small range (42°-45°), and the conclusion may be valid only for this range of ϕ.

2.7.2 Das

He presented a technique to improve the ultimate bearing capacity and settlement conditions of shallow foundations on soft clay soil, which consists of placing the footings over a compact granular fill, lay over the clay layer. Placing geotextile at the interface of the clay layer and the sand layer can further increase the bearing capacity. The purpose of placing the granular layer is to distribute the load on a larger area of the

clay layer, and the purpose of placing the geotextile mesh is to reduce the depth of the sand layer required to distribute the load. The objective of this research was primarily to present the results of model tests conducted on a strip foundation resting on a sand layer overlying a weak clay layer, and compares the results with the theory of Meyerhof and Hanna (1978). Secondly, to compare results of the bearing capacity of footings on layered soil with and without the use of the geotextile mesh at the interface of the two layers in order to evaluate any advantage derived from the inclusion of the geotextile. A number of laboratory model test results for the ultimate bearing capacity of strip footings resting on a sand layer underlain by a weak clay layer with and without the inclusion of geotextile at the interface of the two layers have been presented in this paper. Based on the experimental results; first, without the inclusion of geotextile, the

results were consistent with the theory of Meyerhof and Hanna (1978). Second, the inclusion of the geotxtile at the interface of the layers increases the bearing capacity, and at the same time, reduces the depth of the sand layer to be placed over the clay layer. Third, the most economical width of the geotextile layer to be used as determined from the study is about four times the width of the strip footing. This paper is experimental and the conclusions deduced are strictly related to the model tests done, so the results may vary with the type of geotextile mesh used, its strength, dimensions, and the depth at which the geotextile is placed. More investigation and experiments are needed regarding the use of geotextile for increasing the bearing capacity of shallow foundations on weak soils.

2.8 Abdel-Baki et al

He investigated the effect of a single strong reinforcement layer, placed within granular soil, on the bearing capacity of footings subjected to eccentric, inclined and concentric loads. The effect of the reinforcement on the bearing capacity was investigated experimentally. The results of the experimental tests proved that the reinforcement had a considerable effect on the bearing capacity of the footings. The bearing capacity of a reinforced layer was about three times the unreinforced one. The effect of the length of the reinforcement was also investigated, and it was found that there is no significant effect on the bearing capacity if the reinforcement length is extended over 1.25 times the width of the footing. The effect of reinforcement continuity below the footing was also investigated in this paper, and it was found that the bearing capacity from the reinforcement decreased as the gap in the reinforcement increased and reached zero when the gap width was equal to the footing width.

2.9 Burd and Frydman

They presented the case of bearing capacity of a rigid plane-strain footing placed on the surface of a soil consisting of a uniform sand layer overlying thick, homogeneous bed of clay. The study is restricted to cases where the thickness of the sand layer is comparable to the footing width, and in all cases the ground surface and the interface between the two soil layers are horizontal. The assumption is made that the clay layer is considered undrained, and the sand layer is drained.

A discussion is given of the various theories previously proposed to solve this case of bearing capacity on two layered soils, followed by the numerical parametric study proposed in this paper. Starting with the load spread models, then the punching shear models proposed by Meyerhof (1974), to the kinematic analysis methods proposed by Flockiewicz (1989) and Michalouski and Shi (1995), and then the numerical models using finite element or finite difference methods in which the soil is subdivided into a mesh of discrete elements. In order to assess the various analytical procedures reviewed and to provide data of direct use in design, a parametric study has been carried out using two distinct numerical modeling procedures. The finite element calculations were carried out using the program OXFEM, and the finite difference calculations were performed using the program FLAC

This study highlighted the importance of the no dimensional group Su/yD in determining the mechanics of the system, which is closely related to the over consolidation ratio of the clay and allows a realistic range of clay shear strength values to be adopted in the study. The results of the study have been used to produce charts

of bearing capacity that may be used directly in design. The data have also been used to study the effectiveness of the sand in spreading the load applied by the footing. It was found that the sand layer is more effective in spreading the footing load when the clay is normally or lightly over consolidated, than when the over consolidation ratio of the clay is large.

2.10 Merifield and Sloan (1999)

They studied the ultimate bearing capacity of surface strip footings resting on a horizontally layered clay profile. Many empirical and semi-empirical formulas can be used, which give approximate solutions to the problem. More recently, Flockiewicz (1989) presented an upper bound method proposing a kinematically admissible failure mechanism. Although this method is useful, but limited results were produced. The upper bound method has been widely used to estimate the bearing capacity of layered clays, but it may lead to a lower factor of safety for design than the real one. A more desirable solution is a lower bound estimate, as it results in a safe design and, if used in conjunction with an upper bound solution, serves to bracket the actual collapse load from above and below. The purpose of this paper is to take advantage of the ability of the limit theorems to bracket the actual collapse load by computing both types of solution for the bearing capacity of footings on a two-layered clay profile. These solutions are obtained using the numerical techniques developed by Sloan (1988) and Sloan & Kleeman (1995), which are based upon the limit theorems of classical plasticity and finite elements.

2.11 M.S.Dixit , K.A Patil

Bearing capacity is very important factor for design of foundation. The important parameter which are to be study is settlement of soil with application of load as we know that soft clay strata is weak in bearing capacity in any structural loads in the construction work. Bearing capacity is affected by water table, including load and other factors. Terzaghi proposed comprehensive bearing capacity analysis for case of strip footing with rough base. It has been also found that bearing capacity is also increase by compaction, grouting etc.. Soils sample were collected from different site for different depth to find out the ultimate bearing capacity of soil by knowing other paarameters optimum moisture content, maximum dry density, water content

2.12 Pradeep Kumar Jain

Plate load test was conducted in tank ,in which a layer of gravel is placed on sand.The bearing capacity was studied for the top layer .Total 18 test were conducted in which 3 test conducted on sand layer , 3 test on gravel and remaining 12 on sand +gravel. The load vs settlement graph was studied for this 3 analysis. The graph was drawn with log-log method and tangent method.it was found that the bearing capacity is more in layered one compare to homogeneous one. While comparing homogeneous layer, It was found that bearing capacity of gravel layer is more than the sand layer.Ultimate bearing capacity increases as top layer increases. Settlement decreases as layer increases.

2.13 Dr.Musa J.Aziz Al Hosawe The bearing capacity of weak soil can be increase by adding different material in it. Material like kaolin and cement –dust were used .It was observes that by adding materials the bearing capacity increases and the settlement decreases .The test performed on this mix soil was done with the help of different instruments and techniques. The test was conducted in a trench in which mix soil is placed.It was found that there was increment in bearing capacity for H/b ratio 3.Square footing give good results fot the clay mixed with cement dust.

2.14 Binal Gopinath

Waste material can also be used for increasing the bearing capacity of soil. Glass material was used as waste for this purposed .trenches were prepared for different shapes of footing to see the behaviour .It was found that the bearing capacity of soil increases for mixture of 36% of glass material and 64% of soil.It was also found that there was decrease in the settlement of soil after adding glass material as waste.The rectangular footing shows good results in the analysis and use of encapsulation also show some reduction in the settlement.

IV. CONCLUSION

It is seen from the above review that the research on bearing capacity of shallow foundations on cohesionless as well as cohesive soils was taken place for many years. However, precise solution capable of predicting load carrying capacity for a wide range of soil relative densities, effective stress conditions and foundation shapes within a practical context remains solitary. The classical methods were developed based on smallscale foundation experiments (Meyerhof 1950[3], 1963[19]; Hansen 1970 [20]; De Beer 1970 [43]; Vesic 1973) [21], whereas large-scale tests at that time indicated the inability of these solutions to predict the actual field behavior (Muhs 1963[34], De Beer 1965a [29], 1965b [30]). Centrifuge experiments conducted over the past 20 years have demonstrated similar problems while providing for an advanced understanding of the problem (Ovesen 1975[35]; Yamaguchi et al 1977[38] ; Kusakebe et al 1991)[58].

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