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Bearing Capacity of Shallow Footings

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BEARING CAPACITY OF SHALLOW FOOTINGS FOR NON-GEOTECHNICAL ENGINEERS

By Richard P. Weber

Introduction

A foundation is that part of a structure which transmits a load directly into the underlying soil. If the soil conditions immediately below the structure are sufficiently strong and capable of supporting the required load, then shallow spread footings can be used to transmit the load. On the other hand, if the soil conditions are weak, then piles or piers are used to carry the loads into deeper, more suitable soil. This course is limited to the former and discusses the bearing capacity of shallow footings. Shallow footings are foundations where the depth of the footing is generally less than the width (B) of the footing.

Geotechnical engineering is the discipline that works with soil properties to establish the allowable bearing capacity of shallow footings. Geotechnical engineers are members of the design team who provide this information to those responsible for design. Often it is stated that geotechnical engineering is an “art form” rather than a science. Much of the geotechnical engineer’s guidance results from an interpretation of subsurface conditions based on an economically reasonable number of explorations. Based on experience and supported by theory, the geotechnical engineer interprets the information in order to predict foundation performance. The prediction usually ends up in a recommendation made by the geotechnical engineer in a report. Architects and structural engineers are probably most familiar with statements such as “The recommended allowable bearing pressure for shallow spread footings at this site is 4000 psf.” Where does this value come from and what was considered when establishing this value?

In this course you will learn that there are two considerations for determining the allowable soil bearing pressure:

- Calculated theoretical bearing capacity and
- Magnitude of settlement

Thus, the magnitude of settlement that a footing might experience under the design load is an equally important criterion for establishing the allowable soil bearing pressure. In fact for footings wider than 3 feet, settlement consideration often controls the magnitude of pressure applied to the soil.

At the end of this course you will have learned:

- How basic engineering values of soil are obtained and used in establishing bearing capacity.
- How the strength of soil determines bearing capacity.
- How settlement considerations determines bearing capacity.

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Subsurface Explorations

Civil engineering projects such as buildings, bridges, earthen dams, and roadways require detailed subsurface information as part of the design process. The ground below us ultimately supports all structures and to be successful, the ground must not fail under the applied structural load.

The geotechnical engineer's task then is to explore the subsurface conditions at a project site and determine the capacity of the soil to carry the load without collapsing or experiencing intolerable movement.

Explorations are used to obtain samples of the soil for classification and testing purposes. Common forms of exploration methods include:

- Soil test borings with standard penetration testing.
- Cone penetrometer soundings with cone penetration testing.
- Test pit excavations.

Testing can be conducted in the laboratory with special samples retrieved for testing purposes. Testing completed as part of the exploration program with methods such as the Standard Penetration Test (SPT) or the Cone Penetration Test (CPT) is used to develop foundation design values. There is a wealth of published information that correlates the test results obtained from the SPT or CPT to certain applicable engineering properties and values. The results of field testing and laboratory testing, coupled with the geotechnical engineer's assessment and experience is usually sufficient to provide sound advice for a successful project.

Test pit excavations are useful for viewing soil type and stratification but have severe drawbacks. Test pits are limited to the depth that the machine can extend, they are impractical to use for explorations below the groundwater level and they produce a large disturbed area, often times within the proposed building footprint. Most importantly, they do not provide penetration test results like the SPT and CPT, which are often used as the basis for making bearing capacity recommendations.

The geotechnical engineer is interested in primarily two pieces of information from the exploration program that can be used to develop foundation recommendations. This information includes:

- Type of material encountered.
- Engineering values.

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The type of soil is important because it provides an indication of how the material will react under load and whether or not the material is even sufficient to support shallow foundations. For instance clay reacts quite differently than sand while peat or loose miscellaneous fill lying below the foundation is not suitable for supporting foundations.

Engineering properties of the soil are important because they provide information on the shear strength of the soil or the ability of the soil to carry the load as well as the settlement characteristics of the soil. Much of the information that the engineer uses is based on published values, results of past testing, empirical relationships and if necessary, the results of project specific testing.

When explorations are conducted, the information is recorded on a log. The log is a collection of pertinent information such as depth, description of the soil encountered, stratification of material and penetration resistance of the soil. By reviewing all of the logs from a particular site, the geotechnical engineer can formulate a three dimensional picture of the subsurface conditions. Of course this is based on taking individual explorations at specific locations on a site and interpreting soil conditions between the explorations. This is sometimes difficult because it involves interpreting what “Mother Nature” or others did without seeing the actual soil conditions between the exploration locations.

In short, the purpose of the exploration program is to provide sufficient site-specific information to enable the engineer to develop a picture of the subsurface conditions and select appropriate soil values applicable to the soils encountered. Often, the subsurface conditions are presented in a graphical geologic profile, which shows information from the log, soil strata and soil description.

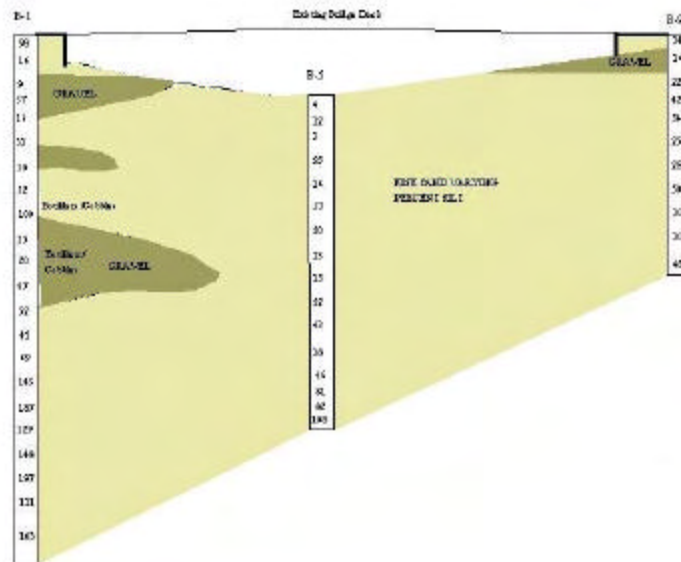


Figure 1 - Geologic Profile

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Bearing Capacity of Shallow Footings

The ability of soil to safely support a structure is of paramount importance. If the capacity of the soil is not sufficient then failure will occur. Failure can be defined as:

- A sudden, catastrophic movement where the ground below the structure collapses because its resistance to the load is less than the applied load. This relates to the capacity of the soil to safely carry the load (Criterion 1)
- Movement that is too great for the structure to accommodate. For instance, if the structure settles too much, cracks can develop in the frame and floor, windows and doors may not operate and the structure can become unsafe. This relates to the settlement potential of the soil under the applied load (Criterion 2).

Bearing capacity analysis is a two-part method used to determine the ability of the soil to support the required load in a safe manner without gross distortion resulting from objectionable settlement. The ultimate bearing capacity (q_u) is defined as that pressure causing a shear failure of the supporting soil lying immediately below and adjacent to the footing. The geotechnical engineer's task is to explore the subsurface conditions at a project site and determine the allowable capacity that the soil can carry without collapsing or experiencing intolerable movement. These precepts apply equally to deep foundations as well as shallow foundations. However in this course, we will focus only on shallow foundations.

Modes of Failure

Generally three modes of failure have been identified:

- General Shear Failure: A continuous failure surface develops between the edge of the footing and the ground surface. This type of failure is characterized by heaving at the ground surface accompanied by tilting of the footing. It occurs in soil of low compressibility such as dense sand or stiff clay.
- Local Shear Failure: A condition where significant compression of the soil occurs but only slight heave occurs at the ground surface. Tilting of the foundation is not expected. This type of failure occurs in highly compressible soil and the ultimate bearing capacity is not well defined.
- Punching Shear Failure: A condition that occurs where there is relatively high compression of the soil underlying the footing with neither heaving at the ground surface nor tilting of the foundation. Large settlement is expected without a clearly defined ultimate bearing capacity. Punching will occur in low compressible soil if the foundation is located at a considerable depth below ground surface.

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Bearing Capacity for Continuous Footings

First we will discuss calculating the bearing capacity for continuous footings using the original equation developed for bearing capacity analysis and then we will expand this to discuss other shapes and conditions.

The failure mechanism for a narrow, continuous footing (length is \gg than width) assumes that a wedge of soil below the footing is pushed downward by the applied load thereby displacing soil adjacent to the wedge both laterally and upward. The ultimate bearing capacity therefore, is a function of the shear strength of the soil and the magnitude of the overlying surcharge due to the depth of footing (D). The ultimate bearing capacity (q_u) of soil underlying a shallow strip footing can be calculated as:

$$q_u = 1/2\gamma BN\gamma + cN_c + \gamma DN_q \quad (1.0)$$

- N_γ , N_c and N_q are bearing capacity factors that depend only upon the soil friction angle (ϕ) as shown in Figure 2. The soil friction angle is commonly assigned by using charts or tables that correlate the penetration resistance obtained during the exploration program to the friction angle.

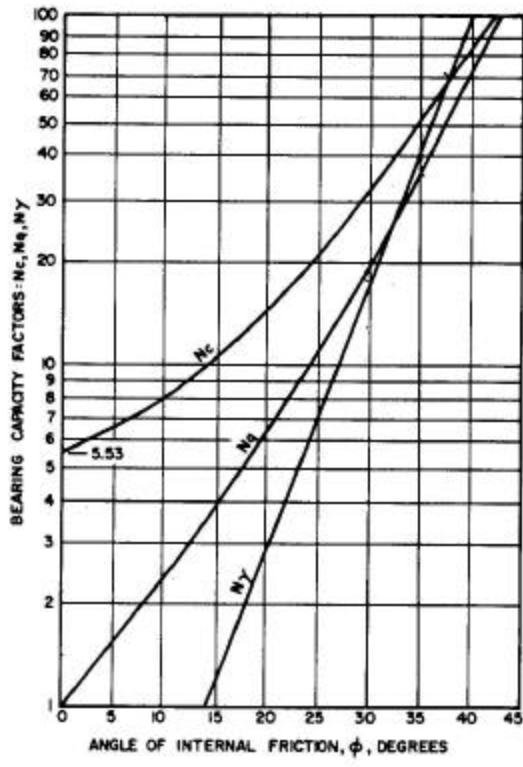


Figure 2 – Bearing Capacity Factors

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[Ref: NAVFAC DM-7]

- The cohesion term “c” is obtained by laboratory or field-testing methods such as using a Torvane. Correlations using SPT results are unreliable for assigning cohesion.
- The unit weight of the soil (γ) is commonly based on a published correlation with soil classification.
- The value “B” is the width of the footing and is the common symbol for the width.
- The value “D” is the depth of the footing below the lowest adjacent backfill. If the footing is backfilled equally on each side then D is the depth below grade. If the footing is backfilled unequally on each side as in a basement, then D is the lesser measurement.



Figure 3 – Depth of Footing

Expression (1.0) above shows that there are three components to bearing capacity.

- The first term ($1/2\gamma BN\gamma$) results from the soil unit weight below the footing.
- The second term (cNc) results from the cohesive strength of the soil.
- The third term (γDNq) results from the surcharge pressure, which is the pressure due to the weight of material between the surface and footing depth. This third term has a significant influence on the calculated soil bearing capacity.

Modification for Shape

The original bearing capacity equation shown in Expression (1.0) applied to continuous footings where the length L is very much greater than the width B . Since many footings however are square, rectangular or circular, the equation for a continuous footing was modified to account for the shape of the footing. Semi-empirical shape factors have been

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applied to each of the three components of the bearing capacity equation resulting in the following modifications:

- Square Footing: $q_u = 0.4\gamma B N \gamma + 1.2c N_c + \gamma D N_q$
- Circular Footing: $q_u = 0.3\gamma B N \gamma + 1.2c N_c + \gamma D N_q$
- Rectangular Footing: $q_u = 1/2(1 - 0.2B/L)\gamma B N \gamma + 1.2c N_c + \gamma D N_q$
In some publications, 1.3 replaces the factor 1.2.

General Bearing Capacity Equation

Later research improved the simple bearing capacity equations shown above by introducing a correction factor for shape of footing with load eccentricity, depth of footing, and inclination of load. Thus, the General Bearing Capacity Equation has evolved as shown in Expression (2.0), which maintains the contribution from the three components identified earlier and incorporates appropriate correction factors for each term.

$$q_u = 1/2\gamma B N \gamma (F_{ys} F_{yd} F_{yi}) + c N_c (F_{cs} F_{cd} F_{ci}) + \gamma D N_q (F_{qs} F_{qd} F_{qi}) \quad (2.0)$$

The factors beginning with “F” are the correction factors for depth (d), shape (s) and inclination of load (i) applied to the original terms proposed in Expression (1.0).

Further refinements include correction factors for sloping ground and tilting of the foundation base.

The calculation of bearing capacity and correction factors can become quite involved. Since there is no clearly defined universal set of values and equations used by all practitioners, it would not be unusual for the calculated results to vary among practitioners even when given the same set of subsurface conditions.

The ultimate bearing capacity obtained when using the General Bearing Capacity Expression (2.0) give bearing pressures that are too large for footings having widths (B) greater than approximately 6 feet. Accordingly a correction factor can also be applied to the first term of the General Bearing Capacity equation.

Groundwater and Bearing Capacity

The groundwater level affects the bearing capacity of soil. The first and third term of the bearing capacity equation includes a factor for the unit weight of soil. A part of these terms are shown below identified as (3.0) and (4.0).

- $(1/2\gamma B) \quad (3.0)$

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- (γD) (4.0)

When the groundwater level rises to a depth less than B (width of footing) below the footing then the first term (3.0) changes. The unit weight of soil (γ) becomes affected by the groundwater. As the groundwater level rises, the unit weight below the groundwater level is replaced by the submerged unit weight ($\gamma - 62.4$) and a weighted average is used to express the effective soil unit weight in term (3.0).

When the groundwater level reaches the depth of footing the value (γ) in term (3.0) is replaced entirely by (γ'), the submerged unit weight of soil. If the groundwater level rises above the depth of the footing, then the submerged unit weight of soil would be used in terms (3.0) and (4.0) as appropriate. Since the submerged unit weight of soil (γ') is always less than the total unit weight (γ), the bearing capacity decreases. Note in particular that:

- Term (3.0) can be reduced by up to approximately one-half of its value depending upon the depth of the water below the footing and the assigned value of γ [$1/2 (\gamma - 62.4) B$].
- When the groundwater level rises above the depth of the footing then Term (4.0) is also affected [$(\gamma - 62.4) D$].
- These conditions reduce the bearing capacity of the soil. Therefore the future highest groundwater level is important.
- If the groundwater level is at an intermediate depth ranging between the bottom of the footing and depth B, a weighted average effective unit weight is used in the bearing capacity equation [$Ave \gamma = \gamma' + d/B (\gamma - \gamma')$] where γ' is the submerged (effective) unit weight of soil, B is the footing width and d is the depth of the groundwater below the footing (i.e. $d < B$).

Factor of Safety

Unlike materials such as steel or concrete, there is no code that specifies the allowable stress or factor of safety used in design. Soil has considerable variability and structures have a multitude of uses and design life. Although the magnitude of the safety factor can vary depending upon uncertainty and risk, a factor of safety of 3 is commonly used in bearing capacity analysis for dead load plus maximum live load. However, when part of the live load is temporary such as earthquake, wind, snow, etc. then the factor of safety can be lower. The allowable bearing pressure used for design is derived by dividing the ultimate bearing capacity (q_u) by the assigned factor of safety (FS). Often the surcharge pressure resulting from the depth of footing (soil surcharge) is subtracted yielding the net allowable bearing pressure.

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The factor of safety is applied to the bearing capacity at failure as presented in Criterion 1 (Page 4). Footings less than 3 feet wide are most affected by this condition. As the footing becomes larger, the potential settlement of the footing plays a much greater role in establishing the assigned allowable bearing pressure as presented by Criterion 2.

Presumptive Bearing Capacity

Building Codes provide the maximum allowable pressure on supporting soils under spread footings. The BOCA National Building Code establishes the presumptive load-bearing value of foundation material based solely on material classification. The materials range from the weaker materials such as clay with an allowable bearing pressure of 2000 psf to very strong material such as crystalline bedrock with an allowable bearing pressure of 12,000 psf.

Other codes base their presumptive bearing capacity on both soil classification and consistency in place, which is a function of the rock quality designation, unconfined compressive strength or Standard Penetration Resistance depending upon the material.

NAVFAC Design Manual 7.2, Foundations and Earth Structures provides a comprehensive tabulation of presumptive bearing pressures and modifications based on size, depth and arrangement of footings as well as the nature of the bearing material. The publication suggests the use of presumptive values for preliminary estimates or when elaborate investigation of soil properties is not justified.

Settlement of Shallow Footings

Settlement consideration is the second of a two-part footing design process. After a bearing capacity analysis has estimated the allowable soil pressure based upon shear strength consideration, settlement must be studied to refine (and possibly further limit) the assigned bearing pressure. The soil design pressure and footing geometry are checked to assure that settlement of the footing under the prescribed load lies within tolerable ranges for the structure.

The total settlement of a structure is not as much concern as the differential settlement that occurs between adjacent columns and structural members. Differential settlement between adjacent footings develops stresses in the structure causing damage. Of course if the predicted total settlement of a structure would affect underground utilities, entryways, building elevations etc., then total settlement is also a concern. Allowable bearing pressures are designed to limit total settlement and by so doing, differential settlement between adjacent footings is also limited.

Where there is a group of footings supporting a structure, it is common to select the footing that might experience the most settlement for analysis. This could be the largest footing because its stress influence will extend much deeper thereby encompassing more soil or it could be the footing supported over the weakest soil at the site. In practice, it is

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common to adjust the design bearing pressure so that the footing will experience total settlement of less than 1 inch. Using this criterion, it is generally assumed that if the maximum settlement of footings is limited to 1-inch then the differential settlement between adjacent footings within the group will be less than $\frac{3}{4}$ inches. This magnitude of differential movement is acceptable for most buildings. Tables and charts have been published which set forth tolerable settlement for various types of structures.

Methods of predicting settlement provide only an estimate of the actual expected movement. The calculations used to estimate settlement are based upon assigned soil properties derived from field-testing and laboratory testing methods that are in themselves imperfect. There is wide room for variation of soil properties and error without close attention to detail. Even under the best of circumstances, soil properties can vary. Factors such as water content, freeze-thaw cycles, groundwater level, degree of consolidation, rate of loading, soil stratification, degree of compaction and relative density of the material can change the soil strength and compressibility properties. Settlement can also occur as a result of both static and dynamic loads applied to the foundation soil.

Components of Settlement

Settlement caused by a loading condition that increases the stress in the underlying soil can be classified into two major components:

- Immediate settlement.
- Consolidation settlement.

Consolidation settlement can be further divided into:

- Primary consolidation
- Secondary consolidation.

Immediate settlement

Immediate settlement (elastic deformation) takes place during construction or shortly thereafter and results from compression of the soil particles.

Primary Consolidation

Primary consolidation is a time-dependent phenomenon that occurs as water is squeezed from the voids lying between the individual soil particles. The time required for primary consolidation to occur is a function of how quickly the soil drains.

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Secondary Consolidation

Secondary consolidation occurs after primary consolidation has been completed. Unlike primary consolidation, secondary consolidation does not depend upon drainage. Secondary consolidation is caused by slippage and reorientation of soil particles (creep) under constant load.

Each of the three components of settlement occurs to some degree in both coarse-grained and fine-grained soil such as sand and clay respectively. Immediate settlement is most often associated with granular, coarse-grained soil such as sand. Although consolidation occurs in coarse-grained soil, it takes place very quickly because the material is relatively pervious and drains quickly. Therefore consolidation is not usually distinguishable from immediate settlement. Although secondary consolidations is thought not to occur in coarse-grained soil, some researchers have identified additional movement (creep) that occurs long after the load has been applied.

Primary consolidation and secondary consolidation are most often associated with fine-grained material such as clay and organic soil. Immediate settlement occurs rapidly in fine-grained material much more so than the time-dependent, long-term settlement associated with primary and secondary consolidation. Primary consolidation is more significant in clays while secondary consolidation is more significant in organic soil.

The total settlement that occurs below a footing is the sum of each of the three components identified above:

$$S \text{ (total)} = S \text{ (immediate)} + S \text{ (primary)} + S \text{ (secondary)}$$

For coarse-grained soil, primary and secondary settlement are ignored.

Settlement of Footings Underlain by Sand

Settlement that occurs in coarse-grained soil (sand) is normally small and happens relatively quickly. It is generally thought that little additional long-term movement (creep) occurs after loading. However, some researchers propose that this might not be entirely true.

Calculations performed to estimate settlement in coarse-grained material are usually undertaken using empirical methods based on data obtained during the exploration program. Since it is expensive and impractical to obtain “undisturbed” samples of coarse-grained material for laboratory testing, predictions are based on field-testing methods such as the standard penetration test (SPT), cone penetration test (CPT), dilatometer test (DMT) and the pressuremeter test (PMT). Researchers have synthesized information collected from testing programs and studies and have developed a number of empirical relationships to estimate the settlement of footings underlain by granular soil.

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Geotechnical engineers have used empirical approaches based on a large number of case studies to estimate the settlement of coarse-grained soil under sustained load. Two widely accepted methods employ the results obtained from the SPT and CPT. Equipment used to make these tests are readily available and relatively inexpensively to employ. These tests are routinely conducted during the site exploration program.

There are numerous empirical relationships available for predicting settlement. Some are apparently better than others in predicting the actual settlement based on the results of full-scale tests conducted on five shallow spread footings under various magnitudes of load. Some of the conclusion derived from a symposium convened during the mid 1900s to evaluate the current industry and academic practice in spread footing design are that:

- No participant who provided a calculated prediction of settlement gave a complete set of answers, which consistently fell within plus/minus 20% of the measured footing settlement.
- The load required to produce 1-inch of settlement was underestimated by 27% on average. The predicted load was on the safe side 80% of the time.
- A large variety of methods were used to calculate settlement and it was not possible to identify the most accurate method because most participants used published methods modified by their own experience or used a combination of methods.
- The profession tends to be over-conservative.

One (of many) empirical methods of predicting the settlement of shallow footings underlain by sand is illustrated below. Researchers based this method on a statistical analysis of over 200 settlement records of foundations supported on sand and gravel. The expression shows a relationship between the compressibility of the soil, footing width and the average value of the penetration resistance derived from the SPT and uncorrected for overburden pressure.

The immediate settlement prediction for sand is:

$$S_i = qB^{0.7}I_c \quad (5.0)$$

Where:

- $I_c = 1.71/N^{1.4}$ and N is the Standard Penetration Resistance derived from the soil test boring exploration program.
- S_i is expressed in millimeters
- B (footing width) in meters
- q (foundation pressure) in kPa

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A modification can be made to this equation if the sand can be established as over consolidated. Although it is normally assumed that settlement will stop after construction and initial loading has been applied, the data suggests that settlement can continue. A conservative assumption is that the settlement will ultimately reach 1.5 times the predicted settlement (S_i) after 30 years.

Settlement of Footings Underlain by Clay

The settlement prediction for footings underlain by clay usually ignores immediate settlement. The magnitudes of primary and secondary consolidation are more important in clay and organic soil. Primary consolidation occurs when the pore water in saturated clay is drained (squeezed out) by the superimposed stress increase cause by the footing. As the material drains settlement occurs.

The phenomenon of primary consolidation can be illustrated as follows. When a footing resting above saturated clay is loaded there is a stress increase in the underlying material equal to the amount of the increased foundation pressure. Initially, the pore water held in the voids of the soil between the clay particles supports all of the increased stress. Since the water is incompressible, the water pressure increases an amount equivalent to the increased foundation pressure (excess pore water pressure). With time, the pore water drains from the voids (decreases) thereby transferring the stress from the water to the soil particles. As the pore water drains, settlement occurs. Primary consolidation is complete when all of the excess pore water pressure has dissipated and the soil particles in close contact with one another support all of the pressure.

In order to predict the amount of settlement that will occur in the clay stratum the engineer must have knowledge of the past history and engineering properties of the clay. This is achieved by retrieving an undisturbed sample of the clay and testing it in laboratory to measure its consolidation characteristics. The results of the laboratory-testing program are presented on a series of semi-log plots. One of these plots shows the decrease in void ratio or strain (vertical axis) in relationship to the increased pressure of load. From this data the engineer obtains important engineering properties of the soil, which are then used to predict the magnitude of settlement.

The settlement for normally consolidated material can be expressed as:

$$S = (C_c H / 1+e_o) * \log ((\sigma_o' + \Delta\sigma)/\sigma_o') \quad (6.0)$$

Where:

- C_c is the compression index derived from laboratory testing
- H is the thickness of the clay layer under consideration
- σ_o' is the effective overburden pressure
- $\Delta\sigma$ is the stress increase resulting from the footing
- e_o is the soil void ratio obtained from laboratory testing

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A slight manipulation of this equation will provide the settlement for an over-consolidated material.

- Normally consolidated material is material that has not experienced a load greater than the existing (current) load.
- Over-consolidated material is material that has experienced a load in the past greater than the existing (current) load.

An example of over-consolidated conditions might be illustrated by a 10-foot high hill that is underlain by clay. If the hill were 20 feet high in the past, then the clay would already have settled under the weight of the 20-foot high hill. Since over-consolidated material is stronger than the same normally consolidated material it is less compressible up to the point where the applied pressure is equivalent to the maximum past pressure. Therefore, if an additional 5 feet of fill is placed over the site to a total height of 15 ft, then the underlying clay would experience very little settlement because it had already settled an amount equivalent to the previous 20 ft high fill.

Since manipulations are made to the equations for calculating settlement based on three possible conditions, the geotechnical engineer must also know the magnitude of the maximum past pressure, which can be obtained from laboratory test results. With this information, the geotechnical engineer can now relate the pressure increase in the underlying compressible soil resulting from the new footing to the existing overburden pressure and the maximum past pressure of the soil. The three possible conditions are:

- Settlement lies entirely within normally consolidated clay.
- Settlement lies entirely within over-consolidated clay where the new foundation pressure plus the existing overburden pressure is less than the maximum past pressure.
- Settlement lies in over-consolidated clay but extend into the normally consolidated zone where the new foundation pressure plus the existing overburden pressure is greater than the maximum past pressure

If secondary consolidation is calculated separately, then the results are added to the predictions for primary consolidation.

Time Rate of Settlement

Aside from predicting the magnitude of settlement that will most likely occur in fine grained-soil, the engineer must also predict the rate at which the total settlement will occur. There is a significant difference on performance and damage to a structure relating to 2-inches of settlement that occurs over a 1-year period and 2-inches of

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settlement that occurs over a 50-year period. The coefficient of consolidation (c_v) required to conduct this study is also derived from laboratory test data.

In addition, the engineer must decide whether there is two-way or one-way drainage.

- Two-way drainage will occur if the clay stratum is located between two more pervious layers of material. The last drop of water to drain from the system is located in the middle of the clay stratum and it only has to travel one-half the thickness of the clay stratum or less until it reaches the pervious layer.
- One-way drainage occurs if the clay is overlain or underlain by a single more pervious stratum. In this case the last drop of water to drain lies at the bottom or top of the clay stratum furthest from the drainage layer.

The rate of consolidation is expressed in Expression (7.0). From this expression, it should be easy to see that two-way drainage occurs more quickly than one-way drainage for the same thickness (H) of clay.

$$\text{Time} = T_v H^2/c_v \quad (7.0)$$

Where:

- T_v is a time factor and is obtained from published values
- c_v is the coefficient of consolidation and is obtain from laboratory testing or published values.

Sometimes the compressible material contains thin sand lenses. Since the sand lenses are also drainage pathways, the actual rate of consolidation can be greater than predicted.

Influence Zone

Whenever a foundation is loaded, a pressure (stress) increase occurs in the underlying soil immediately below the footing. Actually the pressure spreads laterally to a certain degree as well. The intensity of pressure decreases with depth until it eventually becomes too small and is of little concern.

- It is the pressure increase that causes settlement to occur in the soil below footings.

The increase in pressure extends to a greater depth below larger footings than smaller footings, hence the depth is influenced by the width of the footing (B). The zone where the pressure increase is significant with respect to settlement varies with the width of the footing. In clay, the zone is also influenced by the intensity of the effective overburden

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pressure (the pressure due to the effective weight of the soil lying above the point in question).

In granular soils, it is generally assumed that the zone extends to a depth of twice the footing width ($2B$) below the footing level. Some engineers however, prefer to use a depth equal to three times the width of the footing ($3B$). Therefore, when calculating settlement using a method such as that shown in Expression (5.0) the average N value or lowest cumulative N value within this zone is used. The values are obtained during a soil test boring program. For compressible soils such as clay however, the pressure increase is considered significant until the pressure increase is less than 10% of the effective overburden pressure. The resulting depth below the footing calculated in this manner defines the height of the compressible layer (H) shown in Expression (7.0).

Deterministic vs. Probabilistic Analysis

The deterministic method of analysis is widely practiced in the United States. In the deterministic method, a single set of soil properties such as friction angle, cohesion, and unit weight are selected by the engineer based on some rational method. The ultimate bearing capacity is calculated using these singular values and a selected factor of safety is applied to yield the allowable bearing pressure. The deterministic method however, does not take into consideration the possible (and likely) variability of the assigned soil values. A primary deficiency of the deterministic method is that the parameters (material properties, strength and load) must be assigned single, precise values when in fact the actual (and appropriate) values might be quite uncertain.

Another approach to assessing the bearing capacity of soil is to use a probabilistic method of analysis, which reflects the uncertainty in the assigned values. Probabilistic methods however are not commonly used. The factor of safety concept is extended to incorporate uncertainty in the parameters. The probabilistic approach is more meaningful than the deterministic approach alone since the engineer incorporates uncertainty into the analysis. Both methods of analysis can complement one another since they each have value that enhances the other method

Other Considerations

Multilayer Soil

The discussion so far has assumed that the soil lying below the footing within the zone stressed by the foundation is uniform. Often foundations are supported on multilayer soils, which influence the depth of the failure surface and the calculated bearing capacity. If the soil lying immediately below the foundation is weaker than soil at depth, then the failure surface might lie within a zone having a depth of less than $2B$. On the other hand, if the soil is weaker at depths greater than $2B$, then the failure surface might extend to depths greater than $2B$. Solutions are available for the cases of: (1) dense sand over soft clay, (2) stiff clay overlying soft clay, and (3) soft clay overlying stiff clay.

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Selection of Engineering Properties

The bearing capacity calculation is very sensitive to the values assumed for the shear strength of soil, namely the friction angle (ϕ) and cohesion. This is especially true at the higher values of friction angle. Therefore, careful consideration should be given to the values selected to define the soil shear strength.

Correction for Soil Overburden Pressure

In granular soils the effective overburden pressure affects the soil resistance. Hence a soil having a Standard Penetration Resistance of 15 blows per foot located at a depth of 5 feet may not have the same strength (measured by ϕ) as the same soil having the same penetration resistance but located at a depth of 30 feet. Therefore it is common to correct the blow count (from the SPT test) and sounding (from the CPT test) obtained in the field-testing program. Although this correction is common, it is not universally applied. Various equations and curves are available to make this correction.

Depth of Footings

The depth of footings is regulated by code. Building codes require that footings extend to the frost line of the locality of construction except when supported on solid rock or otherwise protected from frost. Building codes also state that when footings are placed on granular soil they shall be located so that a line drawn between the lower edges of adjoining footings shall not have a steeper slope than 30 degrees. This prevents an interaction between the two footings. Local building codes might modify these two conditions.

Problematic Soils

Footings supported on soil that expands or shrinks due to changes in the moisture content present special conditions.

Dynamic Bearing Capacity

Footings supporting dynamic loads such as machines require special consideration.

Example

Assume that a 4-foot square shallow spread footing is supported on sand at a depth of 4 feet below ground surface. The friction angle of the sand is 30-degrees, the unit weight of soil is 120 pcf and cohesion is zero. The groundwater level can rise to the depth of the bottom of the footing but no higher. The cumulative average standard penetration

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resistance of the sand within a depth of 8 feet (2B) below the footing is 12 blows per foot. Determine the allowable bearing capacity.

First, determine the allowable bearing capacity based on the shear strength of the soil and the ability of the soil to resist the applied pressure.

- Select the ultimate bearing capacity expression for square footings:

$$q_u = 0.4\gamma B N_\gamma + 1.2c N_c + \gamma D N_q$$

since cohesion = 0,

$$q_u = 0.4g B N_g + g D N_q$$

- For a friction angle of 30-degrees determine the bearing capacity factors from Figure 2. $N_\gamma = 16$ and $N_q = 18$
- The unit weight (γ) is given as 120-pcf. However, since the groundwater will rise to the depth of the footing, use the submerged unit weight ($\gamma - 62.4$) in the first term. Thus, $\gamma' = (120 - 62.4) = 57.6$ pcf.
- The ultimate bearing capacity is:

$$q_u = 0.4\gamma B N_\gamma + \gamma D N_q$$

$$q_u = (0.4)(57.6)(4)(16) + (120)(4)(18) = 10115 \text{ psf (rounded)}$$

- For a factor of safety of 3, the allowable bearing capacity is $q_a = q_u / 3 = 3372 \text{ psf}$
- If the footing were loaded to a pressure of 3372 psf (161.45 kPa), is the settlement within tolerable ranges?
- From Expression (5.0) with values expressed in SI units,

$$S_i = q B^{0.7} I_c \text{ and } I_c = 1.71/N^{1.4}$$

$$I_c = 1.71 / (12)^{1.4}, \quad I_c = 0.052$$

$$S_i = (161.45)(1.219)^{0.7} (0.052) = 9.83 \text{ mm (approx. } \mathbf{3/8\text{-inches})}$$

Thus the allowable bearing capacity is 3372 psf. At this pressure approximately 3/8-inch of total settlement is expected, which is less than the 1-inch criterion.

- Assume the groundwater level never rises above a depth of B below the footing.

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$$q_u = (0.4)(120)(4)(16) + (120)(4)(18) = 11712 \text{ psf (rounded)}$$

$$q_a = 11712/3 = \mathbf{3904 \text{ psf}}$$

This value is 532 psf higher and illustrates the affect of the groundwater on the calculated theoretical bearing capacity.

Important Points

The purpose of this course is to present basic subject matter to a diverse audience in order to convey the general concepts used when establishing the soil bearing capacity for shallow footings. The reader should understand the following:

- The foundation is that part of a structure which transmits the load directly into the underlying soil.
- Shallow spread footings distribute the load over a wide area so that the bearing pressure does not exceed the capacity of the soil to carry the load without objectionable settlement.
- Shallow footings are footings where the depth of the footing is generally less than the width of the footing.
- If the capacity of the soil is insufficient, failure can occur as a sudden, catastrophic movement or movement that is too great for the structure to accommodate.
- Bearing capacity analysis seeks to prevent catastrophic movement and to limit movement to within tolerable ranges for the structure.
- Explorations are conducted in order to present a picture of subsurface conditions including the nature of the material and the engineering properties. Often correlations are used between test values obtained during the exploration program and published engineering properties of the soil.
- Empirical relationships are often used to predict the bearing capacity of the soil and the settlement potential.
- Given the same set of soil information, different engineers can arrive at different but equally correct values for bearing capacity.

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