Chapter 9 – Soils and Foundations

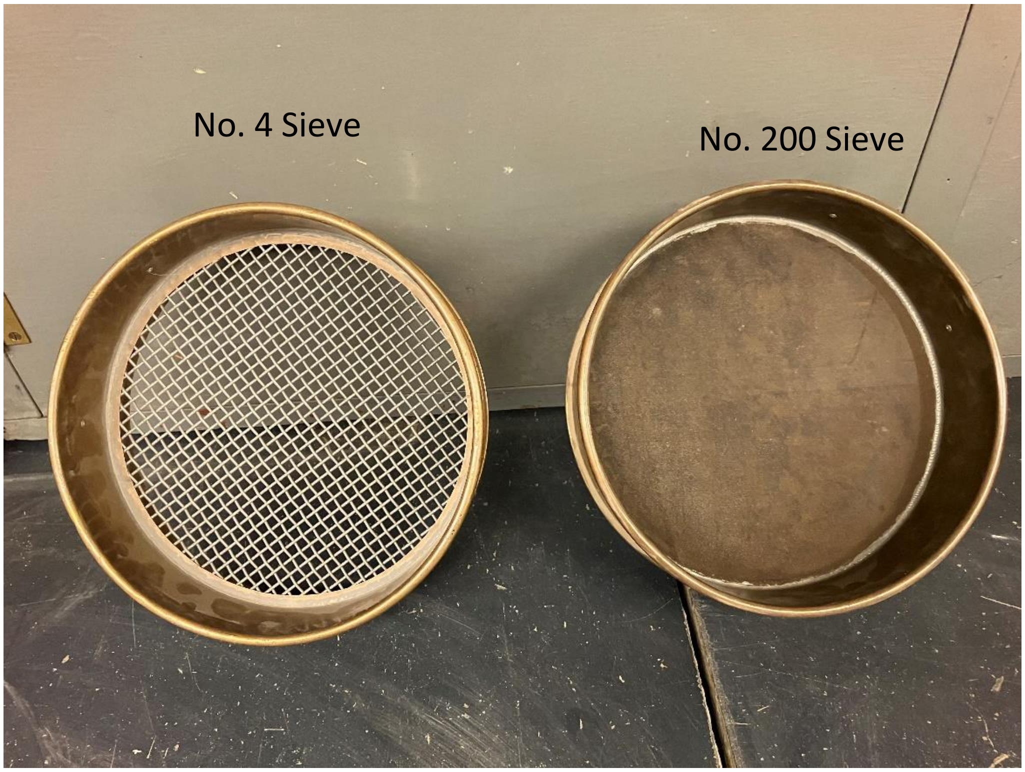
9.1 Introduction

The fundamental expectation of a structure is that it can safely carry loads (dead, live, environment, etc.) to the ground beneath it. While the previous chapters have focused on the materials being used for a structure's beams and columns, this chapter will explore the "other" ubiquitous construction material—soil— and examine its interaction with the foundation to successfully deliver the loads imposed on the structure. This chapter will provide an introduction into soil as a material and its role in the design of a structure. This chapter will also cover basic behavior and design of foundations which should provide the construction management student with a basic understanding of this important piece of the overall structure.

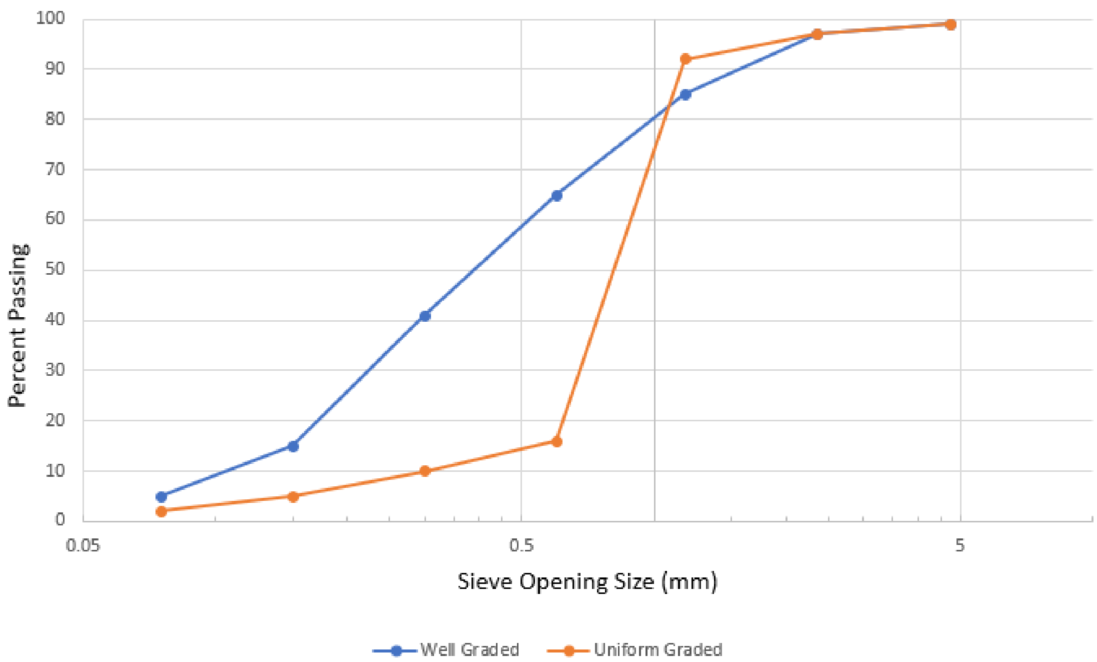
9.2 Soil Types and Classifications

The soils our structures sit upon are relatively unique when it comes to composition, properties, and behavior. Basically, the soil beneath our feet may change from one side of our construction site to the other and because of this, a sampling and testing program by a qualified geotechnical engineering firm, is an absolute necessity before a project can enter the design phase with any certainty. Determining the types, depths, and strength of soil that exists on a project site, as well as the location of the water table will have an enormous impact on the types of foundations we can successfully and economically use.

Soils can be categorized in many different manners and one of the basic methods to group soils is by the size of the soil particles. We accomplish this by using "pans" with screens at the bottom which are called sieves. The screens have different opening sizes, and the standard U.S. sieve is referred to by its "number". For instance, a No. 4 sieve has a screen that has four openings per lineal inch (opening width is 4.75 mm) while a No. 200 sieve uses a screen with 200 openings per lineal inch. A No. 4 sieve is typically considered the dividing line between gravel and all other soil particles. A comparison of a No. 4 sieve with a No. 200 sieve is shown as follows:



Soils can be composed of four basic soil types—gravels, sands, silts, and clays which are listed from largest soils particle size to the smallest. A sieve analysis test uses multiple sieves and describes the gradation of soil particles in a soil. “Gradation” refers to the distribution of sizes in a soil. This distribution of soil particles is typically displayed graphically in what is referred to as a grain size distribution graph which is a graph of the percent of a soils sample which “passes” through the various sieve sizes. The term “well-graded” means there is a good distribution of a variety of sizes in the soil, while “poorly-graded” soils lack a good distribution of sizes. A poorly-graded soil may have a large percentage of particles being one size (this can be referred to as a uniform gradation) or may be missing a certain size of particle (this is referred to as a gap-graded soil). For most construction applications a well-graded soil is preferred as it is likely more dense and less apt to consolidate under load. The difference between a well-graded soil and a uniformly graded soil is displayed in the following grain size distribution graph.



Gravels, sands, and some silts are "cohesionless soils" meaning they do not have any tensile strength and will not stick together by themselves (some may refer to cohesionless soils as "granular soils"). Clays and some silts are "cohesive soils" meaning that they will stick together (especially in the presence of water). The reason that cohesive soils "stick" together is that their particles are electrically charged. This leads to a very different behavior when they get wet because water is also an electrically charged molecule. Hence, when clays get wet they exhibit a stickiness which is a very different behavior from cohesionless soils.

Different classifications systems exist but one that is commonplace is outlined by ASTM D 2487 and is called the *Unified Classification System*. This system attempts to classify soils based on two letter symbol with the first letter identifying the primary component of the soil, and the second describes its grain size or plasticity characteristics. The first letter would be one of the following:

- G - gravel
- S - sand
- M - silt
- C - clay
- O - organic soil

The second letter is based on the gradation of the soil or the plasticity of the soil if it is a silt or a clay. The plasticity of a soil is related to a standard test (ASTM D 4318) known as the liquid limit test. The liquid limit test indicates the degree to which a soil might compress. A soil generally becomes more compressible as the liquid limit increases. Therefore the "second" letter in the Unified Soil Classification system would be one of the following:

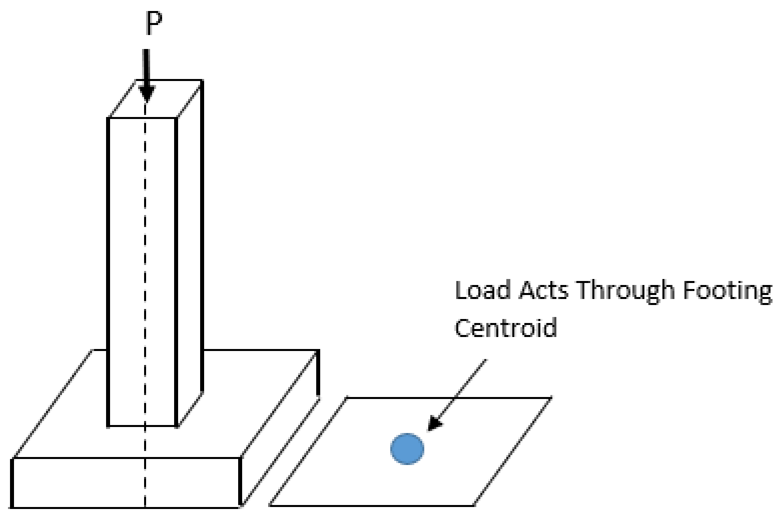
- W – well-graded
- P – poorly-graded
- M – the fine particles are silts
- C – the fine particles are clays
- L – Low compressibility soil
- H – High compressibility soil

So, a soil designated GW would represent a well-graded gravel and a soil designated as a SC would be a sand with a clay fraction comprising more than 12% of the soil. Some of the more common soil designations following the Unified Classification System are as follows:

- GW – well-graded gravel
- GP – poorly graded gravel
- GC – clayey gravel
- GM – silty gravel
- SW – well-graded sand
- SP – poorly graded sand
- SC – clayey sand
- SM – silty sand
- CL – lean clay (lean refers to lower liquid limit, i.e., lower compressibility)
- ML – silt
- CH – fat clay (fat refers to a higher liquid limit, i.e., higher compressibility)

9.3 Simple Foundation Design

The purpose of footings and foundations is to take the loads from the structure and transfer these to the soil below in a manner which is acceptable (i.e. settlement is within expectations). In order to ensure that this occurs, many designers employ allowable stress design. In this regard, the actual stresses placed upon the soil by a footing or foundation (referred to as the bearing pressure) must be less than or equal to the allowable bearing pressure. A concentrically loaded footing is one where the load from a column or wall acts at the footing centroid as shown in the following figure.



For the purposes of a footing subjected to a concentric compressive load, the allowable stress design philosophy can be expressed as follows:

$$\text{Actual Bearing Stress} \leq \text{Allowable Bearing Stress} \qquad \text{(Eq. 9-1)}$$

The allowable bearing stress is typically set by the geotechnical engineer who determines this value based on field sampling of the soil on a project and subsequent laboratory testing. Since the actual bearing stress is simply calculated by the formula:

$$\sigma = \frac{P}{A}$$

The allowable stress design philosophy can be restated as follows:

$$\frac{P}{A} \leq \text{Allowable Bearing Stress}$$

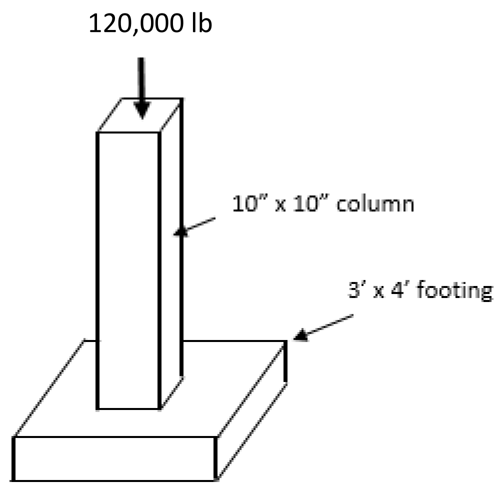
The area of the footing or foundation can be found as follows:

$$Area\ of\ footing = \frac{P}{Allowable\ Bearing\ Stress} \qquad \text{(Eq. 9-2)}$$

The following examples will illustrate the basic calculation of bearing stress under a footing and how the allowable stress design philosophy can be used to properly size a footing.

Example 1

A column is supported by a concrete footing measuring 3 ft. x 4 ft. Calculate the bearing stress on the soil beneath the footing.



The stress felt by the soil under the footing is a bearing stress and is calculated by the following formula:

$$\sigma = \frac{P}{A}$$

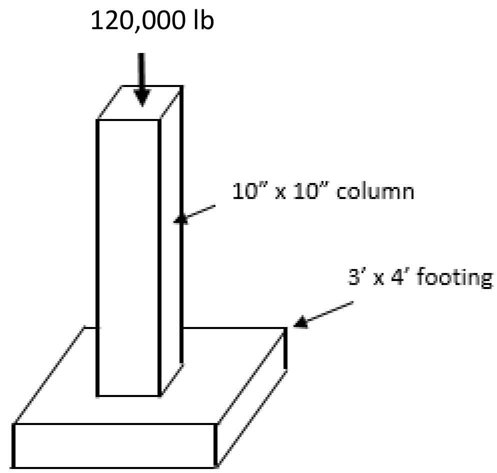
Then the stress in under the footing is calculated as follows:

$$\sigma = \frac{120{,}000\ lb}{12\ sq.ft.}$$

$\sigma =$ 10,000 psf

Example 2

The column in Example 1 was found to have a bearing stress in the soil under the footing of 10,000 psf. If the geotechnical engineer determines that the soil has an allowable bearing stress of 2500 psf, would the footing size have to be redesigned?



The footing size has to be redesigned because the actual stress (10,000 psf is greater than what is allowed 2500 psf). So the 3 ft. x 4 ft. footing size has to be increased. We can perform a redesign using the following formula but re-arranging it:

$$Area\ of\ footing = \frac{P}{Allowable\ Bearing\ Stress} \qquad \text{(Eq. 9-2)}$$

Using allowable stress under the footing is calculated as follows:

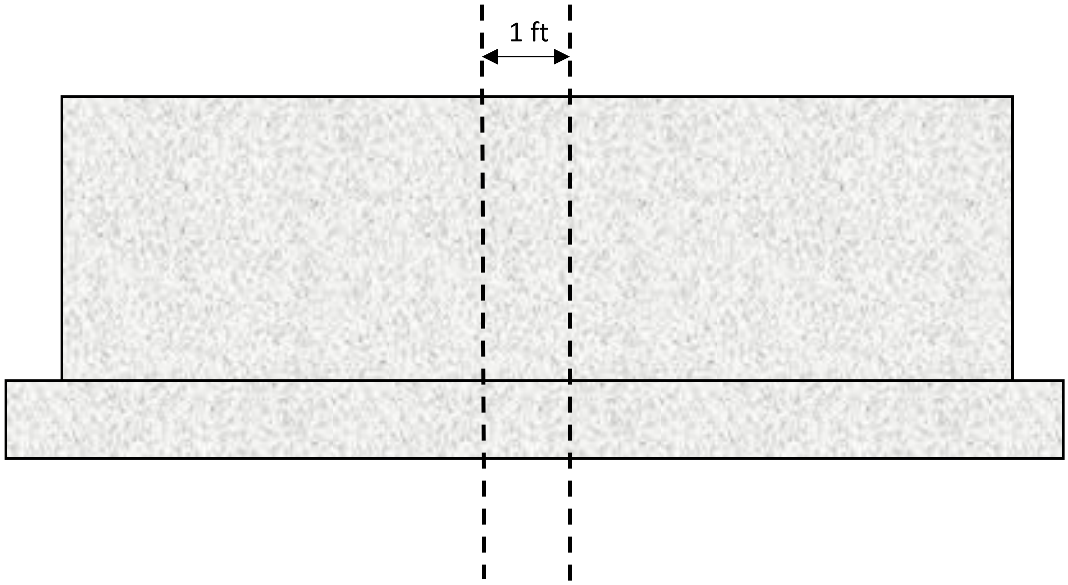
$$Area\ of\ footing = \frac{120{,}000\ lb}{2500\ psf}$$

$A = 48\ \text{ft}^2$

So, one redesign that could work would be a footing measuring 6 ft. x 8 ft. If a square footing was desired, then a 7 ft. x 7 ft. footing size would work. Of course, there are many other possible solutions as well.

The previous examples investigated footings that carried a concentrated (or point) load , these are sometimes called spread footings. The footings that occur under walls are sometimes referred to as continuous footings since the extend the length of the wall itself. The vertical loads that walls are assumed to carry uniform loads instead of point loads.

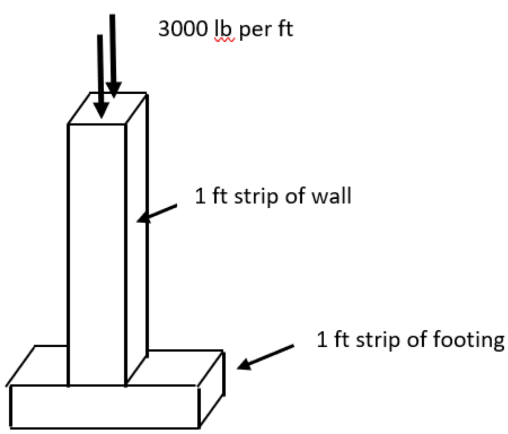
If these uniform loads are concentric to the footing beneath, the simplified analysis and proper sizing of the continuous footing is very similar to the spread footing examples. One difference is that the analysis of the wall (and therefore footing) is usually considered to be a "1-foot" long strip. The designer assumes that every 1-foot strip of the wall behaves essentially the same way, therefore by considering a “strip” we have essentially considered the entire length of wall.



solutions as well.

Example 3

An 8” thick foundation wall sits on top of a continuous footing. The allowable bearing stress in the soil has been determined to be 2000 psf. The load carried by the wall is determined to be 3000 pounds per foot applied to the top of the wall. The weight of the wall and the footing is estimated to be 1500 pounds per lineal foot. What is the minimum width that this continuous footing should be designed for?



The total load on the 1-foot strip is 4500 pounds per foot (i.e. 3000 +1500). The area of the continuous footing over a 1-foot strip would be:

$$Area\ of\ footing = \text{Footing width x 1ft}$$

Given the load as 4500 pounds per foot and the allowable bearing stress to be 2000 pounds per foot., then the bearing area of the footing should be:

$$Area\ of\ footing = \frac{P}{Allowable\ Bearing\ Stress} \quad \text{(Eq. 9-2)}$$

or

$$Area\ of\ footing = \frac{4500\ lb\ per\ foot}{2000\ psf}$$

$$Area = 2.25\ \text{ft}^2$$

Since we are using a 1-foot strip then the footing width would be 2.25 feet (or 27 inches).

9.4 Presumptive Allowable Bearing Values

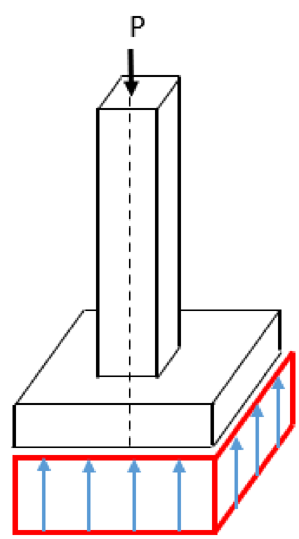
In the previous section it was noted that the geotechnical engineer typically determines the allowable bearing pressure based on a combination of soil sampling and testing, in addition to their experience when working in a particular geographic area. However, geotechnical engineering is a relatively new discipline and footings and foundations for years have been successfully designed for years. Building codes for years have recognized as appropriate the use of presumptive allowable bearing pressures which are the allowable bearing capacity that can be used for footing design based on past experience. Although care should be used with these values, the International Building Code in Section 1806 lists the following presumptive allowable bearing stress values:

Type	Presumptive Vertical Foundation Pressure (psf)
Crystalline Bedrock	12,000
Sedimentary and foliated rock	4,000
Sandy gravel and gravel (GW and GP)	3,000
Sand, silty sand, clayey sand, silty gravel and clayey gravel (SW, SP, SM, SC, GM and GC)	2,000
Clay, sandy clay, silty clay, clayey silt, silt, and sandy silt (CL, ML, MH, CH)	1,500

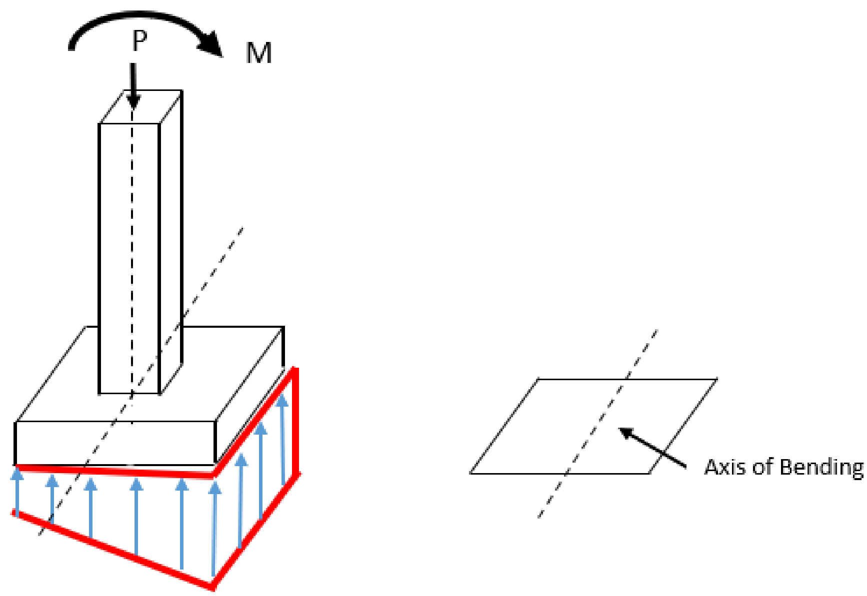
Generally these values are considered to be on the conservative side, if the building official has any doubt regarding the strength, classification, or compressibility of a soil they can require a geotechnical investigation be conducted.

9.5 Footings Subjected to Axial Loads and Moments

The footing examples considered so far have consisted of footings subjected to concentric loads or loads that through the centroid of the footing. When that occurs the bearing stresses under the footing are assumed to be uniform – that is the bearing stress is the same everywhere under the footing. This is shown as follows:



However in addition to purely axial loads, footings and foundations can also be subjected to bending moment which can arise due to load eccentricity or lateral loads. These bending moments cause the footing to bend and similar to the bending stress on beams (which we discussed earlier in the text), bending stresses under the footing will be compressive on one side and tensile stresses on the other. What occurs in this situation is that the bearing stresses under the footing are nonuniform – that is the bearing stress will be different under the footing. It will be maximum on the side where the moment is "bending" the footing into the soil and minimum on the side where the moment is "bending" the footing away from the soil. This is shown as follows:



This "combined" bearing stress is a combination of the direct compressive stress, $\frac{P}{A}$, and the bending stress caused by the moment M (remember bending stress is equal to $\frac{M\,c}{I}$). If we assign stresses that create compression a negative sign and stresses that cause tension a positive sign, then the maximum and minimum bearing stresses are as follows:

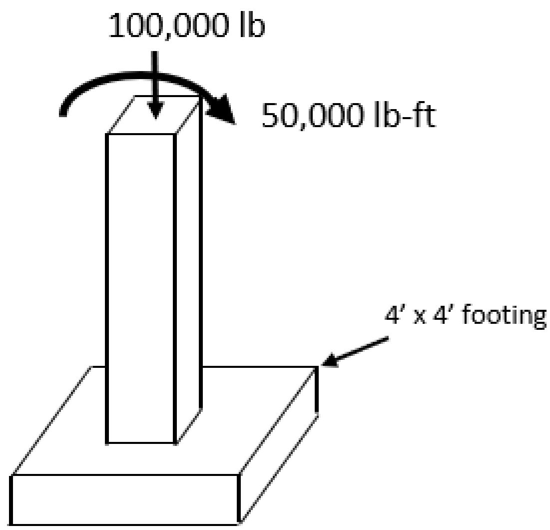
$$\sigma_{maximum} = -\frac{P}{A} - \frac{M\,c}{I}$$

$$\sigma_{minimum} = -\frac{P}{A} + \frac{M\,c}{I}$$

The result of this combination of stresses is a non-uniform distribution of bearing stress underneath the footing. The following example will demonstrate this principle.

Example 4

A column is supported by a concrete footing measuring 4 ft. x 4 ft. The axial load is 100,000 pounds and the bending moment is 50,000 lb-ft. If the maximum allowable bearing stress that the soil can take is 4000 psf will this size footing be adequate?



The maximum bearing stress will occur on the "right" side of the footing while the minimum bearing stress will occur on the "left" side. The stress is always maximum of the side where the moment is "pointing". Compressive stresses will be assigned a "negative" sign. The formulas to be used are as follows:

$$\sigma_{maximum} = -\frac{P}{A} - \frac{M\,c}{I}$$

$$\sigma_{minimum} = -\frac{P}{A} + \frac{M\,c}{I}$$

The direct compressive stress, $\frac{P}{A}$, is calculated using P = 100,000 lbs and the footing area of 16 ft^2. This gives us a stress of:

$-\frac{P}{A}$ = 100,000 lbs / 16 ft^2 = - 6250 psf

The bending stress caused by the moment will be compression on the right side of the footing and tension of the left side. The values used in the bending stress formula are as follows:

M = 50,000 lb-ft

c = 2 feet (distance from neutral axis to outside edge of the footing)

I = 1/12 bh^3 (with b = 4ft and h = 4ft this calculates to 21.33 ft^4)

The bending stress formula then becomes:

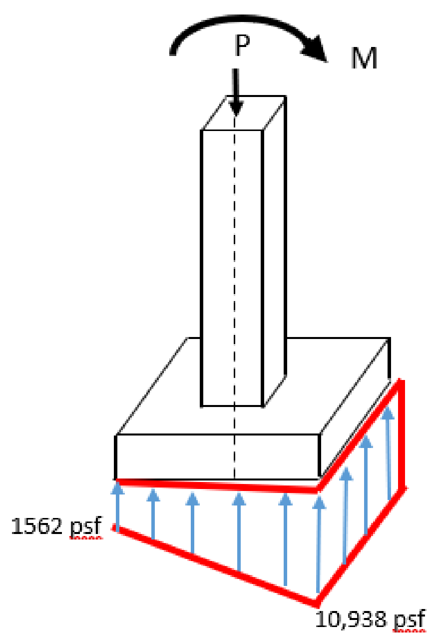
$\frac{M\,c}{I} = \frac{50000\ lb{-}ft(2\ ft)}{21.33\ ft4}$ = 4688 psf (negative on the “right side and positive on the left)

The combination of direct compressive stress and bending then becomes:

$$\sigma_{maximum,right} = -6250\,psf - 4688 = -10{,}938\,psf$$

$$\sigma_{minimum,left} = -6250\,psf + 4688\,psf = -1562\,psf$$

The maximum bearing stress of -10,938 psf (negative indicates compression) is much greater than the allowable bearing stress of 4000 psf, so this footing will need to be redesigned. The bearing stresses under the footing are shown as follows:



Homework Exercises

1. Design the size of a square spread footing if the soil it bears upon has an allowable bearing stress of 3000 psf. Consider the footing to be loaded concentrically with a 120,000 pound load.

2. Design the size of a rectangular spread footing if the soil it bears upon has an allowable bearing stress of 4000 psf. Due to site constraints the footing length needs to be 1.5 times larger than its width. Consider the footing to be loaded concentrically with a 120,000 pound load.

3. Using presumptive allowable bearing pressures, design the size of a square spread footing if the soil it bears upon is classified as silty sand (SM). Consider the footing to be loaded concentrically with a 150,000 pound load.

4. A foundation wall supports a compressive load of 3000 pounds per foot. Determine the width of the continuous footing that supports the wall if the allowable bearing stress on the soil is 2000 psf.

5. Using presumptive allowable bearing pressures, design the width of a continuous footing if the soil it bears upon is classified as silty clay (CL). Consider the footing to be loaded concentrically with a compressive load of 3000 pounds per foot.

6. A column is supported by a concrete footing measuring 4 ft. x 4 ft. The concentric axial load is 60,000 pounds however there is also a bending moment is 20,000 lb-ft. If the maximum allowable bearing stress that the soil can take is 4000 psf will this size footing be adequate?

7. Redesign the size of the square footing in the previous problem so that the footing is adequate for an allowable bearing stress of 4000 psf.

8. A column is supported by a concrete footing measuring 6 ft. x 6 ft. The concentric axial load is 120,000 pounds however there is also a bending moment is 40,000 lb-ft. If the maximum allowable bearing stress that the soil can take is 5000 psf will this size footing be adequate?