Foundation Design

Understanding Geotechnical Factors of Safety in the Design of Foundations

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Figure 1: Typical sampling method

A rift in design practice is slowly forming at the interface of building foundations and the soils that support them. As structural design practice gradually evolves toward strength design (LRFD), the allowable stress (ASD) concepts of geotechnical recommendations are falling behind. Someday there may be a unified approach to allow structural engineers to seamlessly track their calculated building loads to the soils that support them, design the foundations using only strength design, and use globally accepted factors of safety. But today is not that day.

Common geotechnical and structural interactions, including spread footings, drilled pier/piles, predicted foundation settlement, and retaining walls, can form a basis of understanding to help the structural engineer navigate from the structural engineering realm to the geotechnical realm with respect to modern geotechnical practices and an understanding where, and to what degree, the typical factors of safety exist.

Figure 2: Soil sample obtained from field

Background

Good design practice requires that structures be durable to a degree that their performance and safety not be compromised by uncertainties with respect to actual building loads, variances in the strengths of their structural components, or the method used to predict their structural behavior. Most structural engineers are intimately familiar with methods such as allowable stress and strength design. They intuitively understand that even under the statistically remote chance of a fully applied service load, modern design practice still incorporates a factor of safety to protect against a failure, i.e. service load and ultimate load.

Structural engineers tend to be conservative in nature and, depending upon the material and the building code used, assume a sometimes conservative value for the assumed strength values of the engineering material; employ a sometimes conservative estimate of the anticipated service load; increase the service load by a load factor, apply a strength reduction factor, and then typically approach the design using a conservative analysis yielding design unity of less than one.

Some structural engineers, depending upon their level of familiarity with the building material, are able to sum the factors of safety used and equate it to a total factor of safety between ultimate strength and the maximum applied service load for an individual member or structure as a whole. It is not uncommon for this calculation to yield a factor of safety on the order of 200 to 300 percent (a total factor of safety of 2.0 to 3.0). Recognizing this value can be beneficial, since it allows an engineer to make a design judgment whether to accept items that may exceed unity by 5 or 10 percent. These types of marginal overstress can commonly be the case for building retrofits, remodels, construction errors, or design errors that are not caught until after construction, if ever.

However, structural engineers often do not have the necessary background or experience with geotechnical exploration and testing to have a sense for the factors of safety and/or level of conservatism used in the geotechnical parameters for the analysis and design of foundations. What is the probability of failure if the maximum allowable soil bearing pressure is exceeded by 10 percent? What is the likelihood of failure if inorganic silt is discovered in lieu of the specified foundation backfill material? Is the drilled pier uplift force specified by the geotechnical engineer an average service value determined by testing, a high conservative value, or a value that has already been multiplied by a factor of safety? What load factors should be applied to active soil pressure with regard to sizing retaining wall concrete reinforcement?

Consider a hypothetical case of a structural engineer designing a new office space. As part of the design work the structural engineer visits the existing facility, counts the number of workers, desks, filing cabinets, coffee pots, potted plants, chairs, etc. and calculates a service load of 8.7 pounds per square foot. Using this value, the beams and columns are calculated based upon the ultimate strength of the members. While this example may seem ghastly, it is a possibility that a foundation design can be based upon numerical values provided by a geotechnical engineer that represents a single test value obtained by one test boring at the construction site with no factor of safety.

Geotechnical engineers evaluate the site, sample the soil, conduct standardized tests, analyze the test results and prepare a written report summarizing findings and provide recommendations. What may be missing is a clear distinction in the results and recommendations with respect to whether they represent an isolated value, an average value, a conservative value, a worst case scenario, or design value that incorporates a structural factor of safety established by the geotechnical engineer.

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Figure 3: Swell / consolidation testing device

Soil Strength and Failure Mechanisms

A basic model of a soil mass is to consider it as a mass of individual particles with its strength properties, dependent upon the interaction of the particles. Soil almost always fails in shear because of its low tensile strength; therefore, soil strength is usually discussed in terms of shear strength. The shear strength of soil, i.e. at what point the soil particles begin to slide past each other, depends upon the frictional strength and the cohesive strength between the soil particles. The frictional strength is directly proportional to the normal force acting between the particles. The cohesive strength occurs when the soil particles are bonded together, such as in clays or cemented soils. In order to be conservative, geotechnical engineers will often assume the cohesive strength is zero. This common assumption introduces a margin of reliability up front.

Soil type, moisture content, loading rate, drainage condition, and stress history are only a few of the numerous factors that can affect the shear strength of soil. For example, the interaction between sand particles is different than the interaction between clay particles. One of the many ways water can reduce the strength of soil is to reduce the effective stress between particles, which results in an overall reduction in frictional strength.

Soil is a compressible material and responds to changes in normal stress when a foundation load is applied. The foundation load will increase the normal stress, which results in a corresponding normal strain. The strain then produces settlement or deformation of the compressible soil mass. A bearing capacity failure occurs when compressive foundation loads imposed upon the soil mass increase the inter-particle stresses to the point that the soil particles slide past each other, causing the soil mass to fail in shear.

Common Design Elements and Factors of Safety

The following is a list of common design elements encountered by structural engineers, and a brief discussion with respect to factors of safety based upon the authors' experience.

Soil as a Dead and Live Load

Where soils impart a live load to a structural system that is being analyzed using strength design, a minimum load factor of 1.6 is appropriate. However, if the soil is loading a horizontal beam element and the weight and long-term moisture is highly controlled, a load factor of 1.4 may be more appropriate. When the dead load of a soil is used to resist seismic and lateral forces, it is appropriate to consider a load factor of 0.9 and 1.6 to determine the worst case scenario.

To state that one geotechnical factor of safety will work in any and all applications is akin to saying that one size of steel beam will work in any and all building designs. Rather than attempt to cover all situations in this article, which is a collaborated effort between a structural and a geotechnical engineer, we will focus on general concepts encountered by structural engineers. The generalizations presented here should not substitute good engineering judgment or replace the necessary dialog between the structural engineer and the geotechnical engineer.

Spread Footings

Typically, the building code's default values and geotechnical engineers alike provide a factor of safety between 2 to 3.5 with respect to contact bearing pressure loading for spread footing foundations. While exceeding the contact bearing pressure may not cause a catastrophic, progressive shear failure, it may cause excessive and undesirable elastic deformation or settlement. One method of increasing a soils bearing capacity is to place the footing further below ground, such that soil on both sides serves to constrain a shear failure. The Uniform Building Codes allowed a 10 percent increase in bearing pressure for each foot a footing was buried below grade, to a maximum of twice the prescribed amount; however, this provision, while still often valid, was not directly carried over into the International Building Codes.

Drilled Pier/Pile end Bearing and Side Shear

Typical recommendations by geotechnical engineers have a factor of safety between 2.0 and 3.5 for pier/pile end bearing and side shear. It should be a final check by the structural engineer that the ultimate load bearing capacity of any pier/pile, including reinforcement, is at least twice the working load. Design/allowable pier/pile loads should not produce a gross lateral movement of more than ½-inch at the ground surface.

Drilled Pier/Pile Uplift loading and Required Reinforcement

For piers/piles subject to heave and uplift loading, the geotechnical engineer may provide swell pressure, uplift as a factor of pier diameter, total uplift load, and/or minimum pier reinforcement.

The swell pressure exerted by expansive soils can be measured in the laboratory. The percentage of the measured swell pressure that is transferred to the pier as an uplift load

Figure 4: Geotechnical / structural interaction failure of retaining wall

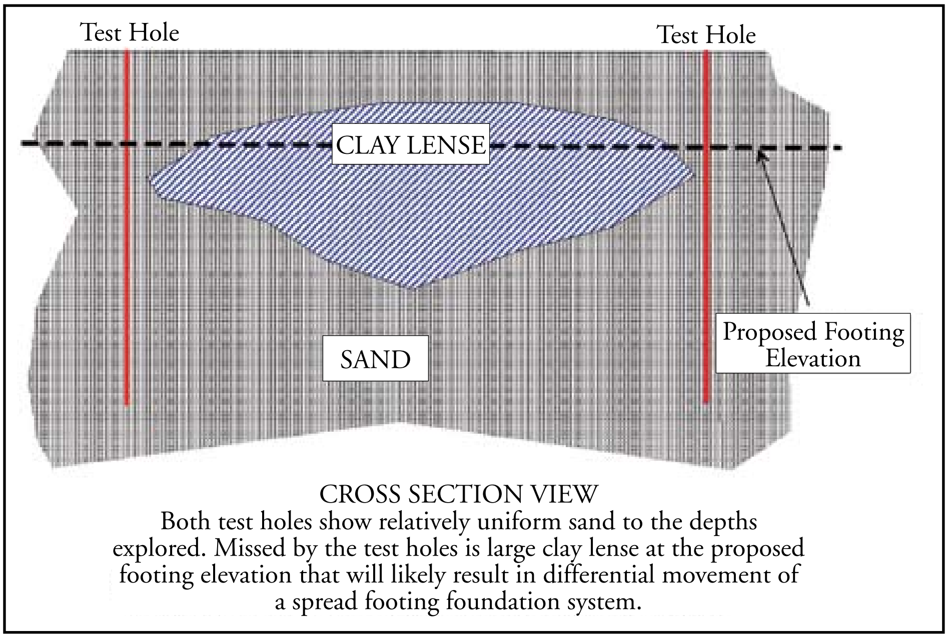

Figure 5a: Cross section view - illustration of an unknown geotechnical condition

is typically determined by applying a swell pressure coefficient. In the Denver area, this value is typically 0.15 and is based upon empirical data from laboratory testing by F.H. Chen. However, the value used for the coefficient can vary and is a function of soil type and the conservatism deemed necessary by the geotechnical engineer. The prescribed area of pier reinforcement may have been derived by experience or dividing the anticipated uplift load by an allowable deformed bar capacity of 36,000 psi (0.6 x 60,000 psi), i.e. a factor of safety of 1.66.

It should be a final check by the structural engineer that the pier uplift is resisted by a total factor of at least two, i.e. the calculated pier withholding force by embedment in bedrock is no less than twice that of the anticipated pier uplift force. It should be further verified that the pier/pile reinforcement is designed with a factor of safety of at least three, i.e. the reinforcement ultimate capacity is three times that of the anticipated uplift load.

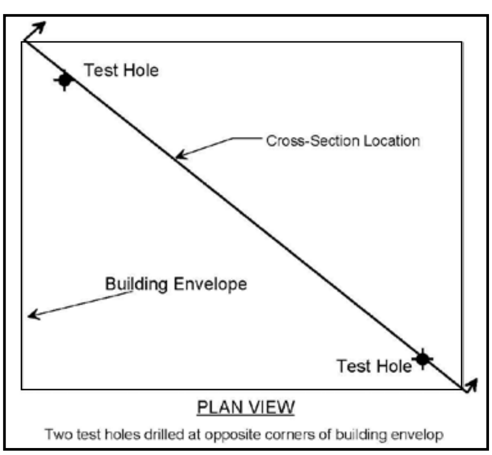

Figure 5b: Plan view - illustration of an unknown geotechnical condition

Predicted Foundation Settlement and Allowable Settlement

Similar to the modulus of elasticity in structural members, predicted foundation settlement is based upon calculations derived from values obtained from laboratory testing and other empirical data. In general, the predicted settlements are conservative, i.e. the predicted settlement is usually more than the measured settlement. Several different methods exist that can be used to predict foundation settlement. Each method carries its own level of conservatism.

Design values for allowable soil bearing pressures given by the geotechnical engineer should consider allowable settlement criteria of the structure, and include a factor of safety of at least 1.5 to 2.0. Typically the allowable settlement criteria used is for 1-inch of maximum settlement and ½-inch of differential settlement. If the allowable settlement criteria used by the geotechnical engineer is not evident, the structural engineer is uncertain if the values are for total or differential settlement, and/or if the allowable settlement criteria of the structure is atypical then the structural engineer should contact the geotechnical engineer for clarification.

Retaining Walls

At a minimum, retaining walls should have a factor of safety of 1.5 with respect to sliding and overturning. Typically, the equivalent fluid density (G_h), soil density (γ), the angle of internal friction (Φ), and the coefficient of static friction are the result of the laboratory tests and do not incorporate a factor of safety; however, they can incorporate a level of conservatism. The type of laboratory tests used, the conditions under which the tests are performed, and the geotechnical engineer's interpretation of the results will affect the level of conservatism. For example, soil strength parameters determined under saturated conditions would be more conservative than if determined under dry conditions. It should be a final check by the structural engineer that seismic loading does not control with respect to the retaining wall's stability.

Seismic Profile

A seismic profile when read from a map typically represents a conservative condition known for that area. If a specific test is performed for a project at a specific site, the results should reflect a true and accurate condition with no factor of safety. The factor of safety for the structure should be developed by the analysis using the procedures of ASCE-7 or the IBC.

Summary Points to Consider

1. Communication between the structural and the geotechnical engineer is essential, so ask questions. Upon receiving a geotechnical report that is vague in terms of soil and geotechnical loading conditions, call the geotechnical engineer of record and ask whether the load listed represents an isolated value, an average value, a conservative value, a worst case scenario, or design value that incorporates a structural factor of safety established by the geotechnical engineer. An ideal approach would be to discuss the project and required design parameters with the geotechnical engineer prior to the commencement of the geotechnical investigation. A well timed phone call could make the difference between under-design, adequate, or overly conservative.

2. Consider the structure being built. The factor of safety for a 4-foot tall retaining wall for a vegetable garden need not be the same for a basement retaining wall next to an MRI machine at a hospital.

3. Consider the site variability. The factor of safety need not be the same for a site with relatively homogenous soil characteristics as a site that spans across an area of geological transition. Different factors of safety may be appropriate at sites with over excavation, soil, stabilization, or necessitate soil importation. For sites with highly variable soil properties one should take into account the worst case for the load condition with respect to factors of safety or implement a protocol for inspection and verification of soils with respect to design assumptions.

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Figure 6: Example of a highly non-homogenous soil

4. Consider the level of testing and inspection performed. A higher factor of safety may be warranted when designing a 3 mile long highway retaining wall where only three random soil tests were performed versus the same wall where testing was performed at 100-foot intervals and continuous geotechnical inspection is anticipated.

5. The factor of safety ultimately held by the foundation designed by the structural engineer will be a function of the geotechnical engineer's pessimism or optimism for the soil and the site alike. Geotechnical practice, testing, and standards have come a long way over the last 100 years but still a considerable amount of the profession is an attempt to predict behavior where the building most likely has not been designed and aspects such as cuts, fills, ground water, and surface runoff may have unforeseen effects. The amount of site-specific data generated during a geotechnical investigation will affect the level of conservatism used in determining the design values provided to the structural engineer.

6. Be mindful of water. As mentioned above virtually all soil failures the structural engineer is concerned about are shear failures. Water can have a lubrication effect on soils reducing their resistance to shear. Consider surface drainage, subsurface drainage, adjacent bodies of water (lakes and retention ponds), and ground water for the foundation during and after construction.

Figure 7: Significant drywall distress resulting from undesirable soil and structure interaction

7. Local and state codes as well as local practice may differ from that listed in this article. Be mindful if you are the out-of-state designer working with a local geotechnical engineer or visa versa. The authors of this paper have witnessed several buildings in the state of Colorado exhibiting distressed foundations that were designed by a structural engineer and/or a geotechnical engineer not familiar with measures adopted locally to prevent damage due to highly expansive clay soils.

Figure 8: Significant foundation distress resulting from undesirable soil and structure interaction

8. Use Judgment. When an ASTM A992 wide-flange beam is specified, it is appropriate to be confident you will get that beam or better. However, never become overly confident or lose site of the variability and inherent unknowns with respect to geotechnical recommendations.▪

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