Safety in Foundation Engineering

Unity of the WSD (ASD) and LRFD Methods

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Geostructural Nature of Foundation Engineering

Foundation design requires knowledge of the behavior of the structure supported by the foundation, as well as that of the soil or rock that furnishes the ultimate support. The superstructure, foundation, and soil or rock must act together, and each must possess its unique serviceability and safety in the interactive system.

It is known that, even though the soil or rock may provide adequate safety of the foundation against outright failure, detrimental settlement may occur prior to any threat of collapse. Such occurrence is analogous to a beam or truss in the superstructure that possesses adequate strength, but does not meet the deflection (serviceability) requirement. It should be emphasized, however, that herein lies one of the basic differences between the design of concrete and steel elements in the superstructure and design of the foundation. That is, strength of the construction material in compression, tension, or shear usually controls superstructure design, whereas deformation (settlement) usually governs the design of the foundation. Nevertheless, the foundation engineer must give due consideration to both aspects of safety in any suitable design.

The performance of a spread footing in terms of the stress-deformation-strength properties of the soil is demonstrated in *Figure 1*. When block A is compressed by the load P, settlement (deformation) occurs. As the load is increased, the shear stresses and accompanying deformations increase in blocks A and B. When the shear strength of the soil is exceeded, a bearing capacity failure occurs, resulting in surface heave. In reality, as in the design of the superstructure, the two types of unsatisfactory behavior (settlement and collapse) are often so closely related that the distinction is entirely arbitrary (5).

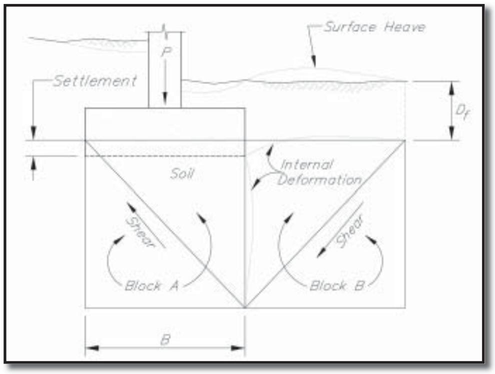

Figure 1: Simplified depiction of the settlement and bearing capacity phenomena of a long spread footing

It is also commonly known that the performance of a foundation depends on its size and shape as well as the nature of loads that it must support. The effect of size of the footing is schematically demonstrated in *Figure 2* for a footing supported on a deposit of uniform sand.

The portion of the curve, *oa*, is a straight line variation based on Terzaghi's bearing capacity equation, modified by Meyerhoff (1)(2). The slope of *oa* is a function of the relative density of the sand, which can be correlated with the dynamic standard penetration test value (N_{60}), surcharge around the footing (D_f), and choice of factor of safety against failure. Between *b* and *c*, the curve is based on extensive observations by Burland and Burbidge (3) and determined primarily by the relative density of the sand and the amount of tolerable settlement. Between *a* and *b*, the curve may be considered a reasonable transition between safety determined by shear strength (bearing capacity) and safety controlled by deformation (settlement).

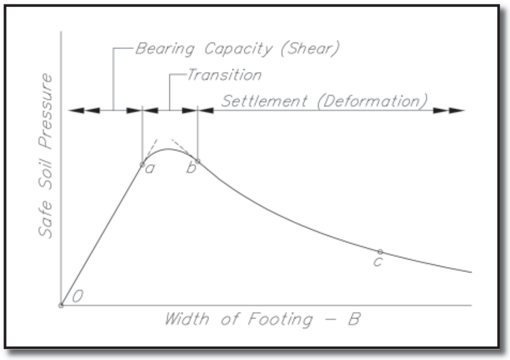

Figure 2: Relation between soil pressure and width of footing on uniform and, for a given allowable settlement and a given factor of safety against outright failure

The theory and observations that serve as the basis for *Figure 2* may be used to construct design aids whereby sizes of footings are selected for further analysis and design. Usually, such charts are based on tolerable settlement, measures of density of the sand, depth of surcharge, and factor of safety against bearing capacity failure. Such a chart is presented in *Figure 3*, where q_a is the allowable soil bearing pressure or allowable soil pressure to limit settlement and N equals the average N_{60} value within the zone of influence of the footing. The effect of the footing shape (L/B ratio) is shown in *Figure 4*. *Figure 3* is, in fact, representative of the design approach under consideration to revise Figure 19.3, first presented in the text *Foundation Engineering* (4). However, *Figure 3* itself is based on specific conditions of grain size, preload history, footing configurations and allowable settlement, and cannot be used indiscriminately as a universal design aid for all shallow depth foundations on sand.

It should be noted that service loads, rather than factored loads, are used to obtain allowable pressures from the charts, because tolerable settlement usually governs safety of the foundation. Nevertheless, factored resistances must also be given due consideration if load and resistance factor design (LRFD) methods are used for design of the superstructure. In other words, the factored resistance of the soil or rock must be equal to or greater than the factored load supported by the foundation. It is hoped that the following discussion and design examples will serve to clarify and unify the working stress design (WSD) and LRFD procedures to obtain safety of foundations.

Interdisciplinary and Rhetorical Obstacles

As a result of specialization in research and practice, geotechnical and structural engineers often do not understand, or even appreciate, each other's concerns in the design process. That is, design philosophies and the choice of appropriate load and resistance factors may be in dispute, and although communication is imperative, it may sometimes lead to misconceptions. For example, misunderstandings often occur when the term "allowable soil pres-

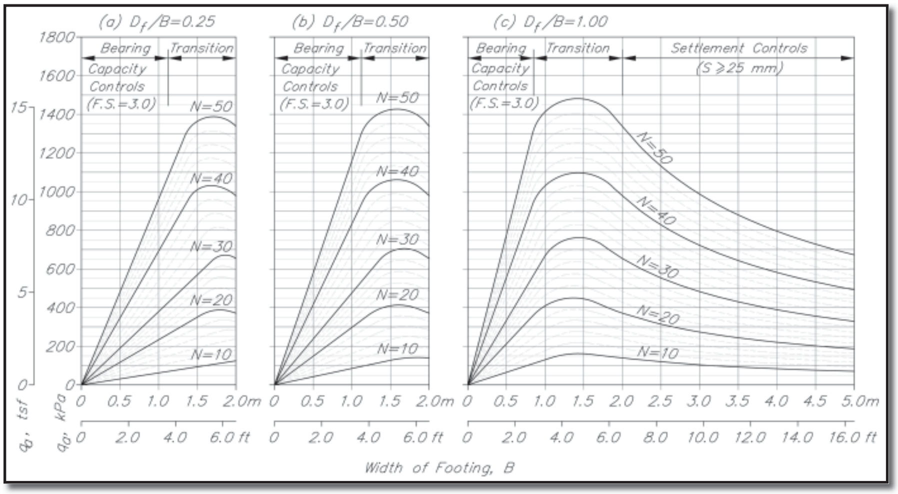

Figure 3: Design Aid for Sizing Shallow Depth Footings on Coarse Sand

sure” is used without reference to whether it has been determined from considerations of deformation (settlement) or ultimate strength (bearing capacity). Such confusion can be avoided if the geotechnical engineer uses such phrases as “allowable soil pressure to limit settlement” to a tolerable amount, and “allowable soil bearing pressure” to indicate pressure associated with safety against outright failure of the foundation.

Analytical Methods of Analysis and Design

Models and procedures for the analysis and design of the structural elements of foundations have evolved over several decades from those based primarily on service loads, assumed elastic behavior, and allowable stresses, to pseudo-plastic assumptions and strength limitations under factored loads. The former is called *allowable stress design* (ASD) or *working stress design* (WSD), while the latter is commonly referred to as *load and resistance factor design* (LRFD). The two procedures are not mutually exclusive, and foundation engineers must use both.

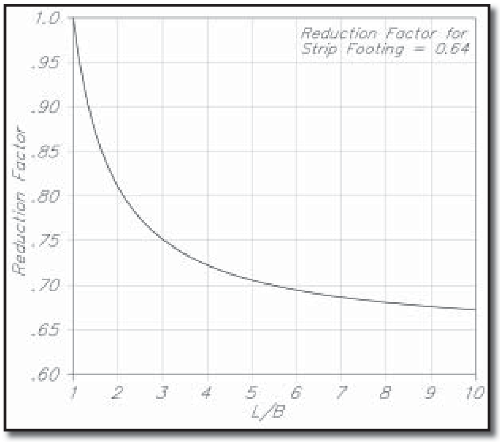

Figure 4: Reduction in q_a from Figure 3 for $B \geq 2.0$m

As discussed previously, regardless of the model used for design, the initial selection of type and proportions of the foundation is usually based on service loads (ASD), because settlement most often governs the design (5). However, if the superstructure loads that the foundation must resist are factored (LRFD), the foundation engineer must also ascertain that the foundation is safe against outright failure under the most probable maximum load. In general, foundations for buildings and bridges will be proven safe for the factored load, except for small or narrow footings supported by loose sand or soft clay. Exceptions may also occur for foundations that are subject to moments and shears due to eccentricity of the loads, or from other moments and shears transmitted to the foundations from columns.

Many structural codes for the superstructures of buildings and bridges have adopted LRFD procedures, although in some instances complete designs by ASD methods are permissible. Presumably, in the future, larger databases of soil tests and field experiences, together with increased usage and recognition of probability reasoning, will lead to greater use of LRFD for foundations. Such development within the profession will necessitate the expansion of effective communication between geotechnical and structural engineers.

Advantages and Limitations of ASD and LRFD for Foundations

Allowable Stress Design (ASD) (WSD) combines into a single, global factor of safety the uncertainties of loads acting on the foundation, and the uncertainty of the resistance of the soil or rock to the load effects. The greatest geotechnical uncertainty lies in the determination of the capacity of the soil or rock to support the foundation. Therefore, in ASD design, safety against failure is expressed in the general form:

$$\Sigma Q \leq R/F$$

where Q is the load effects; R is the resistance of the soil or rock, and F is the global factor of safety.

Along with the considerations of ultimate bearing capacity or other failure modes, ASD also involves evaluation of foundation movements and proportioning of the foundations to limit deformations to acceptable limits. As previously discussed, unlike the design of structures, the deformation criteria is most often the controlling issue in geotechnical designs, and in this case, the factor of safety is selected to limit foundation movements rather than to protect against outright soil rupture or collapse. In this respect, the ASD methodology does not rigorously encourage distinction of allowable soil pressure based on settlement from that based on strength.

The advantages of the ASD method to geotechnical engineers include its familiarity of use, the substantial database of experience available, and the successful application of ASD to many different soil and rock problems. The disadvantages include: (1) less ability to account for variability in loads and resistances, (2) an allowable resistance that is not a direct function of the ultimate strength of the soil or rock, and (3) use of a safety factor that is seldom directly correlated to the probability of failure.

Load and Resistance Factor Design (LRFD) is a form of Limit State Design (LSD) that considers, separately and in turn, each of the conditions under which a structure no longer performs its intended function. Two classes of these conditions (i.e., limit states) are normally considered: (1) the serviceability limit state (SLS) related to function, and (2) the ultimate limit state (ULS) related to safety. The SLS conditions (such as settlement of the foundation) are checked using unfactored loads in a manner essentially identical to that used in the ASD method. The ULS conditions (such as ultimate bearing capacity or sliding failure) are checked using factored loads and factored resistances. The load factors (γ) depend upon the load type, and account for uncertainties in loads and their probability of occurrence. Therefore, the factors are generally greater than 1.0, except when the load acts to reduce the magnitude of the condition being evaluated. The resistance factors (ø) are less than 1.0 and account for the quality of geotechnical data available and method or theoretical model used for calculation of resistance. The LRFD criterion for safety against outright failure is expressed as:

$$ø R \leq \Sigma \gamma\ Q,$$

where R and Q are as defined previously.

The load and resistance factors for geotechnical design are available in various standards and codes; however, special circumstances may necessitate the development of resistance factors by reliability theory, or "fitting" to ASD specifications, if sufficient statistical data are not available.

The advantages of LRFD for geotechnical design are that it separately accounts for variability in both soil resistance and load, has potential of providing more uniform levels of safety for different limit states and foundation types, and provides greater consistency with the design of structural elements. Some of the challenges that remain include: (1) the need for more statistical information to support selection of load and resistance factors, (2) becoming accustomed to new code requirements after years of ASD usage in geotechnical practice, and (3) greater emphasis on observations of performance during construction and the life of structures.

Design Team and Communications

The unity of ASD (WSD) and LRFD must be understood by all members of the team involved with the design of foundations, regardless of the paradigm used for analysis and design. Indeed, such unity and understanding should exist before any foundation borings and soil tests are made, and they should continue throughout the design of the whole structure.

It is important to recognize that when LRFD is used in the design of a foundation, the engineer responsible for this work must know a limiting soil pressure, pile or pier load that attends the factored loads, thus providing safety against outright failure. This is usually a geostructural matter requiring thorough evaluation of the data and respectful communication between the geotechnical, structural and foundation engineers. When ASD is used in design, the engineer must know if the "allowable" pressure or resisting force is based on settlement or bearing capacity (strength) considerations, again, a geostructural matter requiring communication.

Regardless of the design methodology used, it is the responsibility of the structural engineer or foundation engineer to complete the design. Moreover, the structural engineer must assume the responsibility of advising the geotechnical engineer of the requirements or constraints for the foundation (loads, serviceability, etc.) and to actively involve the geotechnical engineer when major changes in the construction or design loadings occur.

Example Design

Before the foundation for a structure can be checked for safety by any analytical method (i.e. ASD or LRFD) the designer must create an initial model. Changes in foundation dimensions, and even the type, may occur as the iterative process advances and the structure loadings become better defined.

As previously discussed, the initial model is assumed to be one that guards against intolerable settlement under working (service) loads (i.e., evaluation of the serviceability limit state of the LRFD methodology). Then, if factored loads are used in superstructure design, the strength of the soil or rock is checked against outright failure when subjected to the factored loading. However, it is important to note that experience has shown that unless the foundation is exceptionally narrow or subjected to eccentric loads, external moments and shears that significantly reduce the effective bearing area, the proportioning for settlement under service loads will provide safety against the factored loads.▪

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Example Design

The following is an example foundation design for a warehouse structure supported by spread footings on sand. This example uses LRFD methods to proportion the warehouse footings, and illustrates design control by both function (settlement) and safety (bearing capacity). The sand charts of *Figure 3* are shown to be a significant aid in the design process, and the importance of communication between the structural and geotechnical engineer is emphasized.

Project Data

A structural engineer is charged with the LRFD-based design of the warehouse shown in *Figure 5*. The site for the warehouse requires excavation into a hillside location and the proposed final grade is 4.42 m (14.5 feet) lower than the existing ground surface. A geotechnical consultant is retained to make test borings at the project site and to provide recommendations for the foundation design. The loads and load factors shown in *Table 1* are provided to the geotechnical consultant for determination of appropriate foundation types and sizes. The structural engineer specifies that the maximum total settlement of any footing should not exceed 25 mm (1.0 inch) in order to minimize differential settlement.

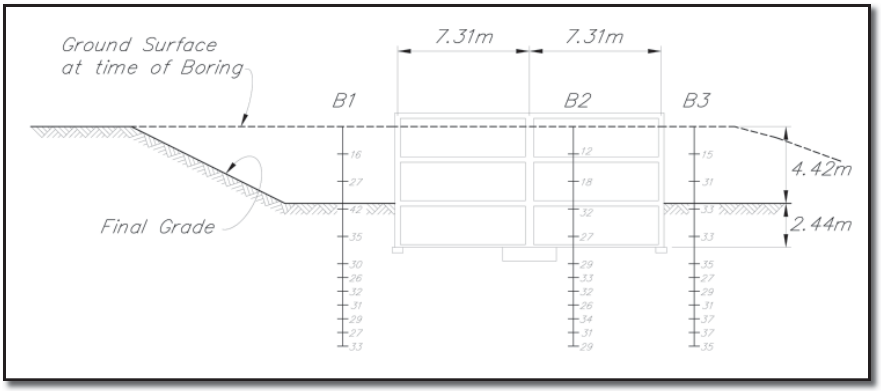

Figure 5: Proposed Warehouse and Test Borings

Obtaining Geotechnical Data

Based on knowledge of site geology and the performance of nearby structures, the geotechnical engineer arranges for test borings using standard penetration test (STP) methods and obtains the N-values shown in *Figure 5*. The borings reveal a relatively uniform deposit of medium dense, coarse sand, and no water table. Based on the granular nature of the subsurface materials and the likelihood that shallow depth footings will be feasible, the geotechnical engineer decides that the WSD design aid shown in *Figure 3* is appropriate for use as the basis for the foundation recommendations. However, it is recognized that the structural engineer will use LRFD methods for the structural design of the foundation, and therefore, the geotechnical recommendations must accommodate both the strength and service limit states of the foundation.

In order to use the relationships of *Figure 3*, the geotechnical engineer's first task is to correct the N-values from the borings for several influences including: (1) borehole conditions of drill rod length and borehole diameter, (2) depth at which the N-value was obtained, and (3) any significant grade changes and/or groundwater level changes that are anticipated during and following construction. The corrected N-values occurring below the proposed foundation level are then compared and the borehole with the lowest average N-value is selected as the basis for design. Judgment is required in selecting the depths over which the N-values are averaged and whether differences in N-values between borings might represent different soil types, modes of deposition or loading history requiring separate analyses. It is also noted that the N-values used with *Figure 3* may require different corrections depending on whether the foundation is controlled by bearing capacity or by settlement. For this example, the geotechnical engineer has determined that the corrected N-values in test boring B1 represent the lowest average N-values and should serve as the design basis.

Proportioning the Footings

The geotechnical engineer uses the corrected N-values from B1 and the service loads in *Table 1* (QDL + QLL + QSL) to determine the footing widths required for both the interior footings and wall footings. This is an iterative process that requires using *Figure 3* to select compatible values of q_a and B in conjunction with a corrected average N-value for a depth below the footing that is a function of B. Also, the appropriate D_f/B curves must be used for footings less than 2.0 m (6.6 feet) wide, and adjustment in the q_a value is required for non-square footings ≥ 2.0 m (6.6 feet) in width (see *Figure 4*). The final iterations for the example warehouse provide the results given in *Table 2*.

The q_a values in *Figure 3* are based on a reasonable probability that the footing will not settle more than 25 mm (1.0 inch) and that differential settlements between footings of the same or smaller widths at the same soil pressure will not exceed about 16 mm (¾ inch). Therefore, the structural engineer's specification for differential settlements is satisfied. Since the q_a values in *Figure 3* are based on a normally consolidated sand deposit, some increase in q_a for the interior footings could be justified on the basis of the hillside excavation to achieve final grade (i.e., the sand beneath the footings is preconsolidated by virtue of hillside overburden removed). However, it is the judgment of the geotechnical engineer to disregard the benefits of the preconsolidation since the increased q_a would not significantly reduce the footing sizes and such increase could potentially be offset by construction disturbances of the footing subgrades.

LRFD Considerations

The structural engineer, using LRFD methods, applies factored loads to the footing sizes given in *Table 2* and uses the resulting pressures at the base of the footings as reactions to determine the required flexural and shear strengths of the footings. Additionally, the calculated reactions at the base of the footings due to the factored loads must not exceed the bearing resistance of the soil at the ultimate limit state. This is expressed in terms of soil pressure as follows:

$\text{ø}\, q_{ult} \geq \Sigma\, \gamma\, Qi / A$,

Where ø = resistance factor

q_{ult} = ultimate bearing pressure of soil

γ = load factor

Qi = load effects (QDL + QLL + QSL)

A = area of the footing

The geotechnical engineer should provide ø q_{ult} to the structural engineer in order that the safety of the soil against bearing capacity failure can be assured when subjected to factored load. The ultimate bearing pressure of the soil can be obtained from *Figure 3* by selecting the q_a value along the straight-line portion of the curve (or extension

Table 1. Warehouse Loads

Location	Load Type	Service Load, Q	Load Factor, γ	Factored Load, γQ
Interior Column	Dead Load (DL)	560 kN	1.2	672 kN
	Live Load (LL)	1609 kN	1.6	2574 kN
	Snow Load (SL)	64 kN	1.0	64 kN
	DL+LL+SL	2233 kN (502 kips)		3310 kN (744 kips)
Exterior Wall	Dead Load (DL)	76 kN/m	1.2	91 kN/m
	Live Load (LL)	112 kN/m	1.6	179 kN/m
	Snow Load (SL)	4 kN/m	1.0	4 kN/m
	DL+LL+SL	192 kN/m (13.2 kips/ft)		274 kN/m (18.8 kips/ft)
Basement Slab	Dead Load (DL)	4 kPa	1.2	5 kPa
	Live Load (LL)	14 kPa	1.6	22 kPa
	DL+LL	18kPa (0.38 ksf)		27kPa (0.57 ksf)

there of) that is associated with the appropriate D_f/B value, N-value and footing width B, and then multiplying the selected q_a value by the factor of safety of 3.0. These values are 2700 kPa (56.7 ksf) and 900 kPa (18.9 ksf) for the interior footing and wall footing, respectively. The resistance factor ø can be obtained by calibration through fitting with the WSD methodology, calibration using reliability theory, or a combination of calibration and judgment. The steps for calibration with WSD are as follows:

- LRFD criterion is given by $øR \geq \Sigma\gamma Q$
- WSD criterion is given by $\Sigma Q \leq R/F$ or $R = \Sigma Q \cdot F$
- Using substitution, $ø = \Sigma\gamma Q \, / \, \Sigma Q \cdot F$
- ø [interior footing] = (3424 kN) / (3.0 · 2309 kN) = 0.49
- ø [wall footing] = (293 kN/m) / (3.0 · 204 kN/m) = 0.48

For this example, the geotechnical engineer has used calibration with WSD and judgment to determine that ø = 0.45 is an appropriate recommendation.

Table 2. Results of Geotechnical Analyses for Footings

Footing Location	Corr. Avg. N-Value	$q_a^{(1)}$	Width, B$^{(2)}$ [Actual Pressure]$^{(3)}$	Design Control for Foundation
Interior Column	28	600 kPa$^{(4)}$ (12.6 ksf)	2.0 m (6.6 ft.) Sq. [594 kPa (12.5 ksf)]	Settlement Δ = 25 mm (1.0 in.)
Exterior Wall	25	300 kPa$^{(4)}$ (6.3 ksf)	0.75 m (2.5 ft.) Strip [272 kPa (5.7 ksf)]	Bearing Capacity [F.S. = 3.0]

(1) Determined from Figure 3
(2) Determined from Figure 3 to nearest 0.25 m (0.8 ft.)
(3) $(Q_{DL} + Q_{LL} + Q_{SL})$ / Footing Area [net pressure for exterior footing]
(4) The estimated $D_f/B = 0.5$

Final Geotechnical Report

The geotechnical engineer prepares a report for the structural engineer that provides the recommendations listed in *Table 3*. The report clearly identifies the allowable pressures associated with service loads, the basis for the allowable pressures under service loads, and the factored resistance of the soil to be used with factored loads. The report should request that the geotechnical engineer be notified of any significant changes in the grading of the site or in the column loadings so that adjustments to the recommendations can be made prior to the structural engineer's final design for the foundation. The structural engineer should also involve the geotechnical consultant during the construction phase if changed conditions in the subsoils are encountered.▪

Table 3. Geotechnical Report Recommendations$^{(1)}$

Foundation Location	Recommended$^{(2)}$ Foundation Type and Size	$q_a^{(3)}$ [kPa]	Basis for Determination of q_a and Footing Sizes	Factored$^{(4)}$ Resistance [$øq_{ult}$]
Interior Column	Spread Footing 2.0 m x 2.0 m (6.6 ft x 6.6 ft.)	600 (12.6 ksf)	Limit Settlement Total ≤ 25 mm (1.0 in.) Differential ≤ 16 mm (3/4 in.)	1215 kPa$^{(5)}$ (25.5 ksf)
Exterior Wall	Strip Footing 0.75 m wide (2.5 ft.wide)	300 (6.3 ksf)	Bearing Capacity Factor of Safety = 3.0)	405 kPa$^{(5)}$ (8.5 ksf)

(1) *Based on proposed site grading and foundation design loadings provided. Significant changes in grading or loadings including changed field conditions may require adjustments to recommendations.*
(2) *Recommended size is based on concentric loading of footing. Eccentric loadings may require increased size.*
(3) *Allowable soil pressure under service loads to limit settlement or allowable soil bearing pressure under service loads.*
(4) *Strength Limit State for bearing capacity.*
(5) *Resistance factor Ø = 0.45.*