Axial Geotechnical Resistance Design of Driven Piles

This Design Guide has been developed to provide geotechnical and structural engineers with the most recent methods and procedures required by the department to determine the nominal and factored axial geotechnical resistance of a pile to help ensure cost effective foundation design and construction.

The Geotechnical Engineer must evaluate the subsurface soil/rock profile, develop pile design table(s) for each substructure, and provide them to the structure designer in the Structure Geotechnical Report (SGR). Each table shall contain a series of Nominal Required Bearing (R_N) values, the corresponding Factored Resistances Available (R_F) for design, and the Estimated Pile Lengths, for all feasible pile types. The number of pile types and sizes covered as well as the range of R_N values provided must be large enough to allow the designer sufficient selection to determine the most economical pile type, size and layout such that the factored loading from the LRFD Strength Limit State and Extreme Event Load Combinations is $\leq R_F$. The corresponding R_N provided on the plans will be obtained during driving as indicated by dynamic formula or other nominal pile resistance field verification method. To develop the pile design tables, the geotechnical engineer shall use the IDOT static method of estimating this nominal pile resistance during driving and provide these values in the SGR as feasible R_N values which can be specified by the designer.

The original IDOT static method was developed over 40 years ago to correspond to the allowable pile resistance indicated during driving by the ENR dynamic formula. With the change to LRFD and FHWA Gates formula in 2007, the department completed an extensive research study with Dr. James Long of the University of Illinois at Urbana-Champaign to evaluate several static methods and dynamic formulas to determine the most accurate method for estimating pile lengths and resistances for the soils, piles, and hammers common to our State. The results indicated that the IDOT static method (with the new Pile Type Correction Factors) was more accurate than all other static estimating methods studied, including the program "DRIVEN". It was also found to correspond closest to the most accurate dynamic formula studied which was the WSDOT formula, developed by Tony Allen of the Washington State DOT in 2005. Based on this research, the WSDOT formula will replace the FHWA Gates formula as the standard method of construction verification and the IDOT static method, described below, shall be used to develop the SGR pile design tables.

<u>Nominal Required Bearing</u> (R_N) represents the nominal pile resistance expected at any specific length during driving that can be specified by the Designer. It must be calculated at various estimated lengths and is the first step in developing the pile design table.

In the case of displacement piles (such as metal shell, precast, and timber piles), R_N shall be calculated as the sum of the side and tip resistance as follows:

$$R_N = (F_S q_S A_{SA} + F_P q_P A_P)*(I_G)$$

Where the nominal side resistance ($F_S q_S A_{SA}$) is the product of the following:

F_S = The pile type correction factor for side resistance (0.758 for displacement piles in cohesionless soils & 1.174 for displacement piles in cohesive soils)

q_S = The nominal unit side resistance

A_{SA} = The surface area of the pile

And the nominal tip resistance ($F_P q_P A_P$) is the product of the following:

F_P = The pile type correction factor for tip resistance (0.758 for displacement piles in cohesionless soils & 1.174 for displacement piles in cohesive soils)

q_P = The nominal unit tip resistance

A_P = The tip area of the pile

In the case of non-displacement piles (such as steel H piles), the R_N shall be taken as the lesser of the following:

The fully "plugged" side and tip resistance defined as:

$$R_N = (F_S q_S A_{SAp} + F_P q_P A_{Pp})*(I_G)$$

And the fully "unplugged" side and tip resistance defined as:

$$R_N = (F_S q_S A_{SAu} + F_P q_P A_{Pu})*(I_G)$$

Where:

F_S = The pile type correction factor for side resistance (0.15 for non-displacement piles in cohesionless soils, 0.75 for non-displacement piles in cohesive soils & 1.0 for non-displacement piles in rock)

F_P = The pile type correction factor for tip resistance (0.3 for non-displacement piles in cohesionless soils, 1.5 for non-displacement piles in cohesive soils & 1.0 for non-displacement piles in rock)

A_{SAu} = The unplugged surface area = (4 x flange width + 2 x member depth) x pile length

A_{SAp} = The plugged surface area = (2 x flange width + 2 x member depth) x pile length

A_{Pu} = The cross-sectional area of steel member

A_{Pp} = The flange width x member depth

In the above equations, the term I_G is the bias factor ratio (equal to 1.04) and is discussed in further detail later in the design guide. The Nominal Unit Side Resistance (q_S) and Nominal Unit Tip Resistance (q_P) shall be calculated as follows:

- *Nominal Unit Side Resistance* (q_S) of **granular** soils is computed using the equations below:

   For Hard Till, the equations below are used for the range of N values indicated:

   $$q_s = 0.07N \qquad\qquad \text{for } N < 30$$
   $$q_s = 0.00136N^2 - 0.00888N + 1.13 \qquad\qquad \text{for } N \geq 30$$

   Very Fine Silty Sand, the equations below are used for the range of N values indicated:

   $$q_s = 0.1N \qquad\qquad \text{for } N < 30$$
   $$q_s = 42.58\,e^{\left[\frac{(N-175.05)^2}{-7944}\right]} \qquad\qquad \text{for } 30 \leq N < 74$$
   $$q_s = 0.297N - 10.2 \qquad\qquad \text{for } N \geq 74$$

   Fine Sand, the equations below are used for the range of N values indicated:

   $$q_s = 0.11N \qquad\qquad \text{for } N < 30$$
   $$q_s = 0.3256N + \frac{182}{N} - 12.51 \qquad\qquad \text{for } 30 \leq N < 66$$
   $$q_s = 0.329N - 9.91 \qquad\qquad \text{for } N \geq 66$$

   Medium Sand, the equations below are used for the range of N values indicated:

   $$q_s = 0.117N \qquad\qquad \text{for } N < 26$$
   $$q_s = 0.00404N^2 - 0.0697N + 2.13 \qquad\qquad \text{for } 26 \leq N < 55$$
   $$q_s = 0.356N - 9.1 \qquad\qquad \text{for } N \geq 55$$

   Clean Coarse Sand, the equations below are used for the range of N values indicated:

   $$q_s = 0.128N \qquad\qquad \text{for } N < 24$$
   $$q_s = 0.00468N^2 - 0.0693N + 2.05 \qquad\qquad \text{for } 24 \leq N < 50$$

$$q_s = 0.394N - 9.42 \qquad\qquad \text{for } N \geq 50$$

Sandy Gravel, the equations below are used for the range of N values indicated:

$$q_s = 0.15N \qquad\qquad \text{for } N < 20$$
$$q_s = 0.00861N^2 - 0.217N + 3.91 \qquad\qquad \text{for } 20 \leq N < 40$$
$$q_s = 0.6N - 15.0 \qquad\qquad \text{for } N \geq 40$$

- *Nominal Unit Side Resistance* (q_S) of **cohesive soils**, shall be calculated using the equations below for the range of Q_U values indicated:

$$q_s = \frac{-1}{2500}Q_u^3 - 0.177Q_u^2 + 1.09Q_u \qquad\qquad \text{for } Q_u \leq 1.5 \text{ tsf}$$
$$q_s = 0.0495Q_u^3 - 0.347Q_u^2 + 1.278Q_u - 0.068 \qquad \text{for } 1.5 \text{ tsf} < Q_u < 2 \text{ tsf}$$
$$q_s = 0.470Q_u + 0.555 \qquad\qquad \text{for } 2 \text{ tsf} \leq Q_u < 4.5 \text{ tsf}$$
$$q_s = 2.67 \text{ ksf} \qquad\qquad \text{for } 4.5 \text{ tsf} \leq Q_u$$

Where Q_U = Unconfined compression strength of the soil in tsf.

Note that Q_U is input in tsf and q_S is output in ksf.

If $Q_U > 3$ tsf and $N > 30$, treat as granular and use Hard Till equations.

- *Nominal Unit Side Resistance* (q_S) of **rock**, shall be calculated using the equations below for the type of rock encountered:

$$q_S = 12.0 \text{ ksf.} \qquad\qquad \text{for Shale}$$
$$q_S = 20.0 \text{ ksf.} \qquad\qquad \text{for Sandstone}$$
$$q_S = 24.0 \text{ ksf.} \qquad\qquad \text{for Limestone/Dolomite}$$

Note that actual pile penetration into rock is related to several factors including rock strength, degree of weathering, hammer energy and pile strength. The IDOT Static Method represents these by rock type, pile size, and nominal required bearing. The above empirical side resistance values, when used with the soil side resistance and rock tip resistance, provide a conservatively accurate representation of pile penetration into rock and thus total estimated pile length.

- *Nominal Unit Tip Resistance* (q_P) of **granular soils,** shall be calculated as follows:

$$q_p = \frac{0.8\,N\,D_b}{D} \leq q_\ell$$

Where:

$$q_\ell = 8N \text{ (for sands \& gravel)} \quad \text{or} \quad 6N \text{ (for fine silty sand \& hard till)}$$

D   = Pile diameter or width (ft.)

D_b = Depth of penetration into soil (ft.)

N   = Field measured SPT blow count (blows/ft.)

- *Nominal Unit Tip Resistance* (q_P) of **cohesive soils,** shall be calculated as follows:

$$q_P = 9\ Q_U$$

Note that Q_U is input in tsf. and q_P is output in ksf.

- *Nominal Unit Tip Resistance* (q_P) of **rock,** shall be calculated using the equations below for the type of rock encountered:

q_P = 120.0 ksf.	for Shale
q_P = 200.0 ksf.	for Sandstone
q_P = 240.0 ksf.	for Limestone/Dolomite

Note that actual pile penetration into rock is related to several factors including rock strength, degree of weathering, hammer energy and pile strength. The IDOT Static Method represents these by rock type, pile size, and nominal required bearing. The above empirical tip resistance values, when used with the soil side resistance and rock side resistance, provide a conservatively accurate representation of pile penetration into rock and thus total estimated pile length.

<u>Maximum Nominal Required Bearing</u> ($R_{N\ MAX}$) is the maximum R_N value that can be specified on the plans to avoid dynamic stresses during driving which would cause damage to the pile. The value may be determined by use of a wave equation analysis considering the site specific soils and driving equipment to permit more cost effective designs. In the absence of a site specific drivability analysis, the $R_{N\ MAX}$ may be conservatively approximated using the following empirical relationships:

- Metal Shell Piles: $R_{N\ MAX} = 0.85 \times F_Y A_S$

Where: F_Y = yield strength of the steel shell (45 ksi)

          A_S = the steel shell cross-sectional area (in.^{2})

- Steel Piles: $R_{N\ MAX} = 0.54 \times F_Y A_S$

    Where: F_Y = yield strength of the steel (50 ksi)

                                           A_S = the steel cross-sectional area (in.^{2})

- Precast Piles: $R_{N\ MAX} = 0.3 \times f'_c \times A_g$

    Where: f'_c = compressive strength of concrete (4.5 or 5 ksi)

                                           A_g = gross concrete cross sectional area of pile (in.^{2})

- Timber Piles: $R_{N\ MAX} = 0.5 \times F_{co} \times A_P$

    Where: F_{co} = resistance in compression parallel to grain (2.7 ksi)

                                           A_P = cross-sectional timber area at top of pile (in.^{2})

<u>Factored Resistance Available</u> (R_F) represents the net long term axial factored geotechnical resistance available at the top of the pile to support factored structure loadings. It accounts for losses in geotechnical resistance that occurs after driving due to scour, downdrag (DD_R), or liquefaction (Liq.), resistance required to support downdrag loads (DD_L) and reflects the resistance factor used to verify R_N. R_F shall be calculated using the following equation:

$$R_F = R_N(\phi_G) - (DD_R + Scour + Liq.) \times (\phi_G) \times (I_G) - DD_L \times (\gamma_p) \times (\lambda_{IS})$$

Where:

       Scour = nominal side resistance (loss) of soil above the design scour elevation.

       Liq.   = nominal side resistance (loss) of soil within liquefiable layers.

       DD_R = nominal side resistance (loss) of soil expected to settle > 0.4 in.

       DD_L = nominal side resistance (load) of soil expected to settle > 0.4 in.

       ϕ_G = the Geotechnical Resistance Factor for the construction verification of R_N

       I_G = the Bias Factor Ratio relating the IDOT static method to the construction verification method used.

       γ_p = the DD_L Load Factor for the downdrag soil loading on the pile

       λ_{IS} = the Bias Factor related to the IDOT static method

Applying the geotechnical resistance factor (ϕ_G) to the geotechnical losses may appear unconservative. However, AASHTO LRFD Article 10.7.3.7 requires the factored loads (R_F +

$\gamma_p DD_L$) be ≤ the factored resistance below the downdrag layers. Thus, the pile must be driven to a R_N equal to the nominal downdrag resistance (DD_R) to install the pile through the downdrag layer plus ($R_F + \gamma_p DD_L)/\phi_G$ which results in both the geotechnical losses and R_N being multiplied by ϕ_G.

The nominal values of the downdrag (DD_R and DD_L), Scour and Liquefaction (Liq.) shall be calculated using the IDOT static method side resistance equations provided above and as described below.

- *Downdrag* is considered twice to represent the loss in side resistance (DD_R) and again to account for the added loading (DD_L) applied to the pile. The LRFD load groups specify that the portion of downdrag which applies a loading to the pile be included with loadings from other applicable sources. However, it is IDOT's policy to require that the downdrag loading (DD_L) and downdrag reduction in resistance (DD_R) for a pile be taken into account by the geotechnical engineer so it can be incorporated in the SGR pile design tables. Thus they should not be included by the structural engineer in calculating the factored loadings.

- *Scour* protection is provided by accounting for the loss in side resistance of soil layers above the design scour elevation in determining the R_F available to designers. The Scour term shall be taken as zero when calculating the R_F to resist Extreme Event I seismic loadings.

- *Liquefaction* is the loss of side resistance in layers expected to liquefy (Liq.) due to the design seismic event. Since liquefied soil of sufficient thickness consolidates, any non-liquefiable layers above such soils will settle and produce downdrag effects which must also be taken into account. Thus, in addition to Liq., losses from DD_R and DD_L for the layers above the liquefied soils shall be calculated and included in the R_F equation. However Liq. and downdrag caused by liquefaction shall only be considered when calculating the R_F to resist Extreme Event I seismic loadings.

The values of geotechnical losses (Scour, DD_R, DD_L, and Liq.) for non-displacement steel H-piles shall be calculated using the surface area assumption, (A_{SAp} representing "plugged" conditions), regardless of whether the controlling value of R_N used "plugged" or "unplugged" side resistance.

Values for the Geotechnical Resistance Factor, Bias Factor and Bias Factor Ratio, and DD_L Load Factor, shall be selected as follows:

- *The Geotechnical Resistance Factor* (ϕ_G) shall be selected to represent the reliability of the construction method used to verify that the R_N has been developed. Our analysis using both national and local driving records and load tests indicated a ϕ_G of 0.55 should be used to compute R_F if the WSDOT formula is specified for construction verification.   When more accurate construction verification methods are proposed, such as with static load test or a Pile Driving Analyzer (PDA), the resistance factor used may be increased to the values provided in the AASHTO specifications.

- *The Bias Factor* (λ_{IS}) is a statistical parameter that reflects the general tendency of the IDOT static method to over or under-predict the nominal pile resistance when compared to the results of static pile load tests. The IDOT static method contains revisions that improve the bias of the method, however it is typically not possible to entirely eliminate all bias. Research indicates that the IDOT static method has a bias factor of 1.09 indicating that the method has a tendency to under-predict pile resistances.   When using the IDOT static method to estimate downdrag effects, DD_L shall be multiplied by a λ_{IS} factor of 1.09.

- *The Bias Factor Ratio* (I_G), shall be included in the calculation for the nominal pile resistance (R_N) and also be applied to the geotechnical losses (Scour, DD_R, and Liq.) to account for differences in bias between the method used to estimate these values (using the IDOT static method) and the construction method used to verify the R_N (typically the WSDOT formula). Similar to that previously described for the IDOT static method, research indicated that the WSDOT formula used for construction verification has a bias factor of 1.05. The ϕ_G of 0.55 that is specified for computing R_F when the WSDOT formula is being specified for construction verification is a function of the statistical parameters resulting from a comparison of the WSDOT formula results and static load tests.   Since the ϕ_G indicated above is based on statistical variables relative to the WSDOT formula, I_G is being applied to the results from the IDOT static method in an effort to try and further equate the two methods. I_G is equal to 1.04 and is the ratio of the bias factors for the two methods (the bias factor for the IDOT static method divided by the bias factor for the WSDOT formula).

- *The DD_L Load Factor* (γ_p) shall be equal to 1.05 for DD_L caused by cohesive or granular soil layers for piles in compression. For cohesive soil layers, it is believed that the research results and enhancements employed with the IDOT static method offers a reliability closer to that associated with the λ method of estimating side resistances contained in the AASHTO LRFD code. As such, the λ method load factor reflected in LRFD Table 3.4.1-2 is specified for use with cohesive soil layers. The side resistances estimated by the IDOT static method for

cohesionless soils is considered to be more consistent with an effective stress analysis (which is used with the above mentioned λ method) and long term drained conditions. Subsequently, the same load factor has been chosen for use with granular soil layers for piles in compression.

γ_p shall be equal to 0.30 for DD_L caused by cohesive or granular soil layers when the pile is required to provide pullout or uplift resistance.

If it becomes clear during the planning process that earthquake forces may govern the pile design, the SGR pile tables should include both the R_F to support Extreme Event I Limit State loadings by setting the ϕ_G to 1.0, as well as the R_F to support Strength Limit State loadings by setting ϕ_G to 0.55.

In load cases requiring piles to provide uplift resistance, the factored tension or pullout resistance of the pile shall be determined using the nominal side resistance equations provided above and applying a geotechnical resistance factor (ϕ_G) of 0.20 for uplift under Strength Limit State loadings and 0.8 for uplift under Extreme Event I Limit State loadings. For non-displacement steel H-piles, pullout resistance shall be computed using the surface area assumption (A_{SAp}) for a "plugged" condition only. This calculation will provide the minimum tip elevation which must be specified on the plans ensure pullout resistance.

Estimated Pile Lengths shall be provided in the pile design tables corresponding to the R_N and R_F values computed using the equations above. Since calculating these values requires assumption of the pile length, the procedures and guidance provided below shall be used in determining how these lengths should be selected and which should be provided in the pile design tables in the SGR:

- The geotechnical engineer should contact the structural engineer to obtain preliminary substructure locations and their total factored vertical loading as well as the ground surface, pile cutoff, and bottom of footing/substructure excavation elevations.

- The geotechnical engineer shall evaluate the subsurface soil and rock boring data to develop the profile of pile design parameters (N and Qu) at each substructure.

- Compute the relationship between R_N and pile penetration expected as the pile is driven from the footing/substructure excavation elevation through the various soil design profile for each possible pile type at every substructure. This is typically done by breaking up the soil profile into smaller (2.5' to 7.5' thick) layers and selecting pile lengths corresponding to the bottom of each layer. This provides the R_N consisting of the cumulative side resistance of all layers above the

bottom of the layer in question and the tip resistance of the layer just below the bottom of the layer in question.

- Determine the maximum nominal required bearing feasible to specify without causing damage to the pile.   This is most often done using the empirical relationships provided above for approximating $R_{N\ MAX}$ but using of wave equations analysis may also be used to determine if higher values of R_N can be provided in the pile design tables.

- Use the total vertical factored substructure loadings divided by the maximum and minimum pile spacing to provide an initial estimate of the range of R_F to provide in the tables.

- Discuss this initial range of R_F and the corresponding estimated lengths with the structural engineer to help finalize the range to be included in the SGR. It is preferred that the tables contain too many, rather than too few values to allow the designer the most data upon which to determine the most economical pile type and foundation design layout.

- It is important to again verify the preliminary information and adjust the pile design tables if any elevations or loads have changed.   The estimated pile length contained in the design tables (and shown on the plans) must include the portions of the pile which will be incorporated in the substructure, footing, and pile encasement. Thus, the ground surface adjacent to the pile during driving and proposed pile cutoff elevations must be accurately determined.