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Implementation of the AASHTO LRFD Code in Geotechnical Design—Piles

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16. Abstract

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The objectives of presented study were to review the available pile capacity analysis methods and develop a user-friendly and possibly more accurate formula. In addition, a procedure was developed for comparison of the pile design and the calculation of the resistance factors.

The following methods of determining the load carrying capacity of a pile were compared: Static Load Test, CAPWAP, Wave equation, Gates formula, and Nebraska modified ENR formula. A formula has been proposed for the calculation of the pile capacity that is in good agreement with the CAPWAP results.

The resistance factor has been calculated based on the assumption that the LRFD AASHTO Code and the AASHTO Standard Specifications result in the same design of a pile. The calculations were carried out for a representative number of design situations (pile material, pile type and soil conditions).

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ABSTRACT

The LRFD AASHTO code (2007) includes substantial changes compared to the AASHTO Standard Specifications (2002). Therefore, State DOT's have to review their current practice and, if needed, develop a new approach that is consistent with the LRFD philosophy. Load and resistance factors in LRFD code were determined in the reliability-based calibration process. However, this calibration was limited to the superstructure. The resistance factors for the piles were mostly based on engineering judgment. Therefore, there is a need for verification of a pile design provisions.

The objectives of presented study were to review the available pile capacity analysis methods and develop a user-friendly and possibly more accurate formula. In addition, a procedure was developed for comparison of the pile design and the calculation of the resistance factors.

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1. BACKGROUND

The Load and Resistance Factor Design of the American Association of Highway and Transportation Officials (LRFD AASHTO) (2007) includes considerable changes as compared to the AASHTO Standard Specifications (2002), particularly in regard to the design provisions for bridge substructures, including piles. In the AASHTO Standard Specifications, foundation design is based on allowable stress design (ASD), with a design formula that can be summarized as follows,

$$DL + LL \leq P_n / SF \tag{1}$$

where DL is dead load per pile, LL is live load per pile, SF is safety factor, and P_n is nominal pile capacity.

In addition to DL and LL, there can be other load components. The design loads are specified in the code. Live load per pile is determined by applying HS20 load (AASHTO 2002). Nebraska Department of Roads (NDOR) uses HS25 live load, which is 25% larger than HS20.

There are several methods available for calculation of the nominal pile capacity. They vary with regard to accuracy, required input data, and computational effort. For the Engineering-News (ENR)-based methods, the safety factor is included in the formula for pile capacity. In the allowable stress design, the safety margin is determined mostly by SF; and SF can vary depending on the method of determining the pile capacity.

In LRFD AASHTO (2007), the design formula can be summarized as:

$$1.25\ DL + 1.5\ DW + 1.75\ LL \leq \phi\ P_n \tag{2}$$

where loads are multiplied by load factors; and pile capacity is multiplied by the resistance factor, ϕ. DW is dead load per pile due to wearing surface, and LL is live load per pile calculated by applying HL-93 load (AASHTO 2007). Nominal pile capacity can be calculated using the same methods as used in the allowable stress design. However, in this case, the safety margin is included in the load factors and resistance factor.

The resistance factors were calculated in the calibration process (Nowak 1999, Allen et al. 2005). However, the calibration was limited to bridge superstructures. Resistance factors for bridge substructures in the AASHTO LRFD (2007) were selected mainly based on engineering judgment. Therefore, the objective of this paper is to determine the values of

resistance factors for piles that would result in the same design as the allowable stress design (Eq. 1). The methods for calculating the nominal pile capacity are reviewed and compared using the available field test data. The intent is to select or develop a practical formula that can improve the design of piles using LRFD code.

This study will facilitate the implementation of the AASHTO LRFD code in the geotechnical design, and this report will help the reader to better understand the new code requirements.

2. OBJECTIVE

The objective of this project is to facilitate the implementation of the AASHTO LRFD Code (2007) in the NDOR design practice, focusing on the design of piles. The new code provisions are very different than AASHTO Standard Specifications (2002). The major differences include design philosophy, concept of limit states, and design loads. Considerable differences are also found in the geotechnical design.

This project reviews the current NDOR practice in designing piles, identifies the differences between current practice and AASHTO LRFD code provisions, and recommends changes in the NDOR practice. The proposed changes are demonstrated on representative pile design cases including:

- H steel piles in fine grain
- H steel piles on rock
- Pipe piles in sand
- Pipe piles in fine grain
- Concrete piles in granular soil

3. CURRENT METHODS TO PREDICT PILE CAPACITY

3.1 General

The axial resistance of a pile can be determined using one of the available methods including:

- Engineering-News (ENR) formula
- Federal Highway (FHWA) Gates formula
- Wave Equation
- Modified ENR formula (Nebraska Department of Roads)
- Case Pile Wave Analysis Program (CAPWAP)
- Static test

The static test provides the most accurate results, but it is difficult and costly to perform. It requires extensive field testing procedures, advanced equipment, and highly qualified staff. The CAPWAP is somewhat easier to apply and less costly, but it provides less accurate results. Other methods provide a formula for pile capacity as a function of two or more of the following parameters: type of pile, type of soil, weight of pile, hammer characteristics, developed hammer energy, and blow count.

3.2 Static load test

A static load test is a reliable method of determining the ultimate pile capacity. Static load test equipment consists of a reaction frame, load cell, hydraulic ram, and other components. The reaction frame can consist of a large load, such as concrete blocks, piles designed for uplift, or a combination of the two. The test pile is incrementally loaded to failure, and the deformations on the top of a pile are recorded at each load step. The disadvantage of the static load test is the large reaction load; moreover, the reaction piles may fail in the uplift before failure of the test pile.

3.3 CAPWAP, Pile Driving Analyzer

Pile Driving Analyzer (PDA) is a method to measure the dynamic response of a pile during driving. The data obtained directly on site by PDA can be processed using the Case Pile Wave Analysis Program (CAPWAP). Another program that is comparable to CAPWAP is TEPWAP (Paikowsky, 1990). A signal matching analysis, such as the CAPWAP,

correlates data from PDA readings with wave theory to obtain results, such as simulation of static load tests. In this paper, the use of the acronym "CAPWAP" is intended to represent the data that was collected with the PDA and processed with the the CAPWAP.

3.4 Wave Equation Analysis

The wave equation method is a numerical procedure developed about 50 years ago by E.A. Smith (1960). Pile capacity is calculated as a function of time, blow count, and hammer stroke. This method has some limitations, such as the soil restrictions or the efficiency of the hammer. However, it is the only method that can predict driving stresses during driving of a pile. The theoretical model used in this analysis takes into account, as parameters, that the real pile is discretized and analyzed using viscoelastic-plastic theory. The soil reaction for one segment of a pile is presented as a set of a dashpots and springs. The segments of the pile and the springs between the segments are modeled as one dimensional. The model developed by Smith was used as a basis for software, such as GRLWEAP, which simulates driving of the pile.

3.5 ENR Formula

The ENR formula was developed over 100 years ago; and it is based on the correlation between the hammer energy and resistance of the pile:

$$R_{ndr} = \frac{12E_d}{(s+0.1)} \tag{3}$$

where R_{ndr} is the nominal pile resistance measured during pile driving in kips, E_d is the developed hammer energy in ft-kips, and s is the pile permanent set in inches per blow.

3.6 AASHTO Gates formula

Similar to the ENR formula, the Gates formula is based on energy approach. This method was developed by Marvin Gates (1957). The basic assumption is that the pile resistance is directly proportional to the square root of the net hammer energy. The Gates formula has been recommended for use by the FHWA. With the usage of this formula, the ultimate pile capacity can be calculated. In such an analysis, the FHWA recommends the use of a factor of safety of 3.5. According to the AASHTO Code (2007), the nominal pile resistance using the Gates formula is as follows:

$$R_{ndr} = 1.75\sqrt{E_d}\log_{10}(10N_b) - 100 \tag{4}$$

where R_{ndr} is the nominal pile resistance measured during pile driving in kips, E_d is the developed hammer energy in ft-lbs, and N_b is the number of hammer blows for 1.0 inch of pile permanent set in blows/in.

3.7 Nebraska Modified ENR Formula

According to the NDOR Standard Specifications for Highway Construction (2007), the bearing capacity of the piles can be calculated from the following formulas:

$$P = \frac{3.0E}{(S+0.1)}\frac{W}{W+M} \tag{5}$$

for driving steel, steel shell, and pipe piles with diesel hammers and

$$P = \frac{7.0E}{(S+0.1)}\frac{W}{W+M} \tag{6}$$

for driving concrete bearing pile with diesel hammers, where P is safe load, in tons, W is the weight of the ram, in tons, M is the weight of pile and driving cap, in tons, S is the average penetration, in inches, of the pile per blow for the last ten blows for steam or diesel hammers, and E is the energy per blow in foot-tons. Those formulas have a built-in safety factor. In NDOR design practice, the safety factor is equal to 2.

4. RESISTANCE FACTOR FOR LRFD

4.1 Nominal Axial Pile Resistance

The resistance factor, ϕ, is to be determined following the formal reliability-based calibration procedure (Nowak 1999 and Allen et al. 2005). However, this is beyond the scope of this project; and, therefore, ϕ is calculated by using Eq. 1 and Eq. 2, so that the LRFD design and AASHTO Standard Specifications result in the same nominal pile capacity. For a given set of load values, the required nominal load capacity of the pile, P_n, can be calculated from Eq.1. Assuming that the required pile resistance using the LRFD approach will result in the same pile capacity as in the allowable stress design, the resistance factor can be calculated as follows:

$$\phi = (1.25\ DL + 1.5\ DW + 1.75\ LL) / P_n \tag{7}$$

where P_n is calculated from Eq. 1

$$P_n = (DL + LL)\ (SF) \tag{8}$$

The resistance factor, ϕ, calculated using Eq. 7 and 8, can be different for different values of load components. To cover a wider spectrum of loads, three cases of load combinations of DL and LL were considered:

- Dead load is 70% of the total load and live load is 30% of the total load
- Dead load is 50% of the total load and live load is 50% of the total load
- Dead load is 30% of the total load and live load is 70% of the total load

Many State DOTs, including NDOR, currently use HS25 live load rather than HS20 (HS25 is 25% heavier than HS20). The ratios of HL-93 and HS20 were taken from the NCHRP Report 368 (1999); and they vary depending on span length, from 1.2 to 1.35. In further calculations, the ratio of HL-93 and HS20 is conservatively calculated as 1.2.

Table 1 shows representative loads used in calculations of the ϕ factor. HS25 live load was calculated using the flowing formula:

$$LL_{HS25} = 1.25\ LL_{HS20} \tag{9}$$

Table 1. Load Components for Piles Used in the Analysis

Load	Symbol	Axial load, [kips]		
		D=70%, L=30%	D=50%, L=50%	D=30%, L=70%
dead load	DC	675	490	290
dead load	DW	75	45	30
live load	LL_{LRFD}	320	535	750
live load	LL_{HS25}	333	557	781

From Eq. 7 and 8, ϕ factor was obtained as follows,

$$\phi = \frac{1.25DC + 1.5DW + 1.75LL_{LRFD}}{2(DC + DW + LL_{HS25})} \tag{10}$$

The resulting ϕ factors, calculated for the load combinations from Table 1, are shown in Table 2.

Table 2. Calculated ϕ Factors

Dead load	Live load	ϕ
D=70% ,	L=30%,	0.70
D=50% ,	L=50%,	0.74
D=30% ,	L=70%,	0.78

Table 2 contains three cases of loads, each with a different dead load to live load ratio. The lowest value of ϕ factor is equal to 0.7, obtained for the case when dead load is 70 % of the total load and live load is 30%.

4.2 Pile Structural Resistance

The pile structural resistance shall be taken according to AASHTO LRFD Code (2007) which shows a noticeable increase in the allowed compressive resistance. To verify the increase following calculation was performed.

- The load combination DL = 50% and LL = 50% was considered.
- The allowable capacity of H piles according to AASHTO Standard Specifications is shown as follows and varies if:

  - neither static nor dynamic tests are performed,

  $$P_n = 0.25\ F_y\ A_s \tag{11}$$

  - static or dynamic tests are performed,

  $$P_n = 0.33\ F_y\ A_s \tag{12}$$

  where F_y is the specified minimum yield strength in ksi, A_s is the gross-sectional area in square inch.

- The design formula for H piles according to AASHTO Standard Specifications is:

  $$(DL + LL) < 0.25\ F_y\ A_s \text{ for no tests} \tag{13}$$

  $$(DL + LL) < 0.33\ F_y\ A_s \text{ for static/dynamic tests} \tag{14}$$

- The design formula for H piles according to AASHTO LRFD is:

  $$(1.25\ DL + 1.75\ LL) < \phi\ (0.66)^{\lambda}\ F_y\ A_s \tag{15}$$

where λ in this calculation was 0 which corresponds to the fully embedded pile.

- ϕ factor was calculated following the same procedure as described in the previous section of this report and using eq. 13, 14 and 15

Table 3. Calculated ϕ Factors for HS20

Calculated ϕ	0.40	no tests
Calculated ϕ	0.55	static or dynamic load test

Table 4. Calculated ϕ Factors for HS25

Calculated ϕ	0.35-0.40	no tests
Calculated ϕ	0.50	static or dynamic load test

- Therefore, for AASHTO LRFD, the ϕ factor corresponding to HS-20 is 0.40 (no tests) and 0.55 (static/ dynamic tests)
- NDOR uses HS25, the ϕ factor corresponding to HS-25 is 0.35-0.40 (no tests) and 0.50 (static/ dynamic tests).

4.2.1 Steel Piles

According to the Article 10.7.3.13.1 AASHTO (2007) the nominal compressive resistance, P_n, is:

- If $\lambda \leq 2.25$:

  $P_n = 0.66^{\lambda} F_y A_s$ (16)

- If $\lambda \geq 2.25$:

  $P_n = (0.88 F_y A_s)/\lambda$ (17)

in which:

$$\lambda = \left(\frac{Kl}{r_s \pi}\right)^2 \frac{F_y}{E} \quad (18)$$

where A_s is the gross-sectional area, in square in. F_y is the specified minimum yield strength in ksi, E is the modulus of elasticity in ksi, K is the effective length factor, l is the unbraced length in in., r_s is the radius of gyration about the plane of buckling in in.

If the pile is fully embedded λ is equal to 0.

4.2.2 Concrete Piles

According to the Article 10.7.3.13.2 AASHTO (2007) the nominal axial compression resistance, P_n, shall be taken as:

- for members with spiral reinforcement:

  $P_n = 0.85[0.85 f_c'(A_g - A_{st}) + f_y A_{st}]$, (19)

- for members with tie reinforcement:

$$P_n=0.80[0.85f_c'(A_g-A_{st})+f_yA_{st}], \quad (20)$$

where f_c' is the specifi ed strength of concrete at 28 days in ksi, unless another age is specified, A_g is the gross area of section in in^2, A_{st} is the total area of longitudinal reinforcement in in^2, f_y is the specified yield strength of reinforcement in ksi.

5. CAPWAP VS. STATIC LOAD TEST

The correlation between the CAPWAP and the static load test can be considered using the database presented in NCHRP Report 507 (2004). The results of the static load test and the CAPWAP values were plotted in Figure 1. This data can serve as a basis for calculation of the statistical parameters of the CAPWAP results, in particular the bias factor and coefficients of variation.

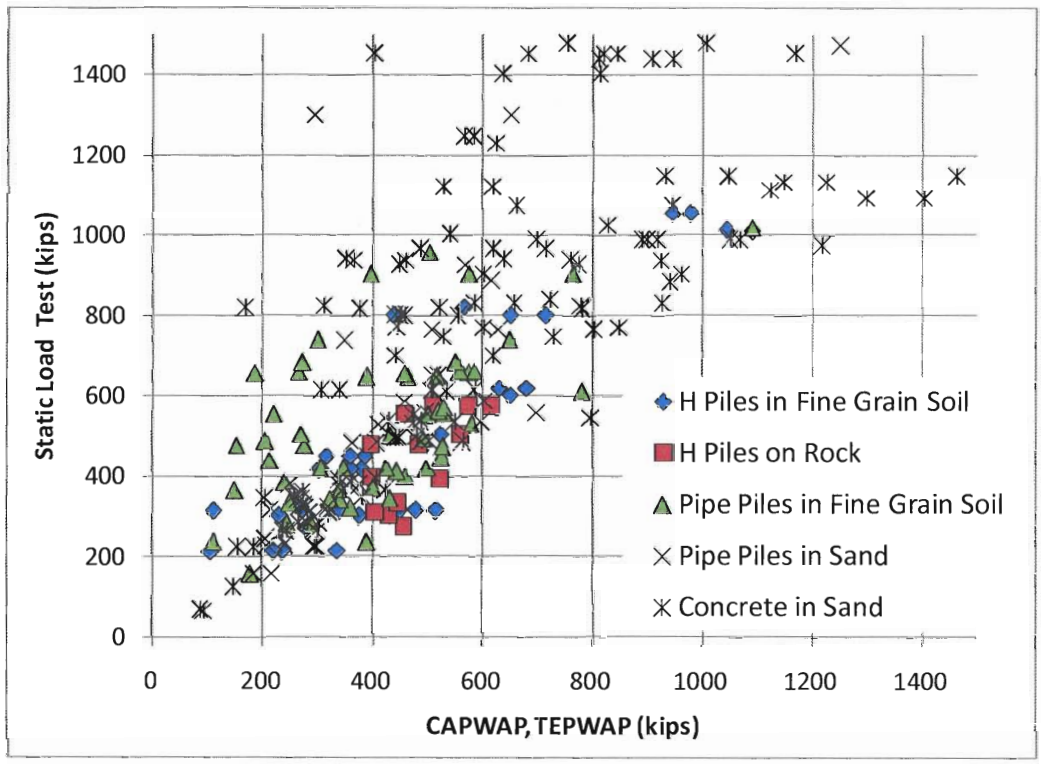

Figure 1. Correlation between CAPWAP and static load test results.

In most cases, the CAPWAP method is conservative and provides a sufficient level of safety margin for the prediction of the ultimate pile capacity (see Figure 1). This confirms the findings of the studies performed by Likins (2004).

6. DATABASE FROM NEBRASKA DOR

A total of 48 samples were collected from the NDOR files. For all of the piles considered, the capacity was determined using the following four methods:

- Pile Driving Analyzer (PDA), CAPWAP
- Nebraska Modified ENR Formula
- Wave Equation, GRLWEAP
- AASHTO Gates Formula

The CAPWAP method is used in NDOR practice to predict the ultimate pile capacity. To compare with the other methods, the CAPWAP ultimate pile capacities were divided by the capacities calculated using other methods. The resulting ratios were considered as random variables, and their cumulative distribution functions (CDF) were plotted on the normal probability paper.

Information on construction and use of the normal probability paper can be found in probability textbooks, e.g., Nowak and Collins (2000) or Benjamin and Cornell (1970). The major property of the normal probability paper is that the CDF of any normal random variable is a straight line, and any straight line represents the CDF of a certain normal random variable. The horizontal axis represents values of the considered random variable. The vertical axis represents the distance from the mean value in terms of standard deviations. Therefore, the value on the horizontal axis corresponding to the intersection of 0 on the vertical scale with the CDF is equal to the mean.

The slope of the CDF plotted on the normal probability paper is an indication of the standard deviation. The more vertical the CDF, the smaller the standard deviation and consequently, the smaller the degree of variation. Therefore, the CDFs can be used for comparing different methods of predicting pile capacity. The methods that provide the best fit to the CAPWAP results can be identified as those with the lowest degree of variation (CDF is more vertical than others).

The ratios of pile capacities were calculated separately for the following pile types and soil conditions:

- Steel H piles on rock
- Steel H piles in fine grain soil

- Steel pipe piles in sand
- Steel pipe piles in fine grain soil
- Concrete piles in sand

The results are shown in Figures 2-7.

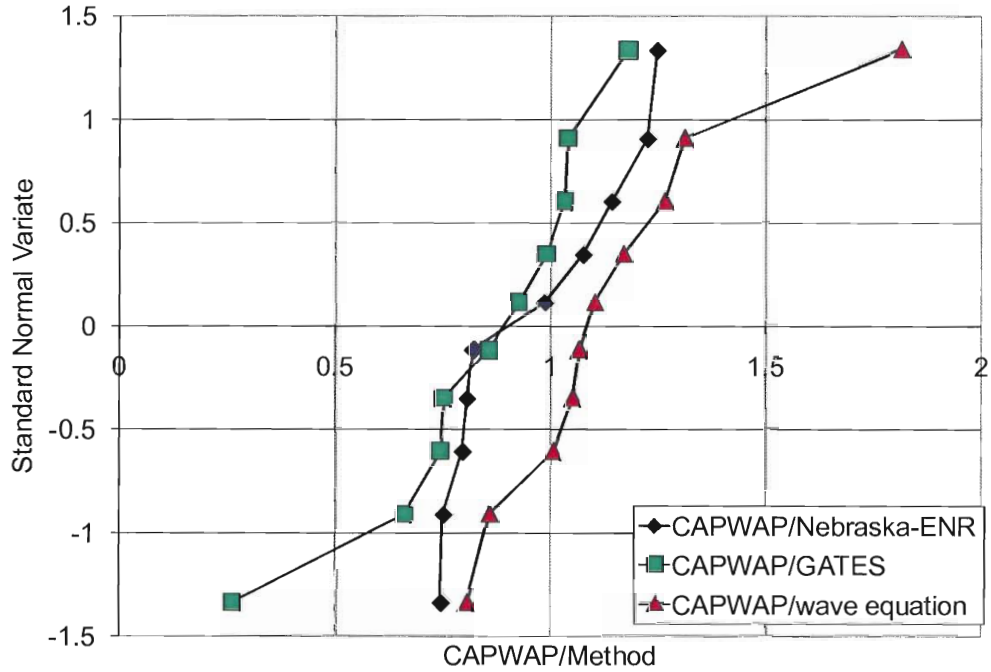

Figure 2. Ratios of the CAPWAP capacity and other methods for Steel H piles on rock.

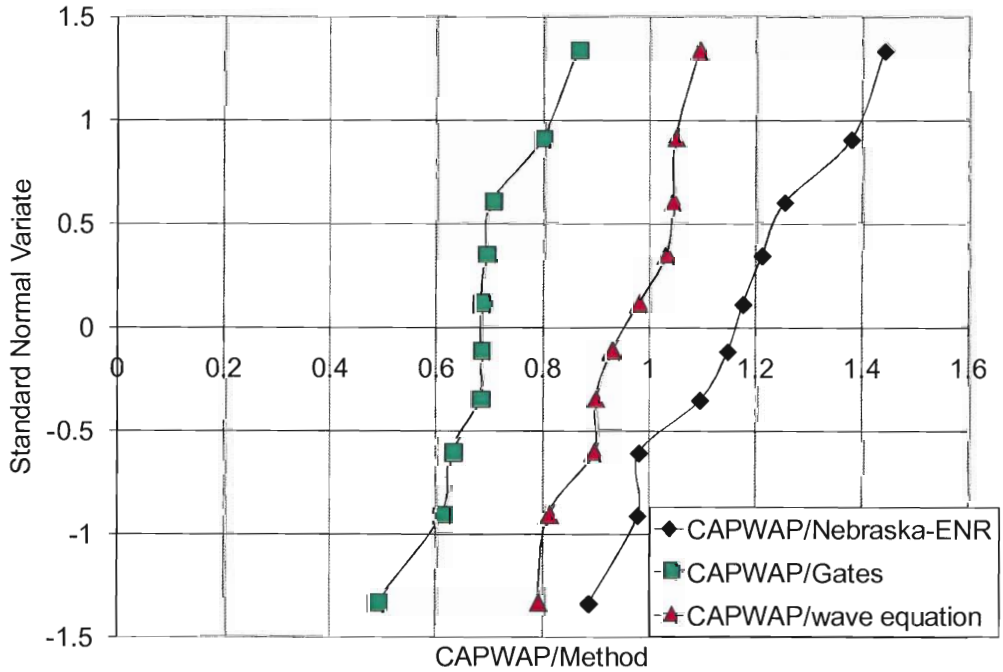

Figure 3. Ratios of CAPWAP capacity and other methods for Steel H piles in fine grain soil.

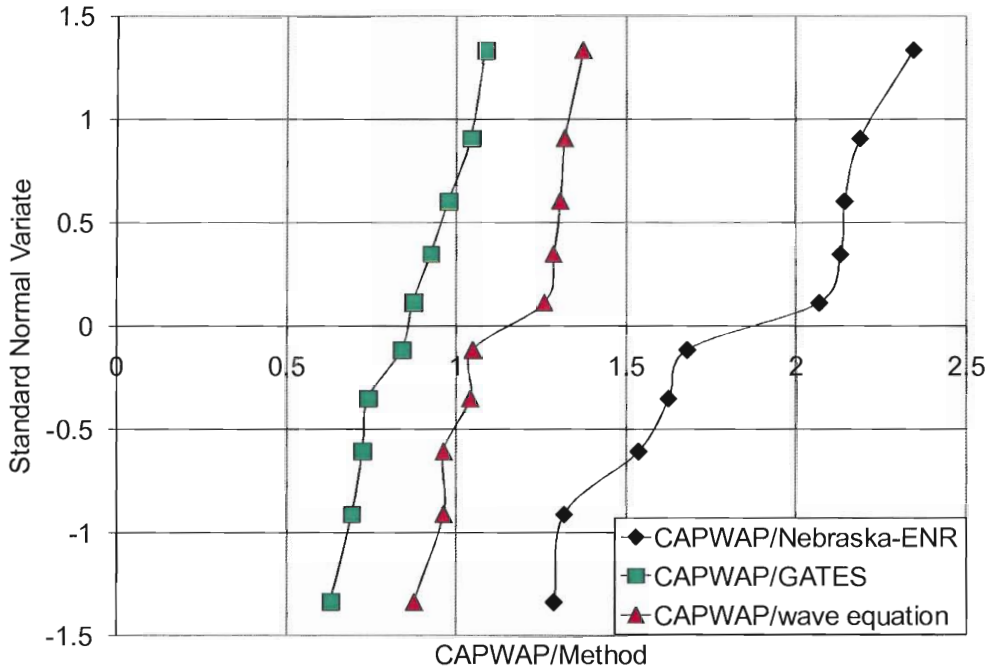

Figure 4. Ratios of the CAPWAP capacity and other methods for pipe piles in sand.

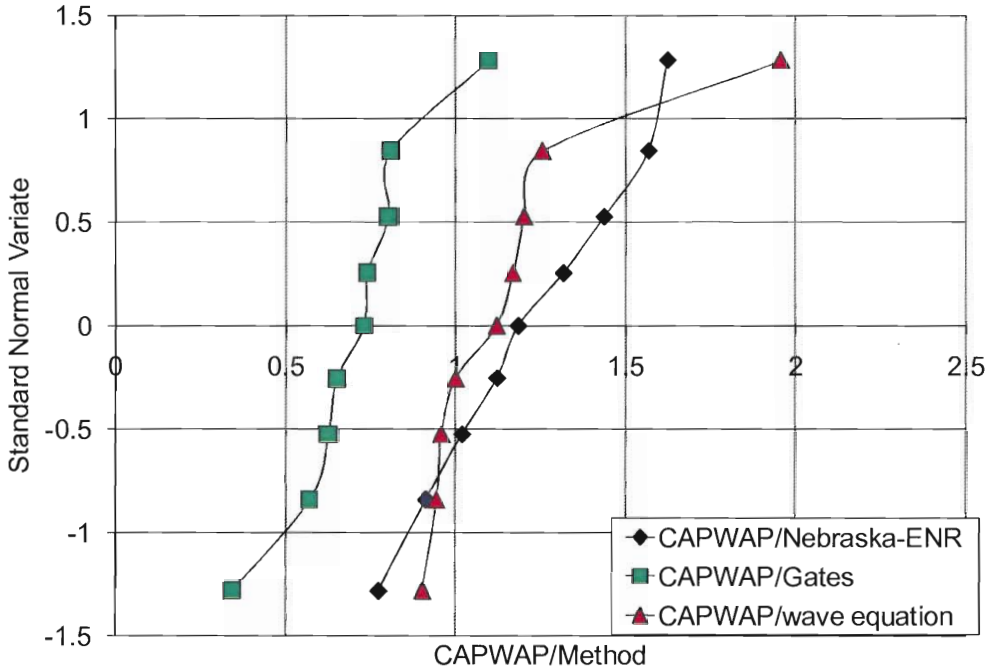

Figure 5. Ratios of the CAPWAP capacity and other methods for pipe piles in fine grain soil.

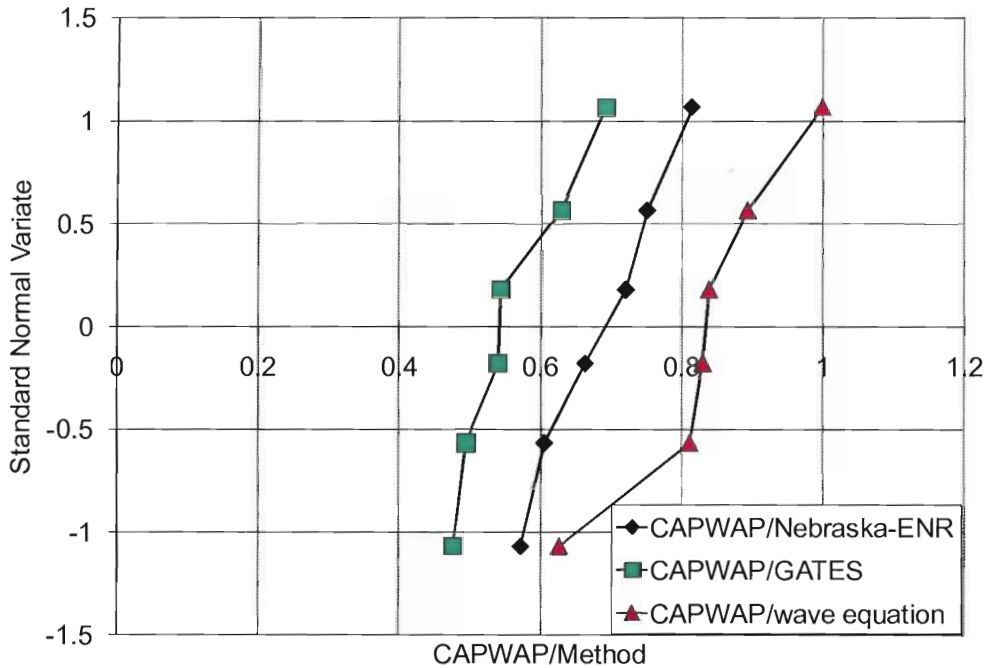

Figure 6. Ratios of the CAPWAP capacity and other methods for concrete piles in sand.

7. PROPOSED FORMULA

The new formula has been developed by trial and error. The selection criterion is shape and horizontal position of the corresponding cumulative distribution function (CDF) plotted on the normal probability paper. The best fit to CAPWAP is provided by the CDF with a minimum degree of variation. Conservatively, the best fit is required for the lower tail of the CDF (below 0 on the vertical axis).

The proposed formula has been calibrated so that the standard deviation for the CDF represented by its lower tail is minimized, and the the ratio of CAPWAP and capacities calculated using the proposed formula are close to 1. The analysis has resulted in the following expression:

$$P = \frac{6\,E}{(S + 0.5)} \tag{21}$$

where P is the nominal pile capacity in kips, S is the average penetration in inches of the pile per blow for the last ten blows for steam or diesel hammers, and E is the energy per blow in foot-kips.

The developed pile capacity formula is adequate for both concrete and steel piles. The equation does not depend on the type of the soil.

Figures 8-12 present a comparison of the new formula, currently using the modified Nebraska ENR formula, and the CAPWAP values for the pile types being considered and soils. In the design practice of the NDOR, the most frequently used piles are steel H piles. The most common soil conditions are fine grain soil and rock.

The comparison of CDFs in Fig. 8-12 indicates that the proposed formula produces results that are closer to the CAPWAP than the modified NDOR equation.

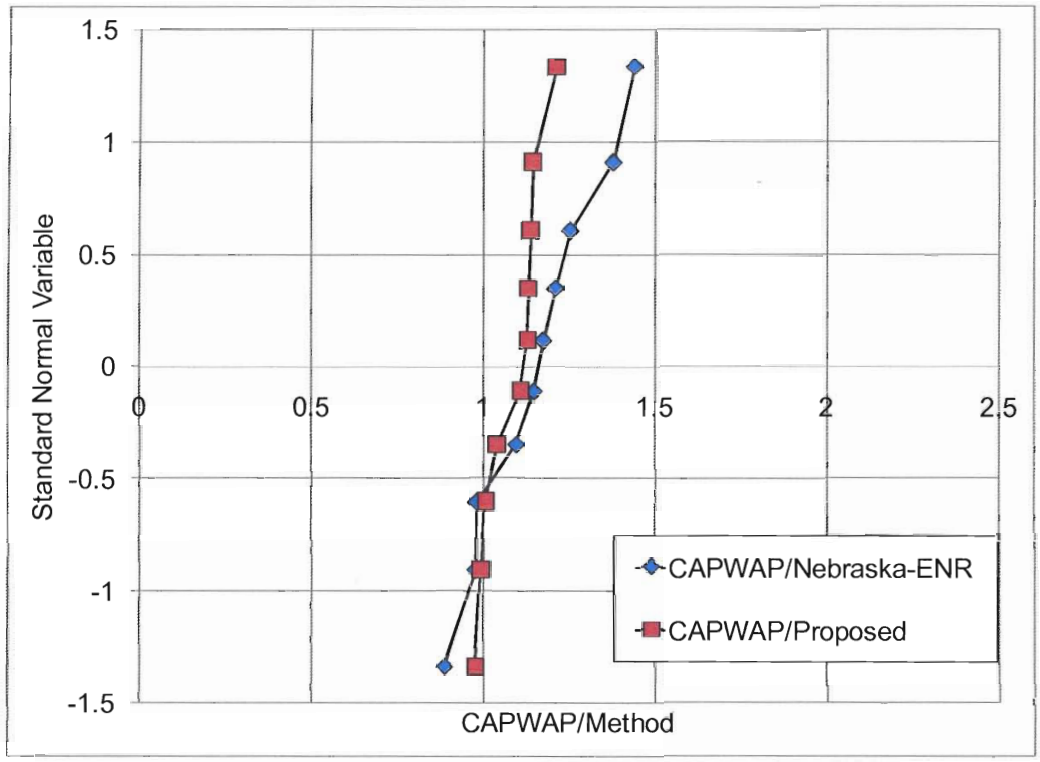

Figure 7. Steel H piles in fine grain soil.

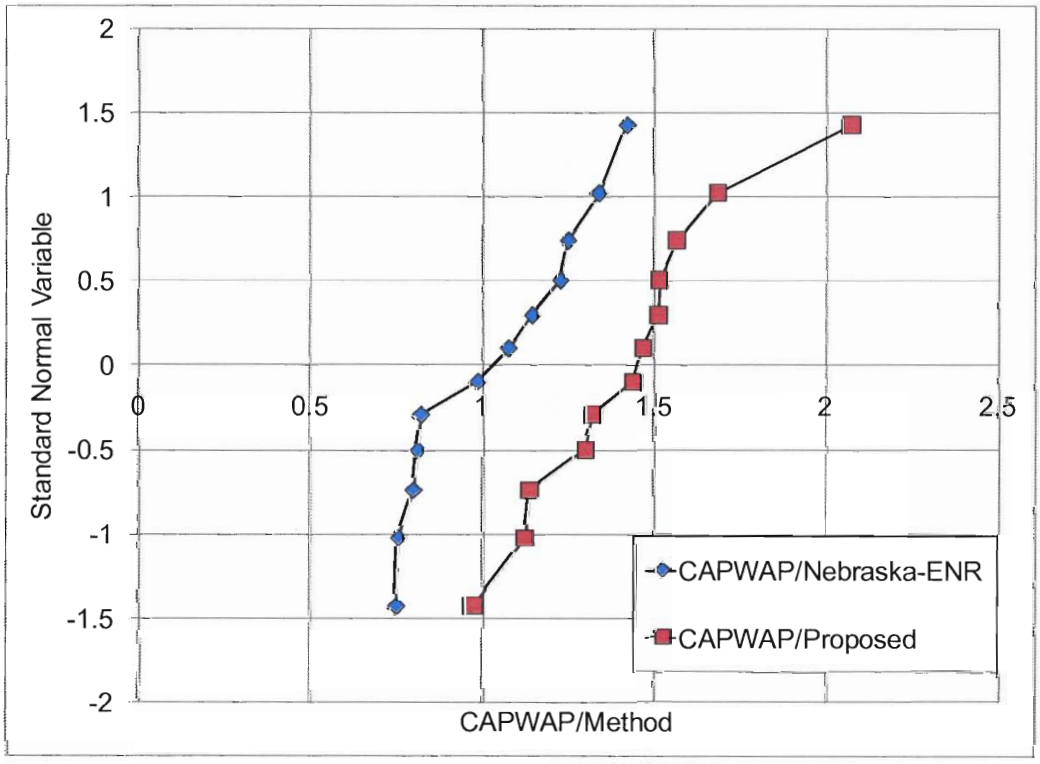

Figure 8. Steel H piles on rock.

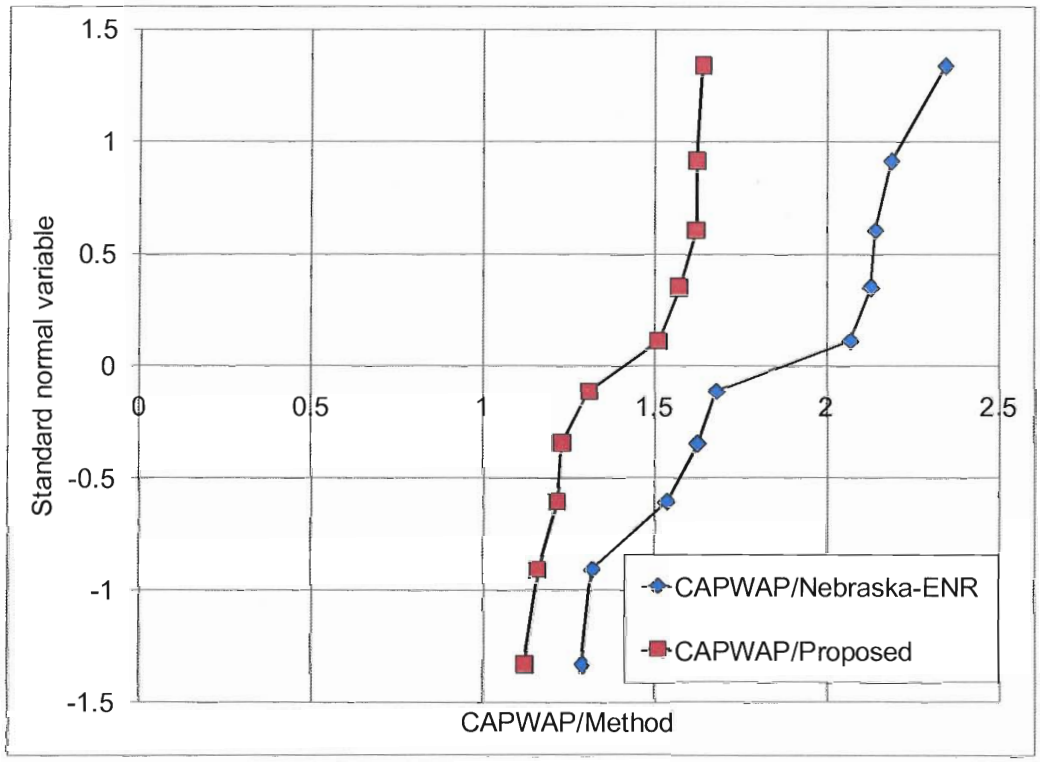

Figure 9. Steel pipe piles in sand.

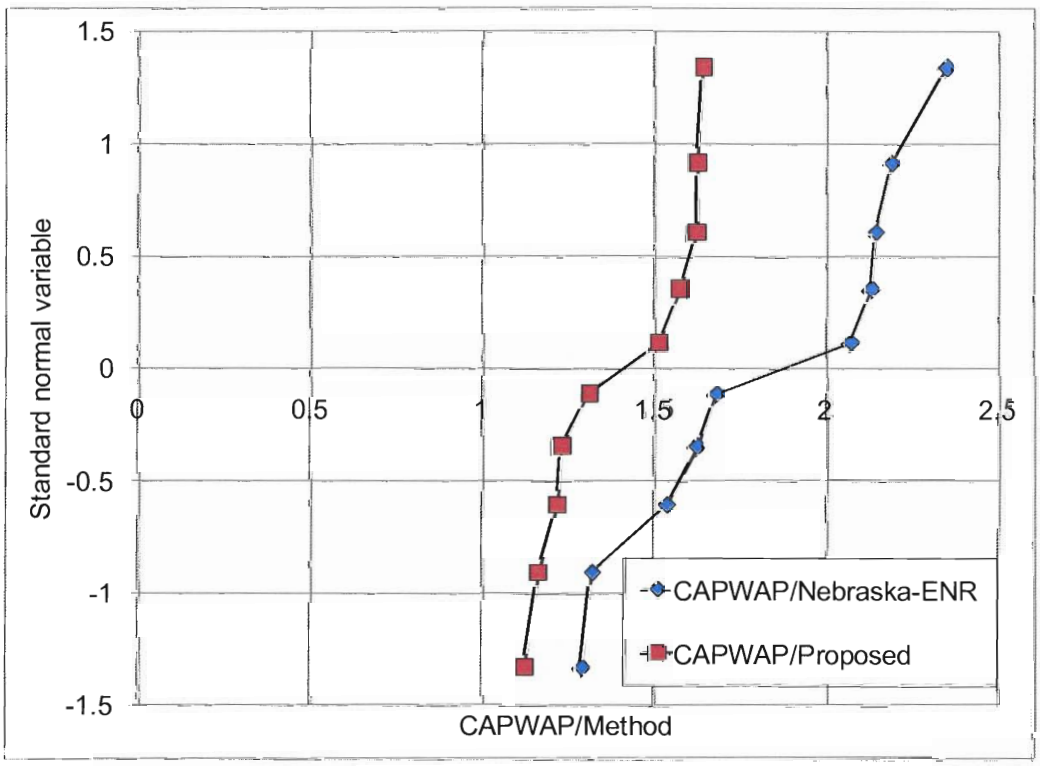

Figure 10. Steel pipe piles in fine grain soil.

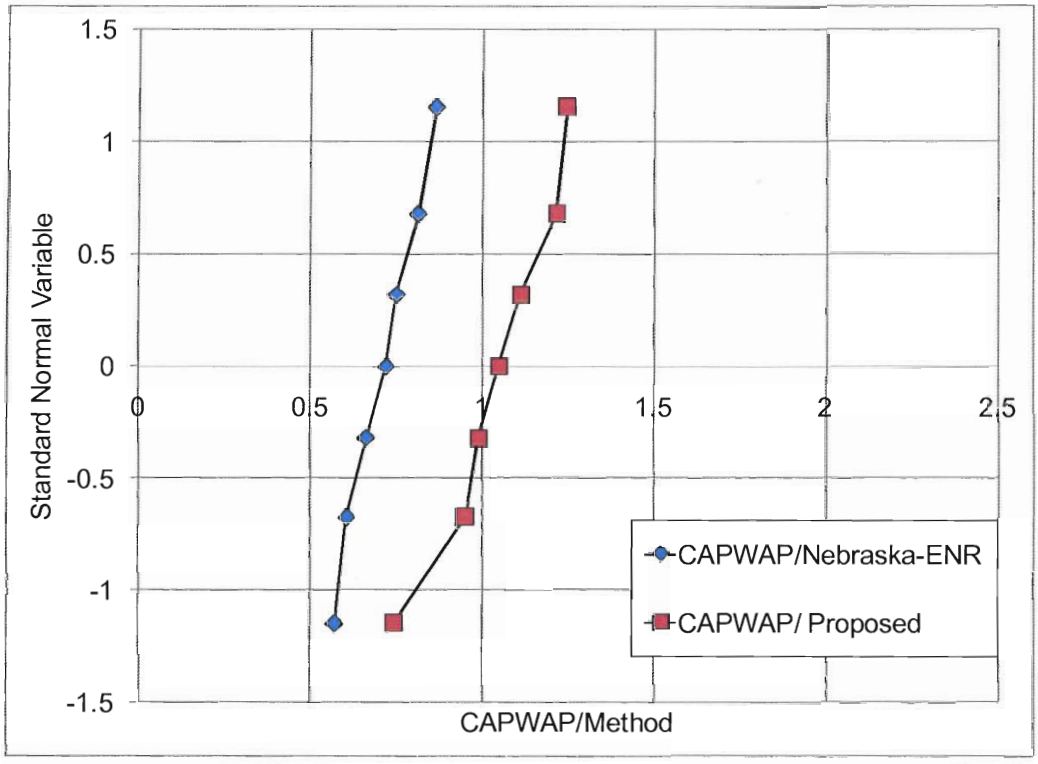

Figure 11. Concrete piles in sand.

8. CONCLUSIONS AND RECOMMENDATIONS

The calibration of the AASHTO LRFD Code (2007) was performed for the bridge superstructure but not for substructure or foundations (Nowak 1999). Resistance factors for piles were selected based on engineering judgment rather than the reliability analysis; and, therefore, there is a need for verification of resistance factors for piles.

The methods for predicting the load carrying capacity of piles varies with regard to accuracy, required input data, and computational effort. The present study showed that the NDOR approach is comparable with other methods of pile capacity verification.

Comparison of the CAPWAP values with the static load test results showed that the CAPWAP results are more conservative; however, in general, they can be considered as a good representation of the actual strength.

A new formula is proposed for the pile capacity calculation based on the modified ENR formula. The proposed method provides results that are in good agreement with CAPWAP.

Resistance factors are calculated for piles. Depending on pile type and soil conditions, resistance factors are from 0.70 to 0.85. The lowest values correspond to design cases dominated by dead load. Therefore, the recommended resistance factor is 0.7.

9. REFERENCES

AASHTO, LRFD Bridge Design Specifications, American Association of State Highway and Transportation Officials, Fourth Edition, Washington, D.C., 2007.

AASHTO Standard Specifications for Highway Bridges, American Association of State and Transportation Officials, Washington, D.C., 2002.

Allen, T.M., Nowak, A.S. and Bathurst, R.J., "Calibration to Determine Load and Resistance Factors for Geotechnical and Structural Design," *TRB Circular E-C079*, Transportation Research Board, Washington, D.C., May 2005.

Benjamin, J.R., and Cornell C.A., *Probability, statistics, and decision for civil engineers*, McGraw-Hill, New York, 1970.

Gates, M., "Empirical Formula for Predicting Pile Bearing Capacity," *Civil Engineering*, Vol.27, No.3, 1957, pp. 65-66.

Likins, G. E., Rausche, F., "Correlation of CAPWAP with Static Load Tests," P*roceedings of the Seventh International Conference on the Application of Stresswave Theory to Piles 2004*: Petaling Jaya, Selangor, Malaysia; August, 2004, pp. 153-165.

Nowak, A.S., Calibration of LRFD Bridge Design Code, *NCHRP Report 368*, Transportation Research Board, Washington, D.C., 1999.

Nowak, A.S. and Collins, K.R., *Reliability of Structures*, McGraw-Hill, New York, 2000.

Paikowsky, S., and Whitman, R., "The Effect of Plugging on Pile Performance and Design," *Canadian Geotechnical Journal,* Vol. 27, No. 4, 1990, pp. 429–440.

Paikowsky, S.G., Kuo, C., Baecher, G., Ayyub, B., Stenersen, K., O'Malley, K., Chernauskas, L., and O'Neill, M., "Load and Resistance Factor Design (LRFD) for Deep Foundations," *NCHRP Report 507*, Transportation Research Board, Washington, D.C., 2004.

Smith, E.A.L., "Pile Driving Analysis by the Wave Equation," *American Society of Civil Engineers, Journal of the Soil Mechanics and Foundations Division*, 86(4), 1960.

Standard Specifications for Highway Constructions, Nebraska Department of Roads, NDOR, NE, 2007.

APPENDIX

Nebraska DOR Guide
for the
Design of Piles using AASHTO LRFD

Nebraska DOR Guide
for the
Design of Piles using AASHTO LRFD

List of Contents

1. Scope of the Guide

2. Design Loads and Required Pile Capacity

3. Determination of soil conditions

4. Selection of pile type and dimensions

5. Determination of pile capacity

6. Design Flow Chart

1. Scope of the Guide

This guide provides the requirements for design of piles using the AASHTO LRFD Code (2007). It covers two verification methods for pile capacity of on site: Nebraska Formula and the CAPWAP. The methods are dependent of two or more of the following parameters: type of a pile, type of soil, weight of a pile, hammer characteristics, developed hammer energy and blow count.

The soil types covered by the guide are:

- sand
- fine grain
- rock

The pile types considered in the guide:

- H piles
- Concrete piles
- Pipe piles

2. Design Loads and Required Pile Capacity

Loads acting on the superstructure should be obtained from the Bridge Division. The loads list, containing all components of unfactored and factored design loads, should be provided.

The required pile capacity:

$$P_n = \frac{factored\ load}{\phi} \tag{1}$$

where $\phi = 0.7$

Load combinations and load factors are selected according to the AASHTO tables as follows:

Load Combination Limit State	*DC* *DD* *DW* *EH* *EV* *ES* *EL*	*LL* *IM* *CE* *BR* *PL* *LS*	*WA*	*WS*	*WL*	*FR*	*TU* *CR* *SH*	*TG*	*SE*	Use One of These at a Time			
										EQ	*IC*	*CT*	*CV*
STRENGTH I (unless noted)	γ_p	1.75	1.00	—	—	1.00	0.50/1.20	γ_{TG}	γ_{SE}	—	—	—	—
STRENGTH II	γ_p	1.35	1.00	—	—	1.00	0.50/1.20	γ_{TG}	γ_{SE}	—	—	—	—
STRENGTH III	γ_p	—	1.00	1.40	—	1.00	0.50/1.20	γ_{TG}	γ_{SE}	—	—	—	—
STRENGTH IV	γ_p	—	1.00	—	—	1.00	0.50/1.20	—	—	—	—	—	—
STRENGTH V	γ_p	1.35	1.00	0.40	1.0	1.00	0.50/1.20	γ_{TG}	γ_{SE}	—	—	—	—
EXTREME EVENT I	γ_p	γEQ	1.00	—	—	1.00	—	—	—	1.00	—	—	—
EXTREME EVENT II	γ_p	0.50	1.00	—	—	1.00	—	—	—	—	1.00	1.00	1.00
SERVICE I	1.00	1.00	1.00	0.30	1.0	1.00	1.00/1.20	γ_{TG}	γ_{SE}	—	—	—	—
SERVICE II	1.00	1.30	1.00	—	—	1.00	1.00/1.20	—	—	—	—	—	—
SERVICE III	1.00	0.80	1.00	—	—	1.00	1.00/1.20	γ_{TG}	γ_{SE}	—	—	—	—
SERVICE IV	1.00	—	1.00	0.70	—	1.00	1.00/1.20	—	1.0	—	—	—	—
FATIGUE—*LL, IM & CE* ONLY	—	0.75	—	—	—	—	—	—	—	—	—	—	—

Table 1. Load combination and load factors (AASHTO, *Table 3.4.1-1*)

Type of Load, Foundation Type, and Method Used to Calculate Downdrag		Load Factor	
		Maximum	Minimum
DC: Component and Attachments		1.25	0.90
DC: Strength IV only		1.50	0.90
DD: Downdrag	Piles, α Tomlinson Method	1.4	0.25
	Piles, λ Method	1.05	0.30
	Drilled shafts, O'Neill and Reese (*1999*) Method	1.25	0.35
DW: Wearing Surfaces and Utilities		1.50	0.65
EH: Horizontal Earth Pressure			
• Active		1.50	0.90
• At-Rest		1.35	0.90
• *AEP* for anchored walls		1.35	N/A
EL: Locked-in Erection Stresses		1.00	1.00
EV: Vertical Earth Pressure			
• Overall Stability		1.00	N/A
• Retaining Walls and Abutments		1.35	1.00
• Rigid Buried Structure		1.30	0.90
• Rigid Frames		1.35	0.90
• Flexible Buried Structures other than Metal Box Culverts		1.95	0.90
• Flexible Metal Box Culverts		1.50	0.90
ES: Earth Surcharge		1.50	0.75

Table 2. Load factors for permanent loads γ_p (AASHTO, *Table 3.4.1-2*)

3. Determination of soil conditions

Soil conditions must be investigated by Standard Penetration Test (SPT). The test determines the layers of soil with respect to the depth, thickness, consistency and the elevation of groundwater. The most common soil conditions in Nebraska DOT practice are: fine grain consisting of silts and clays, rock (limestone, shale, siltstone, sandstone) and sand.

4. Selection of pile type and dimensions

Selection of the pile depends on the soil conditions. The common practice in Nebraska DOR is:

- H piles are being used for the fine grain, clay or on the rock conditions
- Concrete piles are being used in sands
- Pipe Piles are being used in sands for the integral abutment.

Depending on soil condition and structural requirements the following dimensions can be used:

- H Pile 10x42,
- H Pile 12x53,
- H Pile 14x84,
- Concrete Pile Type I (section 12"x12"),
- Pipe Pile 12"-13" diameter , 0.375" wall thickness

5. Determination of pile capacity

The pile capacity can be verified using two methods:

- CAPWAP
- Nebraska Formula

5.1. CAPWAP Method

CAPWAP method is based on the data from Pile Driving Analyzer (PDA). PDA is a method to measure the dynamic response of a pile during driving. The data obtained directly on site by PDA can be processed using Case Pile Wave Analysis Program (CAPWAP). The signal matching analysis such as CAPWAP correlates data from the

PDA readings with the wave theory to obtain results such as simulation of the static load tests. Input data for CAPWAP obtained with the PDA are force and velocity during pile driving. Equipment used for pile testing during driving:

- Drop weight or diesel hammer
- PDA Analyzer,
- Accelerometers,
- Strain transducers attached to the pile
- Tape measure

5.2. Nebraska Formula

The pile capacity can be calculated using the following formula:

$$P = \frac{6\,E}{(S + 0.5)} \tag{2}$$

where:
P is the nominal pile capacity in kips,
S is the average penetration in inches of the pile per blow for the last 10 blows for steam or diesel hammers,
E is the energy per blow in foot-kips

Equation (2) can be used for concrete and steel piles.

6. Design Flowchart

The design procedure for piles is presented in Figure 1. Shaded blocks are the responsibility of the Bridge Division.

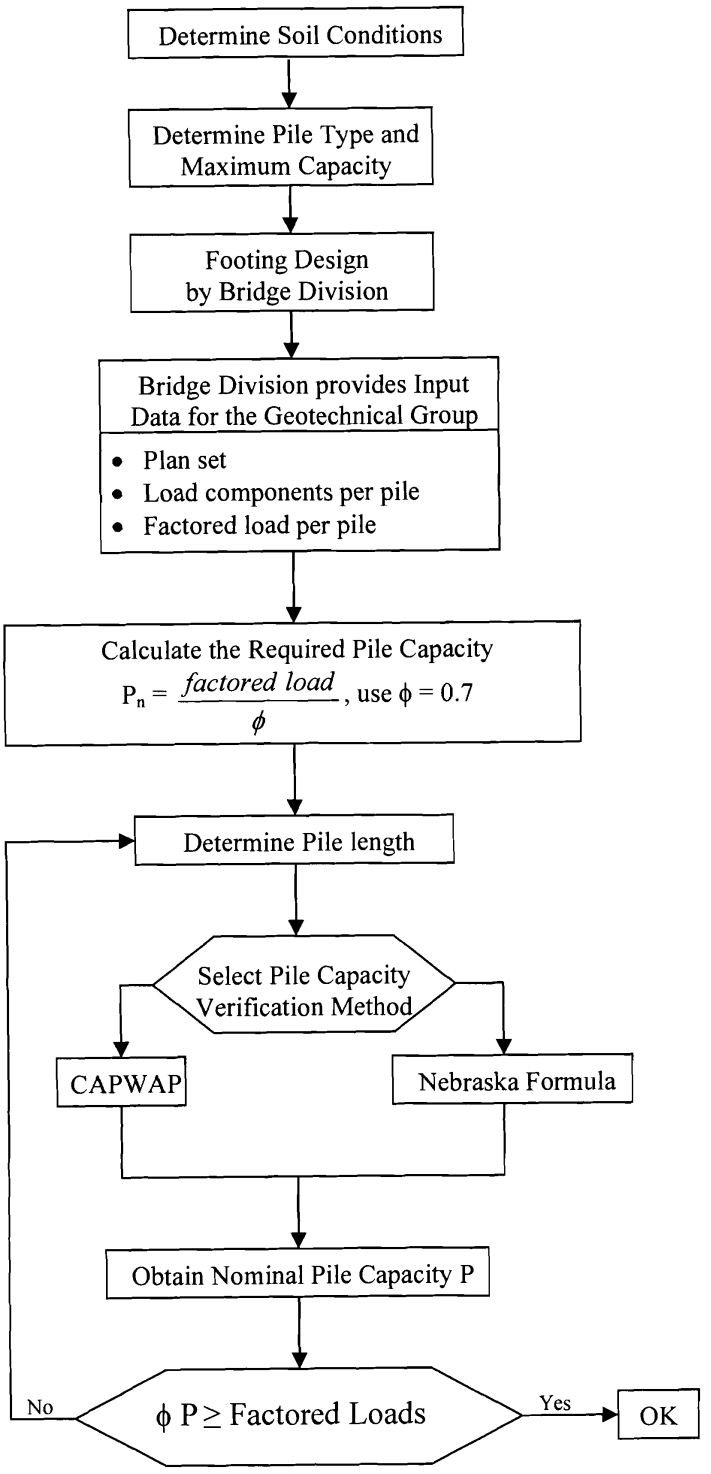

Figure 1. Flow-Chart for Design of Plies