Load and Resistance Factor Design (LRFD) for dynamic analysis of deep foundations

La méthode de "Facteurs de Charges et de Résistances" pour les dondations profondes

S.G.Paikowsky – *University of Massachusetts Lowell, Lowell, MA, U.S.A.*

ABSTRACT: An effort supported by the NCHRP is aimed at rewriting AASHTO Deep Foundation Specifications. The AASHTO specifications are traditionally observed on all federally aided projects and generally viewed as a National code of the US Highway practice. The new code is based on Load and Resistance Factor Design (LRFD) principles with resistance factors obtained from a probabilistic analysis of data. The currently developed databases relate to axial capacity of single driven piles and drilled shafts. For the dynamic evaluation of driven piles, a database (PD/LT2000) containing information related to 210 piles and 403 dynamic measurements was compiled. Details are provided for the performance of the various dynamic analysis methods when compared to static load testing to failure. The parameters that control the accuracy of the predictions are analyzed. Statistical analyses are then utilized for the development of the recommended resistance factors to be used in the new specifications.

RÉSUMÉ: Ce projet, supporté par NCHRP a pour but de re-écrire les Spécifications AASHTO pour les fondations profondes. Les Spécifications AASHTO sont utilisées sur tous les projets payés fédérallement et sont acceptées comme code national pour le transport aux Etats Unis. Le nouveau code se base sur les principes de la méthode de "Facteurs de Charges et de Résistances" où ces derniers facteurs sont obtenus par l'analyse de probabilité. Les banques de données qui sont developpées donnent la capacité de pieux enfoncés et de caissons forés. Pour l'évaluation dynamique des pieux enfoncés, une banque de donnée (PD/LT2000) a été développée pour 210 pieux utilisant 403 mesures dynamiques.. Les diverses méthodes d'analyse dynamique sont comparées aux résultats de tests statiques de pieux. Les paramètres qui controlent la précision de ces prédictions sont analysés. Finallement, l'analyse de probabilité est utilisée pour développer les Facteurs de Résistance recommendés pour les nouvelles Spécifications.

1 INTRODUCTION

National Cooperative Highway Research Program, project, NCHRP 24-17, "LRFD Deep Foundations Design" was initiated to provide recommended revisions to the driven pile and drilled shaft portions of section 10 of AASHTO Specifications. The current AASHTO specifications as well as other existing codes based on Load and Resistance Factor Design (LRFD) principles were developed with insufficient data utilizing mostly back-calculated factors. The main challenges of the project are therefore: (a) Compilation of large, high quality databases and (b) Framework for a procedure and data management to enable: (i) LRFD parameter evaluation and (ii) Future updates. These challenges require the reorganization of the factors following the design - construction - quality control sequence (i.e. independence in resistance factors according to the chronological stage and the evaluation procedure). The project team, headed by the author, is divided into three major groups dealing with static analyses (Univ. of Florida and the Univ. of Massachusetts, Lowell), probabilistic approaches and structural analyses (Univ. of Maryland), and dynamic analyses (Univ. of Massachusetts, Lowell). The present paper provides a condensed summary of the LRFD resistance parameters developed for use with driven pile capacity evaluation based on dynamic measurements. A more complete presentation is provided by Paikowsky and Stenersen (2000). A final report of the project is expected to be completed by Summer 2000.

2 PD/LT 2000 DATABASE

The database PD/LT2000 contains information related to 210 driven piles that have been statically load tested to failure and dynamically monitored during driving and/or restrike (403 analyzed measurements). PD/LT2000 is comprised of the integration of databases PD/LT (Paikowsky et al. 1994) and PD/LT2 (Paikowsky and LaBelle, 1994) with expansion by an additional 57 pile cases (Stenersen, 2000). The data of PD/LT2000 were carefully examined and analyzed following procedures described by Paikowsky et al. 1994, resulting in detailed static and dynamic pile capacity evaluations. Paikowsky and Stenersen (2000) presents a summary of the data contained in PD/LT2000 broken down according to site location and soil type, pile type and capacity, driving behavior and time of driving.

3 REFERENCE STATIC CAPACITY

The dynamic methods are assessed by comparing the pile capacity of the evaluated method with a reference static capacity of the pile. The determination of the pile's static capacity based on load displacement relations is not unique. The test results depend on the load testing procedures and the applied interpretation method, often being subjective. Examination of these factors and their influence on the reference static capacity was carried out as a prerequisite for the calibration of the dynamic methods.

Past work (Paikowsky et al. 1994) have resorted to a "representative" static pile capacity based on the assessment of five interpretation methods; Davisson's Criterion (Davisson, 1972), Shape of Curve (similar to the procedure proposed by Butler and Hoy, 1977), Limiting Total Settlement to 25.4 mm and to 0.1B (Terzaghi, 1942), and the DeBeer log-log method (DeBeer, 1970). A single representative capacity value was then calculated for the analyzed case as the average of the methods considered relevant (i.e. provided reasonable value). The development of a framework for specifications requires that the evaluated resistance factors be based on an objective, repetitive procedure. Paikowsky and Stenersen (2000) have shown that Davisson's criterion was found to perform the best overall with a mean of 1.018 and standard deviation of 0.101 (186 cases) when compared with the representative value. Davisson's criterion was therefore chosen as the single method to be used when analyzing load-displacement curves. The method was also found to perform well for piles exceeding a diameter of 610mm (examined through 30 pile cases).

The influence of the static load testing procedure (loading rate) on the designated pile capacity was examined in two ways: (i) Two detailed case histories in which piles were tested using three types of static load testing procedures varying in time form 45 hours to about 15 minutes. The interpretation of the load-

displacement relationships in both cases suggested that the test type had an insignificant influence on the pile capacity, (referring to a failure criterion irrespective of the displacement).
(ii) The effect of the test type was further investigated utilizing a database containing information related to 75 piles tested under slow maintained and static-cyclic load testing procedures presented by Paikowsky et al. (1999). The obtained relations and the associated statistical information (mean = 0.930, standard deviation = 0.136) suggest that the applied pseudo-static load rate has no significant influence on the static pile capacity.

These evaluations led to the conclusions that Davisson's pile failure criterion can be used as a method to determine the reference static pile capacity irrespective of the static load-testing procedure.

4 THE CHOSEN DYNAMIC METHODS AND THEIR CONTROLLING PARAMETERS

4.1 *Overview*

Prior to detailed analyses leading to the determination of resistance factors, two components must be established: (a) the type of the dynamic methods to be evaluated and (b) the conditions under which these methods need to be examined.

4.2 *Methods of Analysis*

The major available dynamic methods for evaluating pile capacity can be categorized according to the project stage (i.e. design vs. construction) and the need for data obtained through dynamic measurements. Wave Equation Analysis Program (WEAP, see Smith 1960 and Gobel et al. 1976) was considered for the design stage. Engineering News Record (ENR, see Wellington 1892), Gates equation (Gates 1957) and FHWA modified Gates equation (FHWA 1988) were the dynamic equations considered for analysis during construction in which dynamic measurements are not available. The incorporation of dynamic equations and WEAP reflects the state of practice in USA highway construction and hence need to be addressed for the specifications regardless of the existing knowledge concerning their effectiveness.

The methods that require dynamic measurements can be broadly categorized as those that utilize a simplified analysis of an instantaneous pile capacity evaluation for each hammer blow, and those that require elaborate calculations (i.e. signal matching, see Goble et al. 1970), traditionally carried out in the office.

Due to the vital importance of static pile capacity evaluation during driving, a short discussion of the field methods follows. The Case method (Goble et al., 1970 and Rausche et al., 1975) is often used in field evaluations, as it is built into Pile Dynamics Inc.'s Pile Driving Analyzer (PDA), the most commonly used in the USA. The method is based on a simplified pile and soil behavior assumptions (free end and plastic soil), resulting in a closed form solution related to the impact and its reflection from the tip. With the years, the method evolved to be implemented into at least five different variations (GRL, 1999). The Case method utilizes a damping coefficient (J_c) that is assumed to be associated with soil type. The Case-damping coefficient was investigated through a back calculation (to match the measured static capacity). The results show no correlation between the soil type and the Case damping coefficient. The recommended practice is the use of the method based on a specific site/area calibration (GRL 1999), has proven to be effective locally; e.g. in Boston (GTR 1997, 1998) and in Florida (McVay et al. 2000).

As no generic conditions exist for the use of the Case method, international or national calibrations are unrealistic. In addition, as the projection of local calibration (of good experience and practice) beyond their geographical location may be unwise and/or unsafe, the Case method was excluded from the examined dynamic analyses.

The Energy Approach is a simplified method, uses basic energy relations in conjunction with dynamic measurements to determine pile capacity. The concept was presented by Paikowsky (1982) and was examined on a limited scale by Paikowsky and Chernauskas (1992). Extensive studies of the Energy Approach method were carried out by Paikowsky et al. (1994), and Paikowsky and LaBelle (1994). The underlying concept of this approach is the energy balance between the total energy delivered to the pile and the work done by the pile/soil system. The basic Energy Approach equation is:

$$R_u = \frac{E_{max}}{Set + \dfrac{(D_{max} - Set)}{2}} \qquad (1)$$

where R_u = maximum pile resistance, E_{max} = measured maximum energy delivered to the pile, D_{max} = measured maximum pile top displacement, and Set = permanent displacement of the pile at the end of the analyzed blow, or 1/measured blow count. For further details regarding the Energy Approach method see Paikowsky et al. (1994) and Paikowsky (1995).

4.3 *The Controlling Parameters*

Preliminary examination of the parameters controlling the performance of the dynamic analyses was carried out prior to a final detailed evaluation of these methods, leading to resistance factors. Such examination influences the sub categorization of

Table 1. Resistance factors for the critical dynamic cases.

Method		*Case*	*Statistics Normal Distribution* No. of Cases	Mean Ksx	Standard Dev.	*Resistance factor, ϕ* $\beta = 2.0$, $p_f = 2.3\%$	$\beta = 2.5$, $p_f = 0.6\%$	$\beta = 3.0$, $p_f = 0.1\%$	*Redundant Piles* $\beta = 2.33$, $p_f = 1.0\%$	ϕ / Ksx
Dynamic Measurements	*Signal Matching*	*General*	377	1.368	0.620	0.68	0.54	0.43	0.59	0.431
		EOD<350 BC<16BP10cm	37	2.589	2.385	0.52	0.35	0.23	0.41	0.158
		BOR	162	1.158	0.393	0.73	0.61	0.51	0.65	0.561
	Energy Approach	*General*	371	0.894	0.367	0.48	0.39	0.32	0.42	0.470
		EOD	128	1.084	0.431	0.60	0.49	0.40	0.53	0.489
Dynamic Equations	*Gates*	*General*	384	1.787	0.848	0.85	0.67	0.53	0.73	0.409
	FHWA Modified	*General*	384	0.940	0.472	0.42	0.33	0.26	0.36	0.383
WEAP		*EOD*	99	1.656	1.199	0.48	0.34	0.25	0.39	0.236

the dynamic methods hence, directing the user to utilize the appropriate resistance factor according to the relevant conditions of the employed method. For example, if soil type is a controlling factor and the accuracy of the signal matching method is largely affected by soil type, evaluation of the method for different soil types will result in the development of resistance factors, depending on the soil type. Conversely, if soil type does not control the accuracy of the specific dynamic method, categorization based on soil type is neither desired nor pursued.

The following summary of the controlling parameters examination is based on the rationale and previous studies by Paikowsky et al. (1994), Paikowsky (1995) Paikowsky and Chernauskas (1996) and Paikowsky and Stenersen (2000).

1. The viscous damping parameters used for modeling the soil is not an intrinsic soil type property. The performance of the signal matching technique cannot therefore be correlated to soil type. This does not preclude other factors associated with soil type to be important (e.g. low driving resistance in soft soils or gain of capacity with time) but suggest that soil type alone is not a controlling parameter for which the methods should be calibrated.
2. Due to change of pile capacity with time, the time in which a dynamic test is conducted remains a controlling factor. The dynamic capacity predictions follow the physical behavior of capacity gain, but do not reflect correctly the actual rate of gain as observed from static measurements. As such, the practical controlling factors remain the evaluation of pile capacity during driving and at any time later during restrike without further specifications (for calibration of available data).
3. Soil inertia due to the pile penetration was proven to be a major controlling parameter (Paikowsky and Chernauskas 1996, Paikowsky and Stenersen 2000 and Hajduk et al. 2000).
4. The assumption of a stationary soil is used by the common soil/pile interaction models for the solution of the wave equation. The unaccounted for soil inertia affects therefore the predictions of the dynamic methods through two factors; soil acceleration and the mass of the displaced soil. Soil Acceleration can indirectly be accounted for through the driving resistance. Under low driving resistance, high acceleration and velocity are developed at the tip and surrounding soil. The driving resistance of 4 Blows Per Inch (4BPI) equivalent to 16 Blows per 100mm was found to be the limiting case that profoundly affect the accuracy of the driving resistance. For example, the signal matching technique is on the average twice more accurate in its prediction beyond the limiting value of 4BPI compared with its predictions for the range below or equal to 2BPI.

The volume of the displaced soil is identical to the volume of the penetrating body (excluding plugging effect) taking place mostly at the tip. The classification of piles was achieved based on the ratio between the embedded surface area and the area of the pile's tip (Paikowsky et al. 1994). The area ratio is:

$$A_R = \frac{A_{skin}}{A_{tip}} = \frac{\text{Surface area in contact with soil}}{\text{Area of pile tip}} \qquad (2)$$

The area ratio of 350 was found to be limiting the parameter, below which the soil inertia effect is significant.

5 RESISTANCE FACTORS

5.1 *Methodology*

The present project calibrates LRFD partial safety factors using the First-Order Reliability Method (FORM). FORM can be used to assess the reliability of a pile with respect to specified limit states, and provides a means for calculating partial safety factors ϕ and γ_i for resistance and loads, respectively, against target reliability levels, β_o. FORM requires only the first and second moment information on resistances and loads (i.e. means and standard deviations), and an assumption of distribution type (e.g. normal, lognormal, etc.). The framework of the calibration process is presented by Thrift-Christensen and Baker, 1982. Before an exact target reliability is established, the resistance factors were evaluated for target reliability values of β = 2, 2.5, and 3.0 associated with probability of failure values for lognormal distribution of P_f = 2.3%, 0.62%, and 0.14%, respectively. The factors were evaluated using load factors of 1.25 and 1.75 for were evaluated using load factors of 1.25 and 1.75 for Dead Load (DL) and Live Load (LL), respectively, and for DL to LL ratios ranging from 1 to 4. The obtained results suggested very little sensitivity to the DL to LL ratio. A parametric study was carried out for a generic case of lognormal distribution with a coefficient of variation of 0.40 and dead to live load ratios ranging from 1 to 10. No significant influence of the dead to live load ratio on the calculated resistance factors was found. The large ratio of dead to live load represent a wide possibility of bridge construction, typically associated with very long bridge spans. A summary of the calculated resistance factors for all three target reliability levels for the identified dynamic methods is provided in Table 1.

5.2 *Preliminary and Inclusive resistance Factors*

The time of driving, driving resistance, and area ratio proved to be the major controlling parameters of the dynamic methods. To facilitate the codes' separation between design and construction, the database was organized into these categories, followed by subcategories of methods that use and do not use dynamic measurements, with subsets following the controlling parameters. The results suggested overall a good fit of the data to a lognormal distribution and provided with the ability to identify the critical 'inclusive' cases. For example, the subdivision of the Energy Approach method for all Beginning of Restrike (BOR) cases resulted with similar distribution parameters for the general BOR case and all six subdivisions beyond it (<16BP100mm, ≥ 16BP100mm and their subdivision of blow count and area ratios combinations). The inclusive case remains therefore the BOR general case. The mean and standard deviation for the major categorization of the inclusive cases were used to evaluate the resistance factors via FORM for reliability indices of 2.0, 2.5 and 3.0 as presented in Table 1.

5.3 *Evaluation of the Dynamic Methods' Efficiency*

The resistance factors alone do not provide a measure for the evaluation of the efficiency of the dynamic methods. The efficiency can be examined through the bias factor (mean of the ratio of the measured over predicted), its coefficient of variation or the ratio of the resistance factor to the bias factor, i.e. ϕ/mean K_{SX}, as proposed by McVay et al. (2000). This ratio is provided for one of the selected cases in Table 1. The efficiency values in Table 1 suggest that overall the higher efficiency is obtained by the signal matching analyses for the last restrike, followed by the Energy Approach at the end of driving (0.561 vs. 0.489).

5.4 *Recommended resistance Factors*

No final resistance factors have been approved yet. The current recommendation is to allow for two sets of resistance factors related to redundant and non-redundant elements. A deep foundation element can be considered redundant when it is a part of a substructure (i.e. pile cap) of five or more piles. Such elements will be assigned with a P_f = 1% and β = 2.3. A non-redundant element will be assigned with a P_f = 0.1% and β = 3.0. For example using the Energy Approach during driving resistance factors of 0.40 and 0.53 will be used for non-redundant and redundant elements, respectively.

6 SUMMARY AND CONCLUSIONS

1. The compilation of a large database allows for the evaluation of the dynamic methods and the development of reliable and logical resistance factors as part of Load and Resistance Factor Design (LRFD) methodology.
2. The dynamic methods performance is controlled by the time of driving and soil inertia, which in turn is controlled by the driving resistance and the ratio of the soil displaced by the pile's tip to the area of the soil along the shaft.
3. The Gates equation and its variation seem to provide a reasonable assessment of the pile's capacity considering the absence of dynamic measurements.
4. The wave equation analysis performs poorly when used for pile capacity evaluation.

5. Signal matching techniques prove to be most reliable for long-term restrike measurements. However, when evaluated on efficiency, the application of the signal matching on re-strikes seem to be marginal compared to the Energy Approach at the End of Driving (EOD).
6. The Energy Approach provides an exceptionally efficient evaluation of pile capacity during driving.

ACKNOWLEDGEMENTS

The presented research was sponsored by the American Association of State Highway and Transportation Officials (AASHTO), under project 24-17, in cooperation with the Federal Highway Administration (FHWA). Drs. Gregory Baecher and Bilal Ayyub from the University of Maryland contributed to section 5.1 and performed the calculations of the presented resistance factors. Dr. Frank Rausche of GRL and Assoc. provided the data pertaining to the evaluation of GRLWEAP. Mr. Nabil Hourani of the MHD kindly translated the abstract to French.

DISCLAIMER

The opinions and conclusions expressed or implied in the paper are those of the entities/individuals performing the research and are not necessarily those of the Transportation Research Board, the National Research Council, the Federal Highway Administration, the American Association of State Highway and Transportation Officials, or the individual states participating in the NCHRP.

REFERENCES

Butler, H.D., and Hoy, H.E. 1977. *Users Manual for the Texas Quick-Load Method for Foundation Load Testing*. Federal Highway Administration, Office of Development, Report No. FHWA-IP-77-8, Washington, DC.

Davisson, M.T. 1972. *High Capacity Piles. Proceedings, Soil Mechanics Lecture Series on Innovations in Foundation Construction*. American Society of Civil Engineers, Illinois Section, Chicago, 81-112.

DeBeer, E.E. 1970. Proefondervindellijke bijdrage tot de studie van het grandsdraagvermogen van zand onder funderinger op staal. English version, Geotechnique, Vol. 20, No. 4, 387-411.

FHWA, 1988. *FHWA Guide Specifications for Driven Piles*. Federal Highway Administration

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

Goble, G., Likens, G., and Rausche, F. 1970. *Dynamic Studies on the Bearing Capacity of Piles – Phase III, Report No. 48*. Division of Solid Mechanics, Structures, and Mechanical Design. Case Western Reserve University.

Goble, G. and Rausche, F. 1976. Wave Equation Analysis of Pile Driving-WEAP Program. Vol. 1-4, FHWA #IP-76-14.1 through #IP-76-14.4.

GRL. 1999. *Pile-Driving Analyzer, PAK Users Manual*. Goble, Rausche, Likins and Associates, Inc.

GTR. 1997. Dynamic Pile Testing Report, Central Artery/Tunnel Project C07D2, I-90/Airport Interchange Arrivals Tunnel – Phase I, East Boston, Massachusetts. Geosciences Testing and Research, Inc. North Chelmsford, MA.

GTR. 1998. Dynamic Pile Testing Report, Central Artery/Tunnel Project C07D2, I-90/Airport Interchange Toll

Hajduk, E., Paikowsky, S., Holscher, P., and Barends, F. 2000. *Accelerations of a Driven Pile and the Surrounding Soil*. Proceedings, 6th International Conference on the Applications of Stress-Wave Theory to Piles, September 11-13, 2000. Sãn Paulo City, Brazil.

McVay, M., Birgisson, Bjorn., Zhang, L., Perez., A and Putcha S. 2000. *Load and Resistance Factor Design (LRFD) for Driven Piles Using Dynamic Methods – A Florida Perspective*. Geotechnical Testing Journal, ASTM, Vol. 23, No. 1, 55-66.

Paikowsky, S. 1982. *Use of Dynamic Measurements to Predict Pile Capacity Under Local Conditions*. M.Sc. Thesis, Dept. of Civil Engineering Technion-Israel Institute of Technology.

Paikowsky, S. 1995. *Using Dynamic Measurements for the Capacity Evaluation of Driven Piles*. Civil Engineering Practice, Journal of the Boston Society of Civil Engineers Section/ASCE. Vol. 10, No. 2, 61-76

Paikowsky, S. and Chernauskas, L. 1992. *Energy Approach for Capacity Evaluation of Driven Piles*. 4th International Conference on the Application of Stress-Wave Theory to Piles. The Hague, Netherlands. 595-601

Paikowsky, S. and LaBelle, V. 1994. *Examination of the Energy Approach for Capacity Evaluation of Driven Piles*. US FHWA Int. Conf. on Design and Construction of Deep Foundations, December 6-8, 1994. Orlando, FL. Vol. II, 1133-1149.

Paikowsky, S., Operstein, V., and Bachand, M. 1999. *Express Method of Pile Testing by Static Cyclic Loading*. Research Report submitted to the Massachusetts Highway Department, October 1999. Boston, Massachusetts

Paikowsky, S., Regan, J., and McDonnell, J. 1994. *A Simplified Field Method for Capacity Evaluation of Driven Piles*. FHWA Report No. FHWA-RD-94-042, September 1994.

Paikowsky, S.G. and Stenersen, K.L., *The Performance of the Dynamic Methods, their Controlling Parameters and Deep Foundation Specifications*, Key-Note lecture in the Proceeding of the Sixth International Conference on the Application of Stress-Wave Theory to Piles, Niyama S. and Beim J. edt., September 11- 13, 2000, São Paulo, BRAZIL, pp.281-304

Rausche, F., Goble, G. and Likens, G. 1975. *Bearing Capacity of Piles from Dynamic Measurements, Final Report*. Ohio Department of Transportation, Ohio DOT-05-75.

Smith, E. 1960. *Pile Driving Analysis by the Wave Equation*. Journal of Soil Mechanics and Foundations, American Society of Civil Engineers, August 1960. 35-61.

Stenersen, K. 2000. *Load and Resistance Factor Design (LRFD) for Driven Piles*. To be submitted in Partial Fulfillment of the Requirements for a MS in Civil of Engineering Degree. University of Massachusetts Lowell, Lowell, Massachusetts.

Terzaghi, K. 1942. Discussion of the Progress Report of the Committee on the Bearing Value of Pile Foundations. Proceedings, ASCE. Vol. 68: 311-323.

Thrift-Christensen, P. and Baker, M.J., 1982. *Structural Reliability Theory and its Applications*. Spring-Verlag, NY, 96-101.

Wellington 1892. Discussion of "The Iron Wharf at Fort Monroe, VA. By J.B. Cuncklee. Transactions, ASCE Vol. 27, paper No. 543, Aug. 1892, 129-137.