EVALUATION OF BEARING CAPACITY OF PILES USING THE RESULTS OF DIFFERENT FULL SCALE PILE LOAD TESTS

Ali Noorzad
Faculty of Water Engineering, Power and Water University of Technology, Tehran, Iran
Mehran Karimpour- Fard
Civil Engineering Department, Iran University of Science and Technology, Tehran, Iran
Ali Reza Mohammadi
Civil Engineering Department, Hormozgan University, Banadar Abbas, Iran

ABSTRACT

The prediction of axial bearing capacity of piles has received the attention of many geotechnical engineers. In the past decades, several approaches have been developed to overcome the uncertainty in the prediction. In the present paper, the in-situ bearing capacity of refused piles of a dry dock construction project is considered. Based on the obtained results a comparison has been made with six common available dynamic formulae. It is demonstrated that although the dynamic formulae have some deficiencies, however it is certainly desirable to estimate the bearing capacity of pile utilizing simple methods employing the results of large load tests.

RÉSUMÉ

De nombreux ingénieurs géotechniciens se sont penchés sur la prédiction de la capacité portante de pieux. Ces dernières décennies, plusieurs approches ont été développées afin d'améliorer la précision des prédictions. Dans l'article présent, la capacité portante de pieux au refus d'un projet de construction en cale sèche a été prise en considération. Une comparaison basée sur les résultats obtenus a été menée avec six formules de calcul dynamique classiquement utilisées. Il a été démontré que, bien que les formules de calcul dynamique aient chacunes quelques lacunes, il est très souhaitable d'estimer la capacité portante des pieux en utilisant des méthodes simples et les résultats de nombreux essais de chargement.

1. INTRODUCTION

The prediction of axial capacity of piles using different approaches has been an interesting issue in geotechnical engineering profession.

Due to uncertainties involved to predict the actual soil behavior, some simplifying assumptions have been made in all methods.

In order to estimate the bearing capacity of piles, five main approaches are presented as follow

- Interpretation of data from full-scale pile loading tests
- Static analysis utilizing soil parameters
- Methods using the results of in-situ tests
- Analysis of propagated wave in piles during or after installation especially by means of the Pile Driving Analyzer (PDA)
- Recommended dynamic formulae

There is no doubt that full scale static pile load test has the highest reliability and precision. However this test is expensive, time-consuming and the costs are often difficult to justify for ordinary or small projects.

On the other hand, static analysis methods which estimate the shaft and base resistances separately include considerable uncertainties. Debate exists over the appropriate choice of the horizontal stress coefficient, Ks, an unreliable approximation of Φ-Nq relationship which coupled with the difficulty of determining a reliable and representative in-situ value of Φ angle as well as the assumption of a proper shear failure surface around the pile tip. Also, the critical depth used in such common approaches has neither theoretical nor reliable experimental support, and contradicts with physics laws.

In recent years, the application of in-situ testing techniques has increased for geotechnical design. This is due to the rapid development of in-situ testing instruments, an improved understanding of the behavior of soils, and subsequent recognition of some limitations. In-situ based bearing capacity prediction methods strongly affected by the number of site investigation boreholes that could represent a reliable stratigraphy of site.

In dynamic analysis using the propagated wave equation through the pile, the bearing capacity of pile is computed. Dynamic testing method that is the modified form of dynamic analysis is based on the monitoring of acceleration and the strain near the pile head during driving. From these measurements, the pile capacity can be estimated by Pile Driving Analyzer (PDA) and numerical analysis of the data using softwares such as CAPWAP. However, the PDA can only be used by an experienced person and the test results apply essentially to the field-testing situations.

2. DYNAMIC FORMULAE

The most simple and oldest methods which were proposed to predict the bearing capacity of driven piles are dynamic formulae. In Table 1, six most current dynamic formulae are presented.

In these approaches the last pile set per blow is used to calculate pile capacity based on the Newton's impact law.

The simplicity of dynamic formulae is the main reason for the popularity of using this approach for many years. More comprehensive dynamic formulae include consideration of pile weight, energy losses in driving system components, and other factors. However using these approaches to predict the bearing capacity of piles should be supported by in-situ measurement and field test results. It means that performing full scale pile load test, static or dynamic, could be a proper approach to modify the pile dynamic formulae.

3. DRY DOCK PROJECT

Shipyard and Offshore Industries Dry Docks, locating on the northern banks of the Persian Gulf, Iran, consist of two docks with 470 m x 80 m and 370 m x 80 m dimensions and are designed to construct, repair and overhaul of VLCC vessels. The design vessel capacity is considered to be 370,000 tons. The docks are supposed to be able to accommodate vessels in critical conditions when their ballast water reservoirs are full to keep balance. As a result, the dock draft is 9 m in L.A.T low tide condition, and considering the natural ground level, the dock height will be 14.5 meters.

Heavy gravity loads from the vessels and considerable uplift forces acting below the 19 concrete raft namely LOT, impose a complex system behavior.

The thickness of the raft is the same for all LOTs which vary from 1.7m in centerline to 1.6m at sides to pass the surface runoff water to culverts. A side view of dry docks as well as a typical LOT and its pile arrangement are plotted in Figure 1.

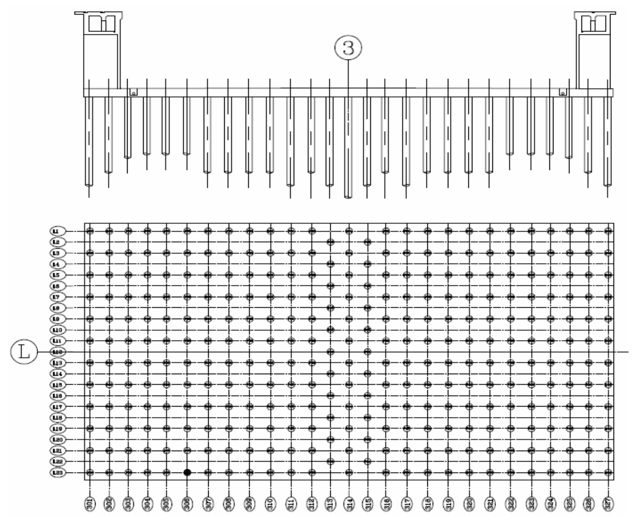

Figure 1. The Dry Dock side view and a typical plan of pile arrangement (LOT – L)

Table 1: Some current dynamic formulas

Method	Equation, R_u	Remarks
ENR, 1893	$\frac{E_h}{S+C}$	C = f (type of hammer)
Modified ENR, 1965	$\frac{1.25 e_h E_h}{S+C}.\frac{w_r + n^2 w_p}{w_r + w_p}$	C = f (type of hammer)
Eytelwein, 1961	$\frac{E_h}{S}.\frac{w_h}{w_h + w_p}$	
Gates, 1957	$a\sqrt{e_h E_h}\left(b - \log S\right)$	a & b = empirical factors
Janbu, 1967	$\frac{e_h E_h}{k_u S}$	k_u = f (w_r, w_p, A, L, E, E_h, e_h, S)
Hiley, 1961	$\frac{e_h E_h}{S + 0.5\left(C_1 + C_2 + C_3\right)}.\frac{w_r + n^2 w_p}{w_r + w_p}$	C_1 = f (driving stress, cushion condition) C_2 = f (driving stress, type of piles) C_3 = f (driving stress)
E_h : hammer energy, S : pile's set per blow, e_h : hammer efficiency, w_r : weight of hammer ram w_p : Pile weight, n : coefficient of restitution, A: cross section of pile, L: pile length, E: modulus of elasticity		

3.1. Site Investigation

In order to provide preliminary information concerning the soil layers, geotechnical investigation have been carried out. Several boreholes were extended to 65m deep till reaching a dense layer that could support the applied load properly. Pressuremeter and Standard Penetration Test were also carried out. SPT graphs indicate that around 30m deep there is a stiff layer which N values are more than 50. The results of site investigation are shown in Figure 2. It should be mentioned that the ground was excavated up to 17 meters to construct the dry docks and hence layers 1 and 2 have no role in calculating the bearing capacity.

3.2. Piling Programme

After the preliminary design, some piles were driven and their drivability were analyzed using GRLWEAP software and PDA (Pile Driving Analyzer) device. The results demonstrate that with respect to the soil layers and their density as well as close clear distance of piles (3 m average), low displacement piles should be chosen. Therefore spiral pipe piles were selected. The pile length varies from 18 to 25m in two different diameters, 1 and 1.2m. Also these results indicate that DELMAG series diesel hammers would be a proper choice to install the piles. Two models of DELMAG hammers were chosen with different capacity namely, D62 with a Max 22.3 ton-m energy and D80 with 27.2 ton-m energy per blows.

As the operation continues, in some locations layer becomes denser resulting the pile refusal before reaching to the design length. This problem has caused some doubt and debate on the bearing capacity of driven piles, therefore the designer should check the bearing capacity of installed piles with the new conditions. Therefore a vast pile load testing programme to evaluate the current bearing capacity of piles has been scheduled.

3.3. Pile Load Tests and Results

In order to assess the impact of pile refusal on the bearing capacity of dry docks foundation, 40 static load tests in compression and tension are conducted.

According to ASTM D1143 (for compression tests) and D3689 (for tension tests) slow maintained load method has been applied. A typical static pile load test results in LOT F is presented in Figure 3.

To evaluate the uncertainties pertinent to smaller embedment of pile length, 50 dynamic tests based on ASTM D4549-89 were carried out. 15 out of these 50 tests were conducted in repair dock and the other 35 were performed in renovation dock. Re-strike tests were conducted at least two weeks after pile installation. A maximum of 10 blows were applied to each pile during this test. Dynamic tests results were analyzed using signal matching technique by CAPWAP software. Pile tip and sleeve contributions to the final bearing capacity mobilization were determined by achieving the best match quality.

In order to mobilize the total bearing capacity of pile, the rate of penetration of the piles per drop has been

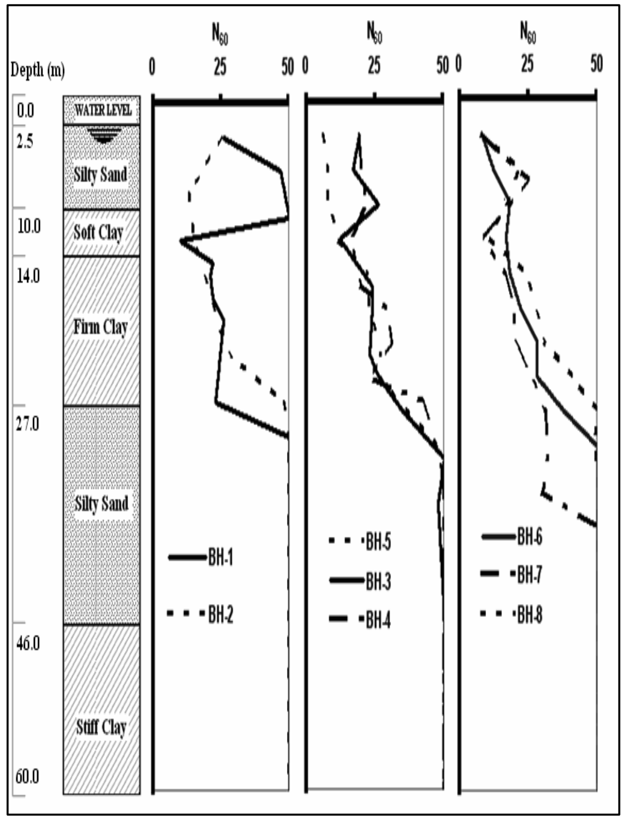

Figure 2. The startigraphy results for the project

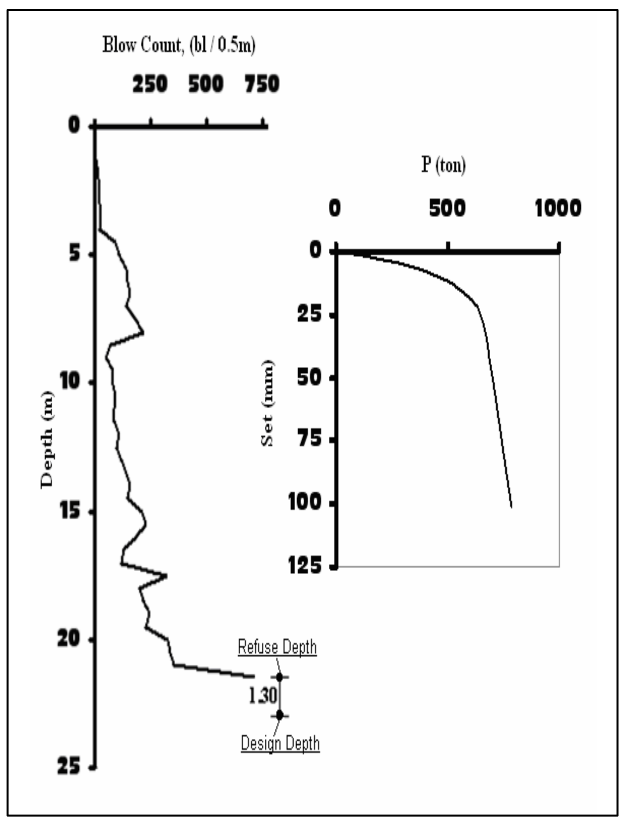

Figure 3. A typical static pile load test result in LOT D

increased by applying a strong hammer, D100. The measured average penetration per blow due to hammering during dynamic tests was 5mm. Two typical dynamic testing results are presented in Figure 4.

4. ERROR INVESTIGATION OF CURRENT DYNAMIC FORMULAS

The results of full scale pile load tests were used to make a comparison with some current dynamic formulae.

First a unique failure criterion is chosen for all full scale pile load test. Based on Likins and Rausche (2004), the ultimate bearing capacity represented by CAPWAP software has most compatibility to Davisson Offset Limit Load (1973). Therefore the results of full scale static pile load test were interpreted by this approach. To make the comparison among pre-mentioned dynamic formulas, Log-Normal approach, was used. The results of this comparison are presented in Figure 5.

These results indicate that Gates (1957) method has minimum scatter among other methods. This method underestimates the bearing capacity of piles. On the other hand, ENR approach has the highest error which highly overpredicts the bearing capacity. From this figure, it is evident that Janbu (1967) method has an acceptable error. The modified ENR (1965) and Eytelwein (1961) method have almost the same error.

In a statistical approach, the arithmetic values of predicted to measured bearing capacity for all cases as well as variance was calculated given in Table 2.

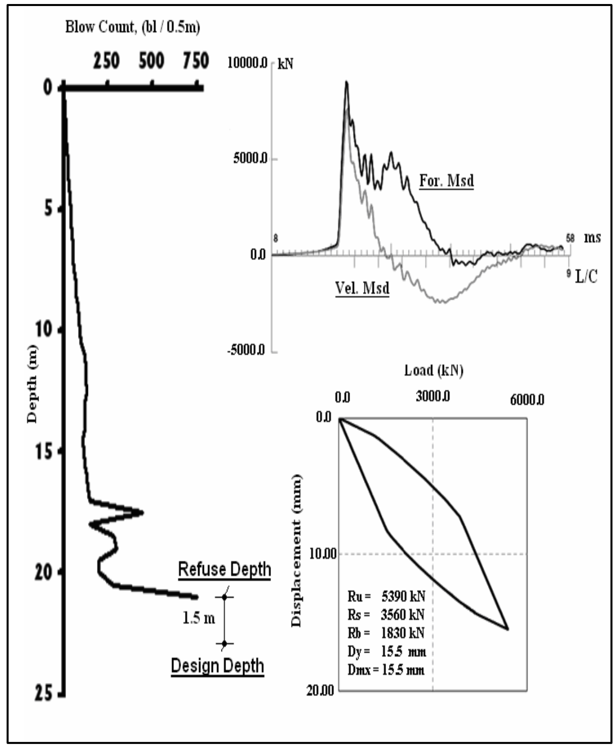

Figure 4. A typical dynamic testing result in LOT F

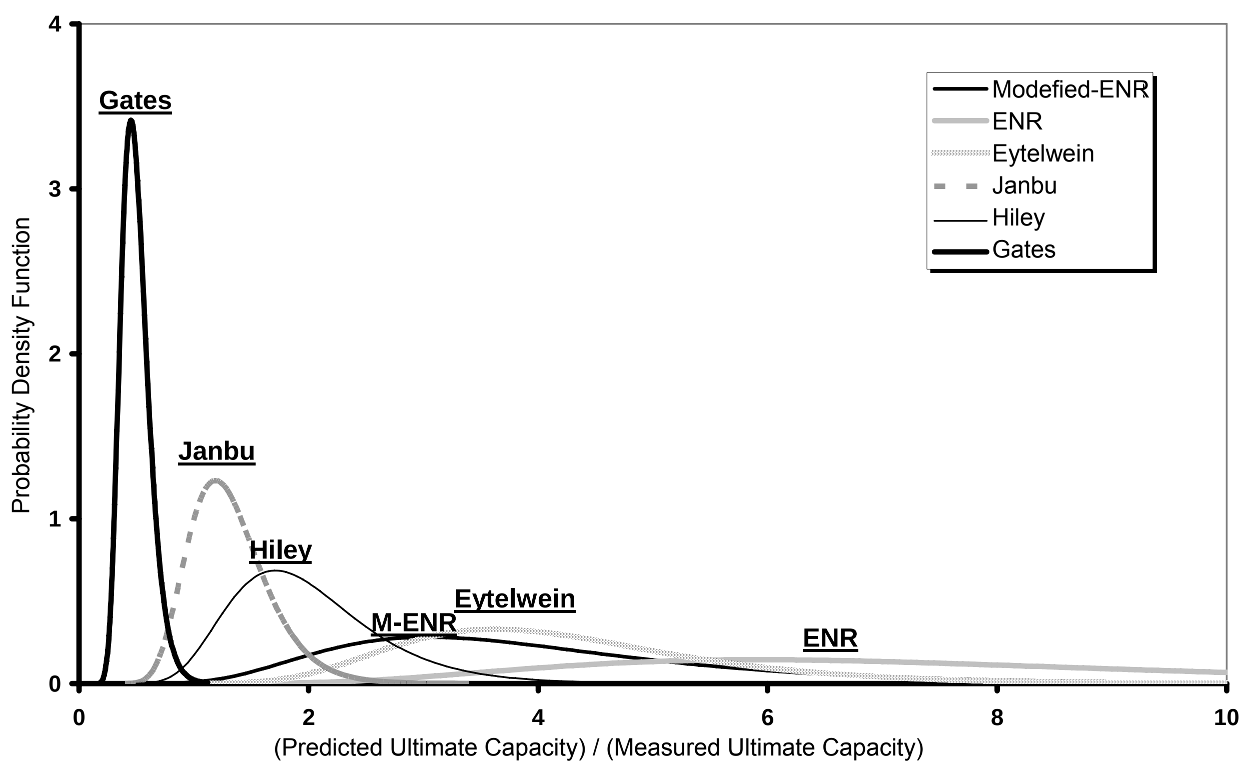

Figure 5. The comparison among six current dynamic formulas

Table 2. The results of statistical analysis on six current formulas

	Method	ENR, 1893	Modified ENR,1965	Eytelwein, 1961	Gates, 1957	Janbu, 1967	Hiley, 1961
In Original Form	Ave. Absolute Error	6.694	2.96	3.22	0.51	0.36	1
	Variance	9.12	2.432	1.85	0.03	0.09	0.38
After Modification	Ave. Absolute Error	0.33	0.33	0.27	0.21	0.22	0.26
	Variance	0.06	0.06	0.03	0.02	0.02	0.03
Modification Factor		7.4	3.8	4.1	0.49	1.3	2

Absolute Error = absolute value of 1- ($R_{prediucted}$ /$R_{measured}$)
Modification Factor = arithmetic average of $R_{prediucted}$ /$R_{measured}$
Modified Form = Original Form / Modification Factor

5. DISCUSSIONS

As mentioned in previous section, Gates (1957) formula has the highest precision and minimum scatter. The results of statistical analysis showed that after applying modification factor the absolute error as well as the variance of this formula, has the lowest value. The Janbu method also is another approach which its precision is almost the same as Gates formula. In the other hand ENR and Modified ENR approaches, have the highest error.

In Figure 6 and 7 the predicted versus measured graphs are plotted and the range of error for ±15% and ±30%, are illustrated. These graphs also indicate that the Gates and Janbu method have a good agreement in comparison to other approaches.

The Gates approach is rather simpler than Janbu method both technically and applicability.

As shown in Table 1, Hiley (1961) method which is based on some empirical factors is not a proper method due to its dependency on operator experience.

Therefore, based on the Gates formula, set criterion graphs, are presented in Figure 7.

These set criterion graphs are for three types of used hammers in this project. In this figure the results of preliminary GRLWEAP which is one of the most current software for drivability analysis, for the same hammers are also shown. However, the similarity between the Gates formula which are modified by full scale pile load tests and GRLWEAP software is interesting.

Figure 8. The set criterion graph based on Gates formula and a preliminary GRLWEAP analysis

6. CONCLUSION

Piling stage in projects which includes a large number of piles specially driven types is one of the most difficult geotechnical operations.

Shipyard and Offshore Industries dry docks which are the largest dry dock in the Middle East located on northern banks of the Persian Gulf of Iran consist of two docks with 470 m x 80 m and 370 m x 80 m dimensions

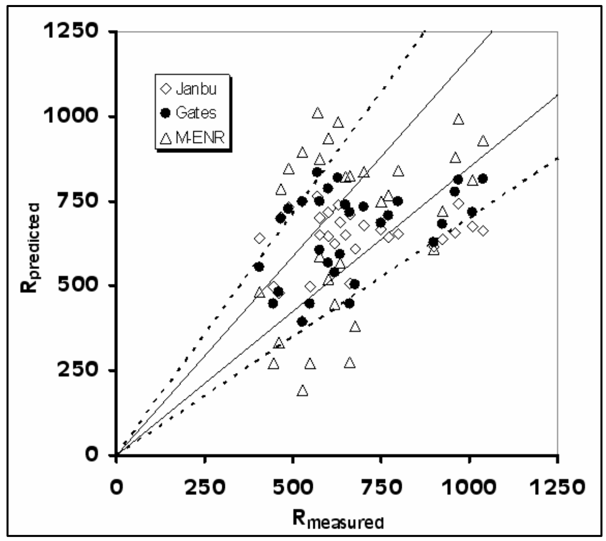

Figure 6. A comparison among the modified form of Janbu, Gates and M-ENR approaches

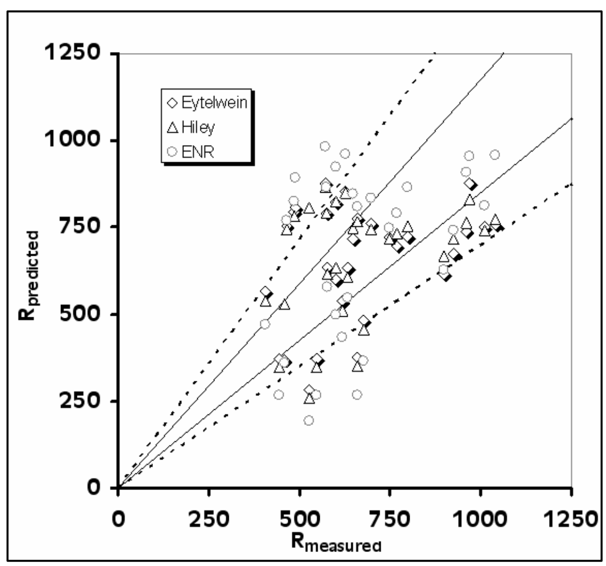

Figure 7. A comparison among the modified form of Eytelwein, Hiley and ENR approaches

and are designed to construct, repair and overhaul VLCC vessels.

In this project 6500 spiral pipe piles for the dry docks pile-raft foundation have been installed. In addition, more that 500 spiral pipe piles has been driven for the crane foundation in each side.

In such project, performing the full scale pile load test to reach a cost effective design and operation is required for pile driving operators to control the piling procedures based on dynamic formulae.

In the piling stage refusal of some piles has caused some doubt and debates on the bearing capacity of piles. To overcome any uncertainty about bearing capacity of piles and to reach a proper understanding of new condition of driven piles, a full scale pile load test programme has been scheduled.

A data bank of refused piles in the project is compiled which consists of driving records and the results of static and dynamic full scale pile load tests. As the predicted bearing capacity by CAPWAP software has the most agreement with Davisson Offset Limit Load criterion, the results of static load test are interpreted by this criterion.

Among several available dynamic formulas, six most current methods were chosen and for all the cases in the data bank the ultimate bearing capacity are predicted.

The results of a statistical and Log-Normal approach demonstrate that Gates method has the best prediction with lowest scatter among other methods. In the other hand ENR method has the most scatter and error.

Based on the statistical approach, some modification factors were applied to the original formulas. The results of modified form of methods in the measured versus predicted graphs indicate the reliability of Gates formula. Due to simplicity and accuracy of the method it is chosen to represent a set criterion.

The agreement among set criteria represented by a modified form of Gates formula and a preliminary GRLWEAP analysis is an indication on the accuracy of represented set criterion.

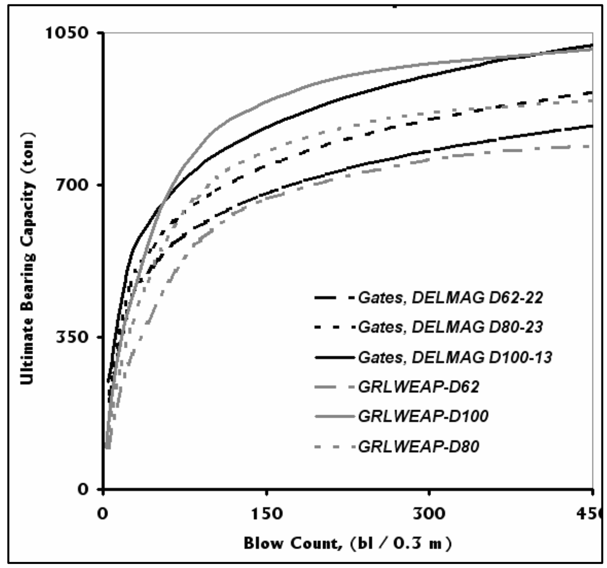

Figure 8. The set criterion graph based on Gates formula and a preliminary GRLWEAP analysis

REFERENCES

Eslami, A., and Fellenius, B. H. 1997. Pile capacity by direct CPT and CPTu methods applied to 102 case histories. *Canadian Geotechnical Journal*, 34: 886-904

Fellenius, B. H. 1995. *Guidelines for the interpretation and analysis of the static loading test.* A Continuing Education Short Course Text, Deep Foundation Institute Publications, P.O. Box 281, Sparta, NJ 07871.

Gates, M. 1957. *Empirical formula for predicting pile bearing capacity*. Civil Engineering, ASCE, Vol.27, No. 3, pp. 65-66

ENR .1965. *Michigan pile test program results are released.* Eng. News-Record, May 20, pp. 26-28, 33-34

Hiley, A. 1930. *Pile-driving calculation with notes on driving forces and ground resistances*. The Structural Engineer, London, Vol. 8, pp. 246-259, 278-288

Karimpour-Fard, M. 2000. Comparison among methods for Prediction the ultimate bearing capacity of piles based on results of pile load test and in-situ tests-study of case histories. *M.Sc. Thesis*, Civil Engineering Department, Iran University of Science and Technology, Tehran, Iran.

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

Mandro Consultant Engineer. 2000. Preliminary geotechnical evaluation of Dry Docks project site. Final Report, Bandar Abbas Dry Docks Project.

Nayak, N.V. 1985. *Foundation design manual*. Dhanpat Rai & Sons pub.

Omran Sahel Contractor Engineering, 2005. Dynamic pile testing and analysis. Final Report, Bandar Abbas Dry Docks Project.

Omran Sahel Contractor Engineering, 2003. Static pile load test and analysis. Final Report, Bandar Abbas Dry Docks Project.

Poulos, H. G. and Davis, E. H. 1980. *Pile Foundation Analysis and Design.* John Wiley & Sons.

Shariatmadari, N., Eslami, A., and Karimpour-Fard, M. 2006. A New Method for Estimation the Bearing Capacity of Piles Based on SPT Results. *31st DFI Annual Conference on Deep Foundations*, Washington DC., 421-429