



## Evaluation of Static and Dynamic Methods for Determining the Bearing Capacity of the Driven Pipe Piles

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### ABSTRACT

Determination of pile capacity is always a major concern for safe geotechnical engineering design. Different direct and indirect methods are proposed for pile bearing capacity determination such as static and dynamic approaches. Each method depends on soil conditions, pile type as well as accessibility to necessary information. In this study bearing capacity of driven pipe piles in cohesive soils are investigated. For this purpose the information of 208 driven piles in four sites in total areas of 1500 m<sup>2</sup> are obtained. Using this information, dynamic relations of pile bearing capacity in fine grained soil is computed and compared with result of static relations. Results indicate the accuracy of the Engineering News Record (ENR), modified ENR and new modified ENR approaches in comparison with static methods.

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### NOMENCLATURE

$r_t$	Unit toe resistance(kPa)	$S$	Dynamic blow count (blows/mm)
$A_t$	Cross-section area of the pile toe(m <sup>2</sup> )	$E$	Hammer efficiency
$r_s$	Average unit shaft resistance of soil layer i(m <sup>2</sup> )	$e$	Reversion constant
$A_s$	Pile shaft circumferential area interfacing with layer i(m <sup>2</sup> )	$W_p$	Weight of pile plus driving appurtenances(kg)
$n$	Number of soil layers along the pile shaft	<b>Greek Symbols</b>	
$Q_t$	Toe bearing capacity(kPa)	$\nu$	Poisson's ratio
$Q_s$	Shaft bearing capacity(kPa)	$\rho$	Unite weight of soil(kN/m <sup>3</sup> )
$B$	Foundation wide(m)	$\phi_d$	Internal friction angle(degree)
$C$	Soil cohesion	$\phi_u$	Short-term internal friction angle(degree)
$q$	Effective overburden Stress at the end of the pile(kPa)	$C_d$	Long- term cohesion(kg/cm <sup>2</sup> )
$N_q, N_c$	None dimension pile bearing capacity factors	$C_u$	Short- term cohesion(kg/cm <sup>2</sup> )
$P_a$	Allowable pile load(kN)	$E_s$	Elastic modulus(kg/cm <sup>2</sup> )
$W_f$	Weight of the drop hammer(kg)	$G_s$	Specific weight(g/cm <sup>3</sup> )
$h$	Height of the whole driving(m)		

## 1. INTRODUCTION

Accurate prediction of pile capacity has always been a challenge of designer engineers. The dimensions of foundation and subsoil layers condition with different behaviors are the difficulties for evaluation of pile

bearing capacity. Also deep foundation as pile is usually applied in problematic soils and massive load. Therefore it is a major concern in foundation design.

Pile capacity evaluation can be present into two categories: direct and indirect methods. The indirect methods include static analyses which can be calibrated by specific coefficients obtained by direct methods. The main idea of direct methods is the relation between pile capacity and in-situ measurements.

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Pile capacity can be considered as geotechnical and structural resistance. Geotechnical resistance or bearing capacity is the load refers to soil failure near the shaft and toe of the pile with large displacement.

Indirect and direct methods are two main approaches for application of geotechnical information to pile design. Indirect methods apply soil parameters, such as the friction angle and un-drained shear strength estimated from the geotechnical investigation as evaluated from bearing capacity theory, which introduce significant uncertainties. The indirect methods discounted horizontal stress; include strip-footing bearing capacity theory, and neglected soil compressibility and strain softening [1].

Indirect methods consider the mean effective stress, soil compressibility and rigidity affect the pile. Therefore, this eliminates the need to supplement the field data with laboratory testing and to calculate intermediate values. Moreover, pile bearing capacity determination categorized into the following four groups;

1. Static analysis
2. Static analysis using in situ test results
3. Static pile load test and
4. Dynamic analysis and dynamic testing

Common theoretical static analysis consider shear strength based on different failure models with interaction of soil and pile in static condition as shown in Figure 1. In-situ tests can be performed as supplement methods such as Standard Penetration Test (SPT; e.g. Shioi and Fukui [2], Davis E.H. [3]), and Cone Penetration Test (CPT; e.g. Fang [4], Eslami and Felenious [5]), both in direct and indirect methods. Static pile load test, a pile loaded in a real condition with monitoring strain and stress behavior exposure to the load. This method is cost and time consuming, but its main advantage is that it can be evaluated directly with more accuracy.

The other methods are dynamic analysis and testing by pile driving. The relations of driven pile based on specific information obtained geotechnical investigation have been extensively used in pile bearing capacity evaluation. The fact that designers are not able to adapt themselves to one or the other formulas related to pile driving because the mathematical relationships governing the pile driving have not been solved for all practical cases. Therefore, more research has been done within the extension driven pile bearing capacity. Pile driving is not a simple impact issue that it can be solved directly by Newton's law, but pile driving is a longitudinal wave transmission issue in a general solution covered by the wave equation. In addition, pile driving requires considering such as pile caps, composite and taper piles, along with the elastic-plastic behavior of ground and other issues of soil mechanism. The consequences coming out of the problems are that all the relations of pile driving are to some extent

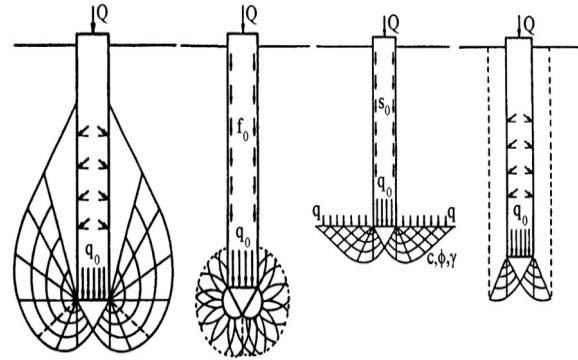


Figure 1. Different failure models with interaction of soil and toe pile [4]

experimental and consequently useful for specific type of piles and specified length of piles. One of the methods to determine the bearing capacity of pile during driving is the use of energy concept. The various relations consider the strength of pile driving is equal to bearing capacity as the number of blows used for moving down the pile to a specific depth. This criterion is reported in the form of blows/cm or blows/m. Hence, the accurate measuring of the pile penetration length is very important.

To this end the paper first reviews previous efforts in pile bearing capacity, then a brief explanation of the case histories under consideration, and the phenomena of pile capacity evaluation are presented. Finally the developed evaluation is described and its accuracy is assessed through validation phase.

## 2. BACKGROUND TO PREVIOUSLY PROPOSED METHODS

Governing relations the bearing capacity as a brief description of the outlines are presented as follows:

**2. 1. Static Analysis Method** Several methods have been developed to calculate the bearing capacity of piles, all including simplifying assumptions and/or empirical approaches regarding soil stratigraphy, soil-pile structure interaction, and distribution of soil resistance along a pile [6]. Pile capacity evaluation includes the sum of the end pile strength and the skin strength. Total pile capacity concluded by toe and shaft pile capacity computation as,

$$Q_{ult} = Q_t + Q_s = r_t A_t + \sum_1^n r_s A_s \quad (1)$$

where

$r_t$  Unit toe resistance(kPa)

$A_t$  Cross-section area of the pile toe ( $m^2$ )

$r_s$  Average unit shaft resistance of soil layer  $i$   
 $A_s$  Pile shaft circumferential area interfacing with layer  $i$  ( $m^2$ )

$n$  Number of soil layers along the pile shaft

$Q_t$  Toe bearing capacity (kPa)

$Q_s$  Shaft bearing capacity (kPa)

Evaluating total pile capacity in static condition,  $r_s$  and  $r_t$  factors are needed to be calculated. The general form of unit tip resistance is the same as bearing capacity of shallow foundation and according to Terzaghi [7] relations. The fact that the pile diameter is not comparable to the pile length, the term  $0.5\gamma BN\gamma$  omitted. So the unit tip resistance of pile is:

$$Q_t = CN_c + qN_q \quad (2)$$

where

$C$ : Soil cohesion

$q$ : Effective overburden Stress at the end of the pile (kPa)

$N_q, N_c$ : None dimension pile bearing capacity factors. Hansen [8], Meyerhof [9], Vesic [10], Janbu [11] and Terzaghi presented none dimension factors and advise their relations such as soil type and soil layer identifications.

In other hand, unit shaft resistance affected by soil layer based on soil shear resistance. Drain and un-drain condition is the main concept of unit shaft resistance determination. Many researchers investigated the unit shaft resistance such as  $\alpha$ ,  $\beta$  and  $\lambda$  method by Tomlinson [12], API [13] and Polous [14].

**2. 2. Dynamic Methods** Dynamic methods are another way of pile load capacity determination. In this method pile bearing capacity is directly counted by the blows of hammer as a resistance of soil. The methods are the Engineering News Record (ENR), modified ENR and new modified ENR.

The driven pile capacity can be determined from the dynamic blow count:

1) ENR:

$$P_a = \left[ \frac{W_r h}{F(S + 0.1)} \right] \quad (3)$$

2) Modified ENR:

$$P_a = \left[ \frac{0.0025 E(W_r + e^2 W_p)}{(S + 0.1)(W_r + W_p)} \right] \quad (4)$$

3) New modified ENR:

$$P_a = \left[ \frac{0.0031 E(W_r + e^2 W_p)}{(S + 0.1)(W_r + W_p)} \right] \quad (5)$$

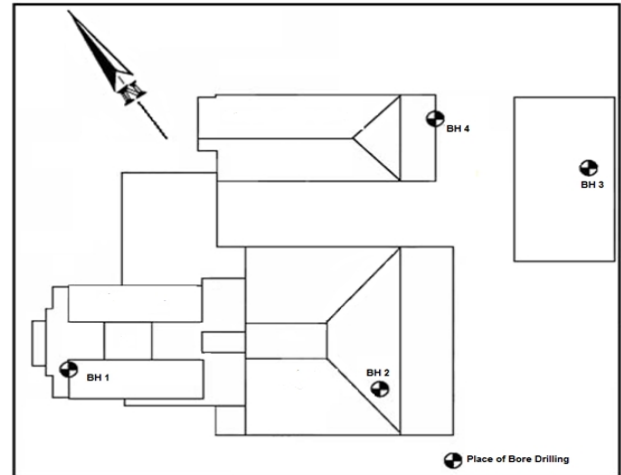


Figure 2. Plan of area classification and place of borehole

where,  $P_a$ : Allowable pile load (kN);  $W_r$ : weight of the drop hammer (kg);  $h$ : Height of the whole driving (m);  $S$ : dynamic blow count (blows/mm);  $E$ : hammer efficiency;  $e$ : reversion constant and  $W_p$ : weight of pile plus driving appurtenances (kg) [15].

### 3. OVERVIEW OF DATABASE AND CASE HISTORY

Bearing capacity of the driven pipe piles was examined in fine grained soils over a project in Amol city (North of Iran) in a region of  $1500 m^2$ . Case history information include geotechnical investigation and driven pile properties. For geotechnical evaluating, the region was divided into four parts with a bore-hole. Figure 2 shows the location of the borehole in the project region.

#### 3. 1. Geotechnical Information of the Case Study

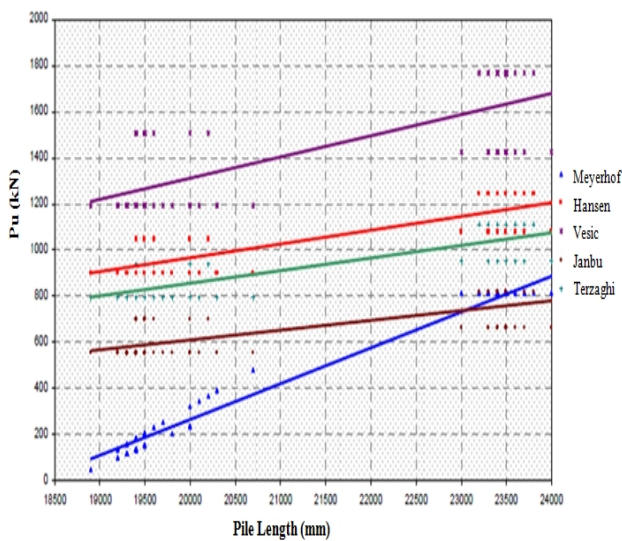
The case study located in eastern part of Amol city. Sub soil up to 2 m, soil classified CL (clay with low plasticity). It can be seen silt, clay and sand soil type alternately after the upper soil layer until the end of borehole 20 meter. The layers of different thickness (less than a few centimeters to several meters) and mostly between 0.5 to 1 meter are based on the unified soil classification system are available in categories SW-SM, SM-SP, ML, CL, CL-ML and SP-SM. The standard penetration blow counts (NSPT) in these layers are between 5 and 17, except in one case, it can see increasing blows along with the increasing in depth. Strength of soil layers are categorized loose to medium and soft to stiff. Underground water level in all the boreholes is seen about 1 meter in depth. Physical and mechanical characteristics of soils for different layers are shown in Table 1.

**TABLE 1.** Geotechnical characteristics of soil

Characteristic of soil	Lower sandy layers	Clay layers	Silty layers	Upper sandy layers	Unit
Internal friction angle ( $\phi_d$ )	28-30	25-37	24-26	30-33	degree
Short-term internal friction angle ( $\phi_u$ )	-	0	0	-	degree
Long- term cohesion ( $C_d$ )	0	0.1-0.2	0.2	0	kg/cm <sup>2</sup>
Short- term cohesion ( $C_u$ )	-	0.4-0.7	-	-	kg/cm <sup>2</sup>
Elastic modulus ( $E_s$ )	80-100	70-100	80-100	130-150	kg/cm <sup>2</sup>
Poisson's ratio( $\nu$ )	0.3	0.4	0.35	0.3	-
Specific weight ( $G_s$ )	1.85-1.95	1.85-1.95	1.85-1.95	1.85-1.95	g/cm <sup>3</sup>

**TABLE 2.** Dynamic analyses parameter

Parameter	Value
$Wr$	1266 kg
$h$	2.62 m
$E$	0.85
$e$	0.4

**Figure 3.** Toe pile capacity according to the length of pile with the best line passing for 4 areas to different methods

**3. 2. Driven Pipe Pile Properties** Steel pipe piles were used with open end with the internal diameter of 35.56 cm and side thickness of 79 mm. Pile driver was Delmak 12 with the approximate weight 12.66 N and fall height 2.62 m [2]. As a sample, the distributions of the pile in site A illustrated in Figure 3. Number of blows per 10 cm pile penetration in different depth measured taking account to pile bearing capacity. The other properties of dynamic analysis parameters in order to pile capacity determination have been shown in Table 2.

## 4. RESULTS

In this part, pile capacity evaluated by different methods as Toe and shaft bearing capacity and dynamic relation. For obtaining this goal, investigation such as geotechnical soil properties and dynamic blow counts per distance gathered.

**4. 1. Toe Pile Capacity** Toe pile capacity according to different methods (Meyerhof, Hansen, Vesic, Janbu, Terzaghi) are evaluated for each four 4 study areas together as in Figure 3. In Meyerhof relation two main factors resulting in strength are the number of dynamic blow count and the rate of pile penetration into the bearing layer, penetration rate into the bearing layer obtained affect results directly, so as it is shown in the chart below, the piles with less depth (about 19.5 m) the obtained number of Meyerhof relations are smaller from all relations and the pile with more depth (about 23.5 m) the value from Meyerhof relation is almost larger than other relationships. It is not necessary to present nomenclature at the beginning of the paper, each variable or symbol used in the text must be clearly defined after its first appearance in the text.

**4. 2. Shaft Pile Capact** Figure 4 Comparison of skin strength of piles to  $\lambda$  methods and sum of  $\alpha$  and  $\beta$  compared together: The diagrams of this figure show that skin strength of piles in 4 areas is very close to  $\lambda$  method and sum of  $\beta$  and  $\alpha$  methods. But for piles 19 to 20 m except piles in D area the obtained number of  $\lambda$  method is slightly greater than value of sum  $\beta$  and  $\alpha$  methods. But piles into the soil 23 to 24 m the total  $\beta$  and  $\alpha$  methods show greater than  $\lambda$ . The thicknesses of layers in D study area (12.7 m) are significantly more than the other parts.

**4. 3. Dynamic Relation for Pile Capacity** Strength of dynamic relations and sum of the tip strength and skin strength compared to relations of static relation for all areas with pile length, for all areas in Figure 5. It's remarkable that the part of the pile length into the cohesion soils in D study area is more than the other areas. Strength of piles in other areas is not more differences in length.

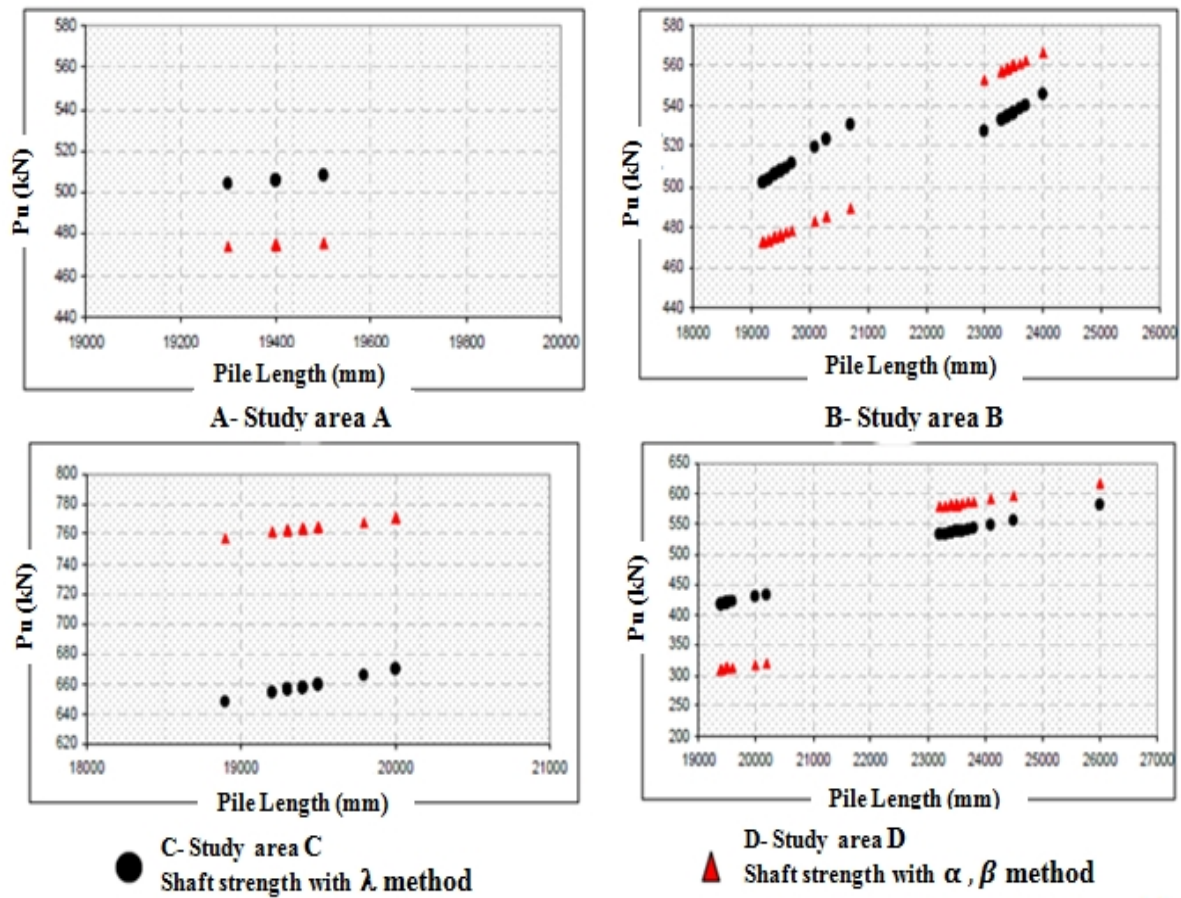
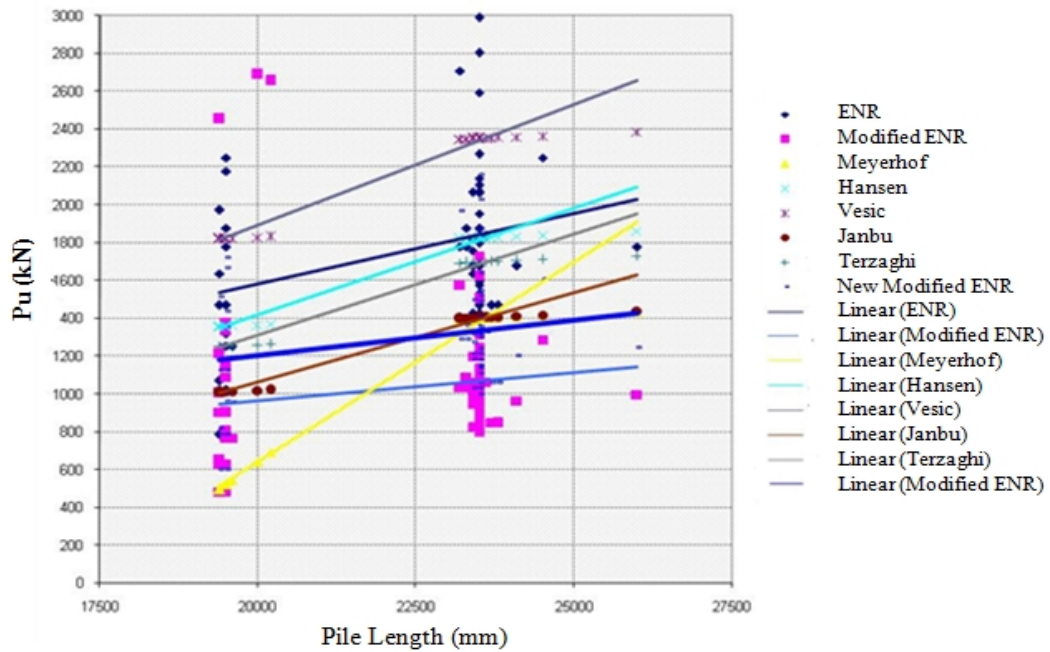


Figure4. Comparison of shaft pile capacity with pile length to different methods



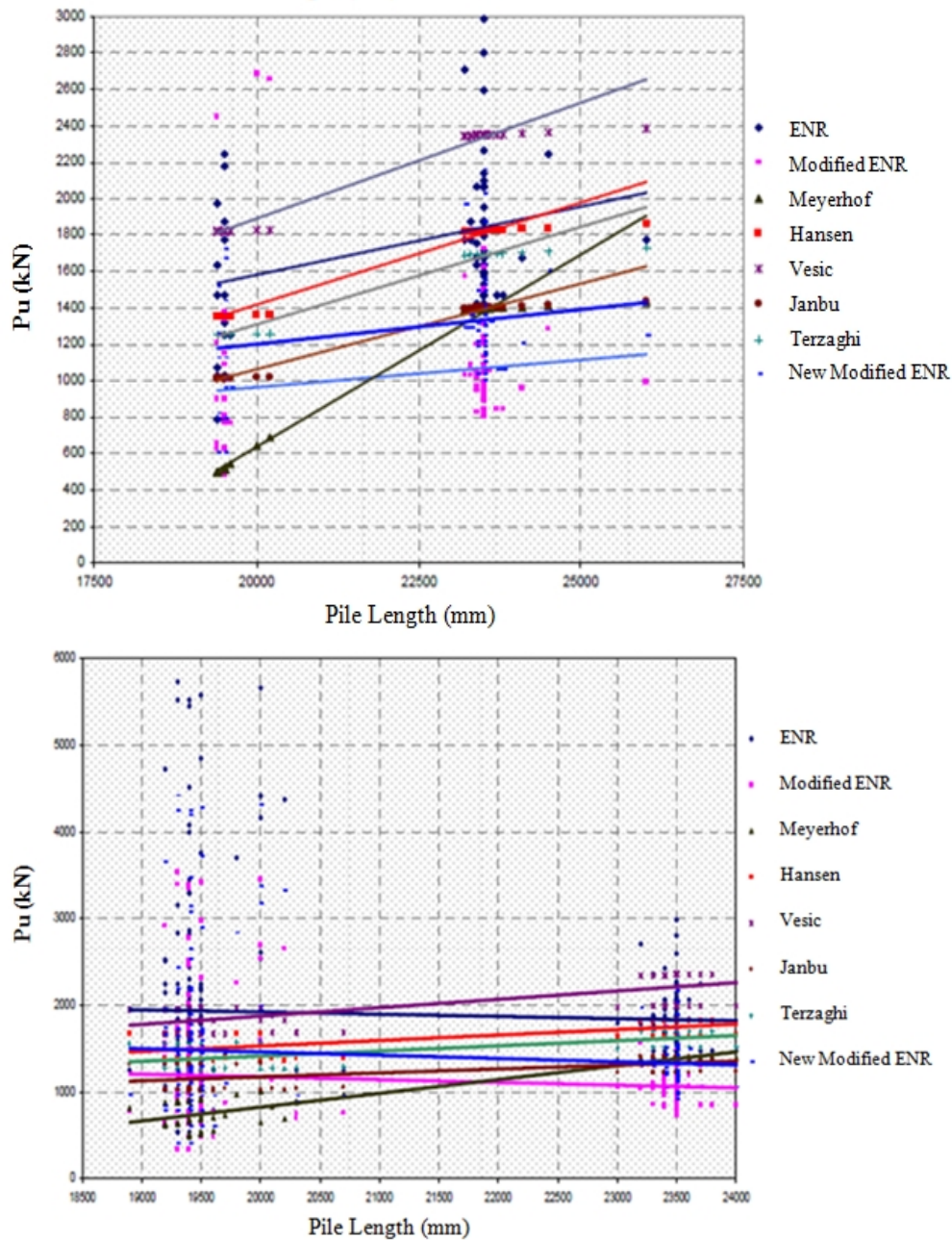


Figure5. Diagram of changes in load capacity of piles according to depth for all study with static and dynamic method

### 5. CONCLUSION

It should be mentioned that every expert person can calculate the pile load capacity and it is possible for them to use different ways but what is important and emphasized collecting of valuable data, comparing and qualitative assessment of information. In this study there are many factors like: how to perform and recorded information and existing theories and it should not just be paid attention to raw values but we should analyze

the existing relations and their ratio to them. Therefore, the following results are presented:

Among the static various methods to determine the pile bearing capacity, Meyerhof and Janbu relations are conservative and Vesic relationships are very high. Perhaps the using of average values from different relations is appropriate solution to increase accuracy and reduce calculation errors.

Strength of soil in end pipe pile of open end are formed before penetrating the layer of hard clay soil

layer (cohesion soil), it means pipe piles performance solidly and increase the tip strength of pile.

It's better to calculate skin strength of different parts of piles in different cohesion and cohesionless layers and their parameters are calculated separately, if the necessary information is not available the results of  $\lambda$  method can be thoroughgoing. Results of dynamic relations of pile bearing capacity in which their researches are used (ENR method, modified ENR and new modified ENR) have good correlation with static relations.

In parts where the clay layers are relatively high, the bearing capacity from dynamic relations to static relations is larger. With increasing thickness of clay layers (cohesion soil) in the place of pile driving and the upper of pile point the load capacity from dynamic and static relations will increase.

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**TEACHNICAL  
NOTE**I. Shooshpasha<sup>a</sup>, H. Mola-Abasi<sup>a</sup>, I. Amiri<sup>b</sup><sup>a</sup> Department of Civil Engineering, Babol University of Technology, Iran<sup>b</sup> Department of Civil Engineering, Mazandaran Institute of Technology, Iran

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تعیین ظرفیت باربری شمع‌ها همیشه یکی از دغدغه‌های اصلی مهندسان طراح خاک و پی می‌باشد. دو روش مستقیم و غیرمستقیم برای تعیین ظرفیت باربری شمع‌ها همانند روش استاتیکی و دینامیکی پیشنهاد می‌گردد. هر یک از روشهای فوق به شرایط خاک، نوع شمع بستگی دارد. در این تحقیق برای تعیین ظرفیت باربری شمع های کوبیده شده از اطلاعات ۲۰۸ شمع که در مساحت ۱۵۰۰ مترمربع کوبیده شده است استفاده گردیده است. نتایج این مطالعه دقت بالای روش ENR، ENR اصلاح شده و ENR اصلاح شده جدید را در مقایسه با روش استاتیکی نشان می‌دهد.

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