Expermental euqation for selecting a proper hammer to avoid overstress condition during pile driving

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ABSTRACT
The most common way of installing a pile is driving it using a hammer. The pile hammer forces the pile into the ground by repeated application of impulsive force. The employed hammer should be able to drive the pile to the desired depth without causing excessive driving stresses. In this paper, the data of the three major projects which involved numerous cases of pile driving were gathered. Using the collected data and employing a wave equation analysis program, GRLWEAP, an equation which estimates the induced stresses in the piles during pile driving, is proposed. Comparison of the results of the proposed equation with GRLWEPA program and a previously developed empirical equation shows a good agreement between them.

RÉSUMÉ
La manière la plus commune d'installer une pile la conduit utilisant un marteau. Le marteau de pile force la pile dans le sol par application répétée de la force impulsive. Le marteau utilisé devrait pouvoir enfoncer le pieu à la profondeur désirée sans causer des efforts moteurs excessifs. En ce document, les données des trois projets principaux que de nombreux cas impliqués de l'entraînement de pile ont été recueillis. Utilisant les données rassemblées et utiliser un programme d'analyse d'équation d'ondes, on propose GRLWEAP, une équation qui estime les efforts induits dans les piles pendant la pile conduisant. La comparaison des résultats de l'équation proposée avec le programme de GRLWEPA et d'une équation empirique précédemment développée montre une bonne concordance entre elles.

1 INTRODUCTION

Driving is one of the most used methods of pile installation even after passing a century by the time of its origination. Impulsive force of the ram which is induced by hammer blow causes a downward travelling stress-wave in pile. Recently, these stress waves can be analyzed by dynamic measurements at the pile top (Webster et al. 2008, Rausche et al., 1985) or can be predicted by wave equation programs (Rausche et al.,1992). Although the proper driving specifications such as use of hammer cushion, pile cushion, and helmet are required to avoid pile damage but transferred energy to the pile head from the kinetic energy of the ram is the main factor that should be taken into consideration. Dynamic measurements require electronic instrumentation and ability to record short duration events (Fellenius, 1996). Majority of the design analyses in the foundation engineering were developed from direct observations in the field by foundation experts (Fellenius, 1996). So, the use of the site specific empirical formulas based on the real cases of pile driving and output analyses of the wave equation analysis programs can be very useful in practice. In this study, an empirical correlated equation is proposed to estimate the induced dynamic stress of the pile by hammer blow. To obtain this site specific equation, the field data of three major projects in the south of Iran which were involved with numerous cases of pile driving were gathered. Then, using the gathered data, a wave equation analysis program called GRLWEAP was calibrated to the driving condition of each one of these sites. A parametric study was undertaken to generate more data and also consider the significance of involving parameters. Eventually, using the gathered and generated data, a site specific equation was proposed which computes induced dynamic stresses during driving a certain pile in certain soil condition.

2 DRIVING STRESSES IN PILE

2.1 EMPIRICAL PROPOSED EQUATIONS AND ALLOWABLE DRIVING STRESSES

As the ram strikes the pile head, both compressive and tensile stresses are created in the pile body due to the hammer impact. In steel piles, tensile stresses have minor significances but in concrete piles this factor plays a leading role in the design stage and should be taken into the consideration. Using a large hammer delivers high amounts of energy to the pile head which may cause excessive driving stresses or even damage the pile body. Generally, permitted material stresses of the pile are determined on the basis of the pile material and soil condition (FinnRA, 2000). To avoid overstress condition during pile driving, the induced stress by hammer blow must not exceed driving stress limits. Finland standard, for instance, recommends that the maximum permitted driving stress of the pile can be taken $0.9F_y$ where F_y is yield stress of the pile material. An estimation of the driving compressive stress has also been given by Finland standard (FinnRA, 2000):

$$\sigma_{max} = f_w . f_\circ . V_\circ . \frac{E}{C} = f_w . f_\circ . \sqrt{\gamma H E} \qquad [1]$$

where f_w is reflection factor pertinent to the soil condition; f_c is coefficient depending on the pile driving rig; V_o is ram velocity (m/s); E is modulus of elasticity of the pile material (kN/m^2); C is stress wave velocity (m/s) (e.g. velocity of the stress wave in steel is about 5100 m/s); γ is unit weight of the steel (kN/m^3); and H is hammer stroke (m).

2.2 COMPUTED DRIVING STRESSES BY WAVE EQAUTION ANALYSIS PROGRAMS

In the wave equation analyses programs, the pile, hammer, helmet, cushions, and soil are modeled as a series of lumped masses, springs, and dashpots (Hannigan et al., 1998). The program calculates acceleration, velocity, displacement, forces, and stresses of each segment over time. These programs can also establish a relationship between hammer energy or stroke and driving resistance for ultimate capacity values. In this way, maximum created stresses can be obtained which enable the user to select a practical hammer energy or stroke range. In this study, the performed analyses were carried out by GRLWEAP which is a wave equation analysis program (Pile dynamic, 2003).

3 FIELD CALIBRATION

In this study, all analyses performed with GRLWEAP program using the gathered data of the three sites. In order to use the analyses result, the program was calibrated to the driving condition of each one of these sites.

3.1 FIELD MEASURMENTS

The used data in this study were provided from three sites which were located in the south of Iran on the coastline of the Persian Gulf. In these sites, numerous cases of steel piles were driven with diesel hammers. More details regarding these projects are presented in the subsequent parts.

3.1.1 SITE A

This site is located on Bahonar harbour in Bandar-Abbas, a port city on the southern coast of Iran, on the Persian Gulf. At this site, abundant numbers of piles were driven as a deep foundation which their characteristics were: piles type = open-ended steel pipe pile, piles total length = 24 to 36 m, piles embedded length = 16 to 30 m, piles diameter = 0.762 m, piles wall thickness = 18 mm. The Delmag D-36 was chosen as a typical diesel hammer with an efficiency of 0.8. The general soil profile was consisted of dense to hard silty sand as described in Table 1. In order to calibrate the input information of the GRLWEAP program, field data of blow counts per meter was collected in each of these projects. For instance, in Site A, the blow counts per meter along the driven length of the 15 cases of pile driving were gathered. For brevity, only the total numbers of blow counts along the entire driven length of these piles are shown in Table 2.

3.1.2 SITE B

This site was in Kish, a resort island in the Persian Gulf and was employed as an expansion phase of Kish commercial harbour. The characteristics of the used piles were: piles type = open-ended steel pipe pile, piles total length = 7 m, piles embedded length = 6.75 m, piles diameter = 0.914 m, piles wall thickness = 16 mm. The hammer which was used to drive the piles was Delmag D-62-22 with approximate efficiency of 0.85. The soil condition of this site is summarized in Table 1. Based upon the field observations, four records of blow counts per meter along the driven length of piles were gathered during the driving process. The total numbers of blow counts along the entire driven length of these piles have been shown in Table 2.

Table 1. Soil conditions

From (m)	To (m)	Description
Site A		
0	12	Dense silty sand
12	18	Very dense clayey silty sand
18	28	Hard silty clay
28	43	Very dense sandy silt
Site B		
0	7	Backfill material
7	17	Sandy soil with some shell debris
17	27	Clayey soil with layers of dense silt
27	-	Clayey soil with layers of very dense silt
Site C		
0	12	Gray silty sand
12	22	Very dense silty gravel with sand
22	27	Very dense silty gravel with sand and cobble
27	-	Very dense silty gravel with sand

3.1.3 SITE C

This site is located in Kangan harbour, a small harbour in Kangan town in the coastline of the Persian Gulf on Bushehr province. Several large diameter piles were driven by Delmag D-100-13 and Delmag D-46 with estimated efficiency of 0.85. Piles characteristics were: pile type = open-ended steel pipe pile, pile total length = maximum 40 m, pile embedded length = 25 to 30 m, pile diameter = 1.422 m, pile wall thickness = 19.8 mm. The soil profile mainly consists of normal to very dense silty sand and gravel. The general soil profile is described in Table 1. Totally, 14 records of blow counts per meter along the penetrated length of pile were gathered. But in this site, these records are only pertaining to the last few meters of driving length which are shown in Table 2. The total number of blow counts along the recorded driven length of the piles are presented in the last column of Table 2.

Table 2. Gathered field records for calibration of the input data in GRLWEAP program

Site A				
Pile No	Total pile length (m)	Driven length of the pile (m)	Hammer model	Total numbers of the blow counts
A1	31.45	16.45	D[a]-36	970
B1	31	16	D-36	848
C1	31	16	D-36	896
B2	35.1	23.1	D-36	1632
C2	35	23	D-36	1570
B3	36.31	29.6	D-36	2925
A4	24.3	22.3	D-36	1521
B4	24.3	22.3	D-36	1367
M1-1	32	18	D-36	1808
M1-2	34.65	23.65	D-36	2115
M1-3	32	18	D-36	2405
M3-1	32	18	D-36	2009
M3-3	32	18	D-36	1856
M4-1	32	18	D-36	1837
M4-3	32	18	D-36	1817
Site B				
Pile No	Total pile length (m)	Driven length of the pile (m)	Hammer model	Total number of the blow counts
L3-AP3	7	6.75	D-62-22	80
L3-AP4	7	6.75	D-62-22	117
L3-AP5	7	6.25	D-62-22	31
L3-AP6	7	6.5	D-62-22	41
Site C				
Pile No	Total pile length (m)	Recorded length of the pile[b] (m)	Hammer model	Total number of the blow counts
B31	38.6	9.48	D-100-13	1134
A32	38.6	5.52	D-100-13	761
A27	38.6	7.34	D-100-13	918
B32	38.6	8.54	D-100-13	984
A34	38.6	8.6	D-100-13	920
C34	38.6	8.33	D-100-13	1089
B35	38.6	7.79	D-100-13	1012
C31	38.6	7.2	D-100-13	946
B37	24	9	D-46	978
A37	24	8.95	D-100-13	1293
E34	39.6	8.64	D-100-13	843
D43	39.6	8.96	D-100-13	1160
D42	39.6	8.71	D-100-13	958
B31	39.6	8.2	D-100-13	1016

[a] D denotes Delmag diesel hammer.

[b] The blow count per meter has been recorded in this length which shows the last few meters of the driven length.

3.2 CALIBRATION PROCEDURE

The main required input parameters of GRLWEAP program consist of soil parameters; pile information, hammer parameters, pile and hammer cushion information. Soil parameters are: toe quake, Q_t, skin quake, Q_s, which describe maximum elastic deformation at the toe and skin of the pile; toe damping, J_t, skin damping, J_s, which describe dynamic behaviour of the soil at the toe and skin of the pile, respectively. The required properties of the hammer and pile cushions information are cross sectional area, elastic modulus, thickness, coefficient of restitution, cushion stiffness and helmet weight. All of the above information were obtained from the field except soil properties and the hammer cushion stiffness.

The unknown parameters were back-calculated from the set of the pile per blow data, which were directly collected in the field as presented in Table 2. To initiate the iterative process, starting estimates are required. The typical values of skin damping and quake parameters recommended by others (Mcvay & Kuo 1999, Nath 1990, Pile dynamic 2003) are used to obtain starting estimates for Q_t, Q_s, J_s and J_t. These values have been shown in Table 3.

Table 3. The values of unknown parameters in GRLWEPA before and after calibration in different sites

The values of unknown parameters used for starting estimates					
Site	Q_s (mm)	Q_t (mm)	J_s (sec/m)	J_t (sec/m)	Stiffness of the hammer cushion (kN/mm)
A	2.5	6.35	0.16	0.5	40000
B	2.5	7.6	0.16	0.5	40000
C	2.5	11.85	0.65	0.5	10000
The values of unknown parameters after calibration					
A	2.5	6.35	0.16	0.5	900000
B	2.5	7.6	0.16	0.5	648000
C	2.5	2.5	0.65	0.5	38180

The hammer cushion stiffness is calculated from EA/t where E is the elastic modulus, A is the cross sectional area and t is the thickness of the cushion. The used hammer cushion material in both sites *A* and *B* were a few rounds of towing wire, while wood hammer cushion was employed in site *C*. Table 3 shows the quantities of the unknown parameters in GRLWEAP before and after calibration. In order to evaluate the calibrated results, measured blow counts per meter of the field were compared with GRLWEAP program output after calibration process. For instance, the calibrated results of site A is displayed in Figure 1.

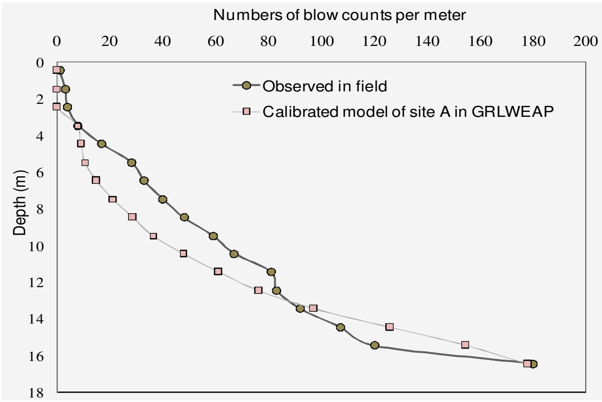

Figure 1. Comparison of the calibrated results of GRLWEAP program with field measurements in site A

4 DATA GENERATION

After calibration of GRLWEAP program, a parametric study was performed for each site to produce more data. One pile of every site was chosen to be analyzed with different hammer sizes in GRLWEAP program in order to compute the maximum induced compressive stresses of the piles. Table 4, for instance, shows the maximum induced compressive stresses of pile No. A1 of site A which has been driven with various hammer sizes.

Table 4. Generated data of the maximum induced compressive stresses of pile No. A1 of site A under the impact of various hammers

Hammer ID	Rated energy of hammer (kJ)	Max. Compressive stress (kN/m^2)
D-08	7.832	92674
D12	12.237	96500
D-15	14.685	109300
D-16	15.664	134800
D-22	21.849	144600
D-25	24.52	169390
D-30	29.37	167500
D-36	35.288	191300
D-44	42.275	180100
D-46	45.123	198300
D-55	52.777	204900
D-62	60.787	223140
D-80	78.409	215800
D-100	98.194	238130
D-200	196.2	217500

This parametric study also considers the effects of various involving parameters on the numbers of the blow counts per meter, *n*. These parameters are (1) coefficient of restitution of the hammer cushion, *C.O.R*, which shows amount of energy dissipation when ram impacts a pile cushion; (2) toe quake, Q_t, which describes maximum elastic deformation of the soil at the pile toe; (3) skin damping, J_s, which describes dynamic behavior of soil at the skin of the pile; (4) helmet weight; (5) stiffness of the hammer cushion, *k*. After conducting the parameter study, following results were obtained:

C.O.R of commonly used material for cushions usually varies between 0.5 and 0.8. By increasing the value of *C.O.R*, no notable changes were recognized in the numbers of blow counts per meter.

According to some recommendations (Mcvay & Kuo 1999, Nath, 1990, Pile dynamic, 2003), toe quake, Q_t, can vary from 2.5 mm to *D/120*, where *D* is pile diameter in millimeter, but skin quake, Q_s, can be taken 2.5 mm for all soil types. Also toe damping, J_t, can be chosen 0.5 sec/m for all soil types while skin damping, J_s, varies between 0.16 sec/m for non-cohesive soils to 0.65 sec/m for cohesive soil. So, here only Q_t and J_t were considered. Slight decreasing of blow counts per meter was experienced while increasing Q_t value. About the toe damping, according to the Figure 2, numbers of blow counts per meter increase with the increase of J_t value.

Helmet weight was varied between 10 and 30 kN to investigate its effect on blow counts per meter. Increasing the helmet weight while the hammer, pile and soil properties are constant, resulted in decrease and then increase of the blow counts per meter values.

The stiffness of hammer cushion, *k*, is calculated based on the $k = E.A/t$ where *E* is elastic modulus, *A* is cross sectional area of the cushion and *t* is cushion thickness. To investigate the effect of hammer cushion stiffness, elastic modulus of cushion material was varied from 250 to 5000 MPa and the thickness was taken as 5 cm. As it can be seen in Figure 3, which shows the effect of the hammer cushion stiffness in site C, by increasing the value of the *k* form 5000A to 100000A *(MN/m3 × A)*, the blow counts per meter are decreased. It means that stiffer cushions transmit greater percentage of the hammer energy to the pile head.

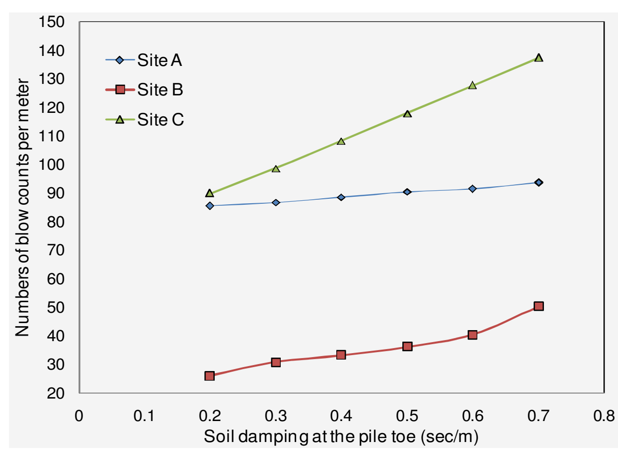

Figure 2. Effect of the soil damping at pile toe on the numbers of blow counts per meter

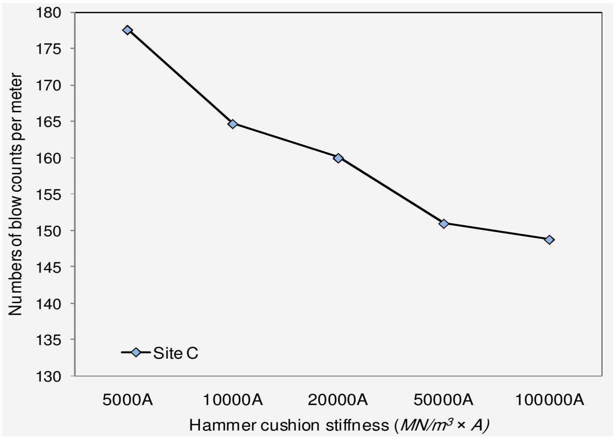

Figure 3. Effect of the hammer cushion stiffness on the numbers of blow counts per meter in site C

5 INVESTIGATION INTO A SIMPLE EMPIRICAL EQUATION

Selection of a proper hammer for driving a pile depends on a number of factors including physical characteristics of the pile and driving resistance of the soil. A small hammer may not be able to drive the pile to the required depth or even may lead to pile refusal. On the other hand, a large hammer may fail to operate properly due to the large displacement of the pile head per hammer blow or may damage the pile body by inducing overstress condition in pile.

5.1 APPROXIMATE EQUATIONS FOR PROPER HAMEMR SELECTION

Authors of this study have previously presented couple of equations which determine the proper range of hammer's rated energy as shown by Equations (2) and (3) (Afshani et al., 2010). As the rated energy of the diesel hammers are given by hammer manufactures, so, the proper hammer can be selected for driving a certain pile in a certain soil condition. Eq. 2 represents the minimum rated energy of the diesel hammer which prevents from pile refusal and Eq. shows the maximum rated energy of the diesel hammer for driving a certain pile without causing failure of hammer operation due to the large displacement of the pile head.

$$E_{min} = \frac{1}{0.64}\left(\frac{R_u}{60e^{0.07L_e}}\right)\left(1+\sqrt{1+\frac{R_u L(60e^{0.07L_e})}{AE}}\right) \quad [2]$$

$$E_{max} = \frac{1}{0.64}\left(\frac{R_u}{30e^{0.05L_e}}\right)\left(1+\sqrt{1+\frac{R_u L(30e^{0.05L_e})}{AE}}\right) \quad [3]$$

where E_{min} and E_{max} are minimum and maximum rated energy of diesel hammers; R_u is total soil resistance; L is total length of the pile; L_e is embedded length of the pile; A is cross sectional area of the pile and E is elastic modulus of the pile.

5.2 PROPOSED EQUATION FOR DRIVING STRESS ESTIMATION

In the current study, an experimental equation is proposed based on the gathered field data and generated data of the GRLWEAP program. Using the Buckingham π theorem, main involving parameters in driving stress are: σ, compressive stress (kN/m^2); E_r, rated energy of the hammer (kJ); D, pile diameter (m); t, pile thickness (m); γ, unit weight of the steel (kN/m^3); E, elastic modulus of the pile material (kN/m^2). The process can now be described by an equation of the form:

$$f(\sigma, E_r, D, t, E, \gamma) = 0$$

Two dimensionless parameters can be stated as follows:

$$\pi_1 = \frac{E_r}{E.D^3}, \pi_2 = \frac{\sigma}{\gamma.t}$$

Using the gathered field records and generated data (Table 4), dimensionless parameter π_1 was drawn versus π_2 as displayed in Figure 4. Eq. 4 shows the best correlated equation between the dimensionless parameters.

$$\sigma_{max} = 3\times10^7\left(\frac{\gamma.t}{D}\right)\left(\frac{E_r}{E}\right)^{0.363} \quad [4]$$

where σ is compressive stress (kN/m^2); E_r, is rated energy of the hammer (kJ); D is pile diameter (m); t is pile thickness (m); γ is unit weight of the steel (kN/m^3); E is elastic modulus of the pile material (kN/m^2).

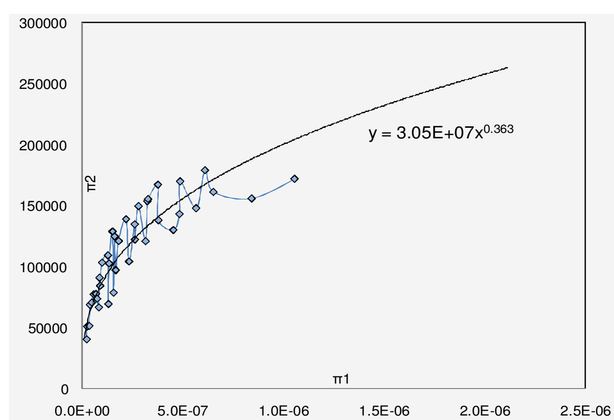

Figure 4. Correlation between dimensionless parameters of π_1 and π_2

Using Eq. 4, the maximum induced compression stress can be estimated for driving a certain pile with a hammer. Thus, comparing the computed stress with allowable stress limit helps to select the proper hammer which does not result in overstress condition in the pile body.

5.3 COMPARISON OF THE OUTPUT RESULTS

In this part, the results obtained from the proposed equation is compared with the GRLWEAP program computation and Finland proposed equation. Figure 5 presents the comparison results using the data of pile No. A1 of site A. It can be seen from Figure 5 that the proposed equation demonstrates good conformity with the wave equation analysis program, GRLWEAP.

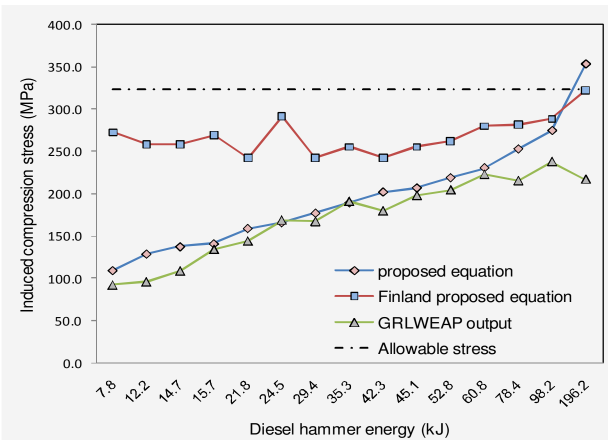

Figure 5. Comparison of the results of the proposed equation with GRLWEAP program computation and Finland proposed equation

6 CONCLUSIONS

In this research a simple practical equation to estimate the driving stresses of piles induced by hammer blow was proposed. For this purpose, the filed data of three major projects in the south of the Iran were collected. Then, using the gathered data, a wave equation analysis program, GRLWEAP was calibrated to the driving condition of each one of these sites. A parametric study was performed to generate more data and also consider the significance of involving parameters. Eventually, using the gathered and generated data, a site specific equation was proposed. Comparing the computed stresses using the proposed equation with the allowable stresses enables the user to select a proper hammer which does not result in overstress condition in the pile body. Comparison of the overall form of the proposed equation with Finland equation (Eq. 1) indicates that:

(1) Dimension of the pile which is an important factor in pile driving attempts has been considered in the proposed equation.

(2) As the hammer stroke or ram velocity varies during the process of driving, the rated energy of the hammer which is given by hammer manufactures is used as a specific indicator of the hammer in lieu of hammer stroke or ram velocity.

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