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COST REDUCTION OF DRIVEN PIPE PILES DUE TO INCORPORATING PILE SETUP CAPACITY

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ABSTRACT

In this paper, data was collected from 21 pipe-pile projects constructed in Ohio (Khan, 2011). Data included the number of piles, restrike time, pile length, pile diameter, initial total capacity, restrike total capacity, and average clay and silt content along the pile length. The effect of including pile setup on the cost was investigated in terms of the reduction in the pile length. The percentage increase in pile capacity due to setup ranged from 6% to 167%; while the average for all investigated piles was 36%. As for the expected pile length reduction, from incorporating setup in the capacity calculations, it varied from 5% up to 67%. Another important factor that was investigated is the restrike time. It was found that there is no need to wait beyond 96 hours for restrike testing to achieve significant setup. It was concluded that the pile capacity increase due to setup was significant and worth including during the design stage of the project.

Keywords: engineering design management, pile foundation, cost reduction, setup capacity, foundation cost, pipe piles, value engineering.

1. INTRODUCTION

As a pile is driven into the ground, it disturbs and displaces the soil. When the soil that surrounds the pile recovers from this installation disturbance, a time-dependant increase in pile capacity often occurs. This phenomenon is referred to as “setup” or “pile freeze”. The increase in pile capacity attributed to the setup phenomenon could be significant. On the other hand, a reduction in capacity is called “relaxation”. The dissipation of excess pore pressure during pile driving rules the setup and relaxation. In the event of setup, the primarily induced positive pore pressure in the soil becomes nearly zero after some time, creating an increase in effective stress. In the case of relaxation, the reduction of primary induced negative pore pressure produces a decrease in effective stress with time.

Setup usually occurs in organic and inorganic saturated clay, loose to medium dense silt, sandy silt, silty sand, and fine sand (Attwooll *et al.,* 2001). Holloway and Beddard (1995) noted minor or no setup in highly silty low-plasticity cohesive materials. Walton and Borg (1998) demonstrated that in sand and gravel setup may not be a significant factor in long-term pile capacity. In cohesive soils (for example: clay), or a mixture of fine-grained granular and cohesive soils (for example: clayey sand, or clayey silt), the excess porewater pressure induced by pile driving takes longer to dissipate. Therefore, some setup is associated with the logarithmically non-linear dissipation (Phase 1), whereas the majority of setup is associated with the logarithmically linear dissipation (Phase 2). For these types of soils, the final aging phases (Phase 3) accounts for relatively little setup. Furthermore, it was found that soft clays setup more than stiff clays (Long *et al.*, 1999). On the other hand, in fine-grained granular soils (like: fine sand, or silt), the excess porewater pressure induced by driving dissipates relatively rapidly (almost while driving). As a result, some setup may occur in Phase 2 (logarithmically linear dissipation); whereas the majority of setup may be associated with Phase 3 (aging) in these types of soils (Komurka *et al*., 2003).

In order to deliver a safe and cost-effective design of driven piles, a reliable estimate of the change in pile capacity is essential. To achieve optimal pile foundations, it is preferable to incorporate setup in the design phase or estimate the expected strength gain from setup so that piles could be installed at a lower End of Driving (EOD) capacity. Several procedures are available to explain the setup phenomenon in cohesionless, cohesive, and mixed soils (Komurka *et al*., 2003). It is common practice in geotechnical engineering to incorporate setup in the design phase during static analysis (Khan, 2011). However, the question remains whether setup will occur at the site or not. To answer this and eliminate uncertainty, full-scale pile load tests are carried out at the field (Khan, 2011). During the construction phase, setup could be calculated using empirical equations used in conjunction with dynamic load tests. Dynamic load tests measure the force and velocity near the pile head during initial driving and later on during restrike (Khan, 2011). These measurements could be used to estimate pile capacity among other attributes like performance of the pile driving system, pile installation stresses and pile integrity. Pile setup can be computed by comparing the restrike capacity with the initial EOD capacity from the dynamic load testing. Once setup has been characterized, it could be applied to the design to optimize the piles sizing. It is therefore important to understand the setup phenomenon to take advantage of it.

Factors influencing setup and relaxation are: pile length, pile diameter, soil type, effective stress at the tip, and time (Tarawneh, 2013). Several researchers have presented empirical formulas to predict pile setup (Skov and Denver, 1988; Svinkin, 1996; Svinkin and Skov, 2000; and Long *et al.* 1999). The semi-logarithmic model of Skov and Denver (1988) is one of the most commonly used equations to predict the setup increase in pile capacity with time. Some researchers recommend

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including setup in the prediction method to determine total pile capacity during the design stage.

Bullock *et al.* (2005a, 2005b) recommended a conservative approach for including side shear setup into the total pile capacity. The same degree of uncertainty was assumed for the measured capacity and the predicted setup capacity; therefore, a single factor of safety was used to account for all uncertainties of loads and resistances. Komurka *et al*. (2005) applied separate safety factors to the end of driving capacity and setup capacity components to account for the different uncertainties associated with the measured versus predicted values. Some researchers have presented artificial intelligence based formulas to predict pile setup with remarkable accuracy (Tarawneh and Imam, 2014; and Tarawneh, 2013). Incorporating pile setup in the design of driven pipe piles could increase the cost-effectiveness by resulting in higher pile capacity. When incorporating the effects of setup during design, it may be possible to reduce pile lengths, reduce pile sections (either by using a smaller-diameter, thinner-walled pipe piles, or smaller-section H-piles), or reduce the size of driving equipment (use smaller cranes and/or hammers). Achieving one, or more, of these reductions could result in cost savings. The ultimate aim is to estimate setup reasonably accurately without significantly increasing subsurface exploration costs. Subsequently, shorter piles would lead to overall cost reduction of piling work. All these reductions can considerably lower the overall cost of a project that involves pile driving. Setup can be estimated and incorporated by using empirical formulas, performing restrike testing, delaying load testing, or developing depth-variable driving criteria.

Geotechnical engineers use dynamic monitoring through a Pile Driving Analyzer (PDA) during initial driving and later during restrike testing, several hours to a few weeks after initial driving, to characterize setup. For projects involving a large number of driven piles, the savings in pile costs from incorporating setup could significantly exceed the cost of the testing required to characterize setup. Nevertheless, on projects involving less number of piles, the cost of testing to characterize setup might exceed the forecasted pile installation cost savings. Therefore, for such small-scale projects, the testing required to characterize setup is generally not justified from an economic standpoint.

2. THE PILE SETUP PHENOMENON

2.1 Evaluation of pile setup

The mechanisms behind pile setup have been the subject of numerous research works. Empirical relations predict the increase in pile capacity with time from the initial End of Driving (EOD) capacity and the elapsed time after driving. The most commonly used formulae are compiled from the literature. Equation 1 is the model presented by Skov and Denver (1988) which is a linear relationship of setup with respect to the log of time. The proposed empirical relationship to describe setup is:

$$\frac{Q_t}{Q_o} - 1 = A\log_{10}\left(\frac{t}{t_o}\right) \tag{1}$$

where:

Q_t = pile capacity after time 't',
Q_o = initial capacity at time t_o, end of driving
A = a constant depending on soil type, and
t_o = an empirical value measured in days.

In Equation (1), t_o is a function of the soil type and pile size and is the time at which the rate of excess pore-water pressure dissipation becomes uniform (linear with respect to the log of time). The value of t_o is suggested to be 0.5 for sand and 1.0 for clay. Parameter *A* is a function of soil type, and pile material, type, size, and capacity, but is independent of depth, and porewater pressure dissipation. *A* is reported as 0.2 for sand and 0.6 for clay.

Guang-Yu (1988) presented an equation for estimating pile capacity of prestressed concrete piles in soft soils. The estimates are given for capacity on the 14th day after driving, and are based on the sensitivity of the fine-grained soil as presented in Equation (2). Guang-Yu (1988) suggested that sands and gravels experience no setup.

$$Q_{14} = (0.375S_i + 1)Q_{EOD} \tag{2}$$

where:

Q_{14} = pile capacity at 14 days
Q_{EOD} = pile capacity at end of driving (EOD)
S_i = sensitivity of soil (clay sensitivity)

Huang (1988) suggested a formula, presented as Equation 3, for predicting the setup rate of steel H-piles in the soft-ground soil of Shanghai.

$$Q_t = Q_{EOD} + 0.236(1 + \log(t)\,(Q_{max} - Q_{EOD})) \tag{3}$$

where:

Q_t = pile capacity at time *t (days)*
Q_{EOD} = pile capacity at end of driving (EOD)
Q_{max} = maximum pile capacity

Svinkin *et al.* (1994) proposed the use of t_o = 1 day in Skov and Denver equation, since the pile capacity gain becomes approximately linear with the logarithm of time 1 day after pile installation. Their formula (Equation 4) predicts setup based on load test data performed on five concrete piles in dense silty sand.

$$Q_t = BQ_{EOD}t^{0.1} \tag{4}$$

The range for *B* is 1.025 (lower bound) and 1.4 (upper bound).

Long *et al.* (1999) have shown for a database of 80 pile load tests on piles of various types (timber, concrete, prestressed concrete, steel or concrete closed-

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ended pipe, steel or concrete open-ended pipe) installed in various types of soil (clays, sands, and layered soil profiles) that pile capacity increases by a factor of 4 to 5 times 100 days after installation. Their proposed model (Equation 5) predicts the rate at which pile capacity increases as an exponential function of time. Long *et al.* (1999) recommends using $t_o = 0.01$ day.

$$Q_t = 1.1 Q_{EOD} t^{\alpha} \quad (5)$$

Values of α: average = 0.13, lower bound=0.05, and upper bound = 0.18

Svinkin and Skov (2000) tested concrete prestressed piles and steel H piles to propose, based on Equation (1), a formula for pile setup (Equation 6) except that the time for EOD is taken as 0.1 days (2.4 hours). The factor B is similar to factor A in Equation (1). Their equation is applicable for clay and cohesive soils.

$$\frac{Q_t}{Q_{EOD}} - 1 = B[\log(t) + 1] \quad (6)$$

where:

Q_t = ultimate capacity
Q_{EOD} = End of Driving (EOD) capacity,
B = a factor ranging from 1.6 to 3.5

In addition to the above listed methods, artificial neural network (ANN) models proposed by Tarawneh (2014); Tarawneh and Imam (2014) could be used to predict pile setup during the design stage to reduce pile diameter and length.

2.2 Setup phases

Komurka *et al.* (2003) divided the soil pile setup mechanisms into the following three phases:

- **Phase One:** logarithmically non-linear rate of excess porewater pressure dissipation and set-up;
- **Phase Two:** logarithmically linear rate of excess porewater pressure dissipation and set-up;
- **Phase Three:** aging, which is independent of effective stress.

Along the pile shaft, it is likely that some overlap between successive phases may occur, resulting in more than one phase contributing to set-up at any given time (for example, aging (Phase 3) may begin before the complete dissipation of excess pore water pressure (Phases 1 & 2). In addition, unless soil conditions are uniform along the entire length of the shaft and beneath the toe, different soil types at different elevations could be in different phases of set-up at a given time.

3. RESEARCH METHODOLOGY

For optimization of pile foundations, piles could be installed at a lower EOID capacity given the predicted strength gain resulting from setup. Therefore, incorporating the setup effect into the design of driven piles can improve the estimation of total capacity of driven piles so that pile length or number of piles can be economically reduced. The procedure adopted in this study to incorporate setup of driven piles included 4 steps as follows:

a) Collecting data on 21 pipe-pile projects constructed in Ohio (Khan, 2011). For these cases investigated, the setup data was compiled along with the number of piles, restrike time, pile length, pile diameter, average clay and silt content.
b) Initial total capacity (Q_o in kN) from dynamic load tests at pile installations was collected and compiled.
c) Based on dynamic load testing, restrike capacity (Q_t in kN) was estimated and the increase in pile capacity due to setup was calculated.
d) Based on the results from step 3 the effect of including setup on the cost is investigated in terms of the reduction in pile length to optimize the design.

4. COLLECTED DATA AND ANALYSIS

Data on 21 pipe pile projects was investigated. Table-1 summarizes the collected data. After incorporating setup in the total pile capacity, pile length reduction was estimated. The total final capacities were calculated by multiplying the restrike capacity of the individual pile (tip+shaft) by the number of piles in each project. This allows for calculating the total savings in pile length. The percentage of pile length reductions ranged from 5% to 63%. The results show that the percentage reduction in pile length was significant; therefore, setup should be incorporated during the design stage.

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Table-1. Summary of the collected data.

Project number	No. of piles	% Clay	% Silt	% Capacity increase $(Q_t/Q_o) \times 100\%$	Total installed pile length (m)	Suggested pile length (m)	Reduction in pile length (%)
1	24	41	40	167.66	426	333	22%
2	3	21	32	84.21	51	40	22%
3	35	18	31	53.23	160	125	22%
4	28	18	32	51.44	160	112	30%
5	32	16	5	47.06	790	549	30%
6	8	12	56	43.79	83	73	12%
7	9	12	56	42.18	69	64	6%
8	14	12	56	38.89	128	121	5%
9	15	12	56	36.97	110	101	8%
10	59	32	38	27.94	809	591	27%
11	59	32	38	27.91	809	703	13%
12	99	23	39	27.59	2,399	1,727	28%
13	84	31	47	25.45	1,357	1,177	13%
14	3	20	43	15.29	50	27	46%
15	52	42	49	15.04	523	472	10%
16	72	42	49	13.50	1,031	673	35%
17	2	18	45	11.32	18	16	10%
18	2	18	45	10.81	19	13	32%
19	26	45	52	8.67	585	466	20%
20	10	5	23	6.74	403	266	34%
21	27	5	23	5.58	1,006	376	63%

Figure-1 shows the initial capacities (Q_o) and tested restrike capacities (Q_t) of the 21 pipe piles studied in this research. The capacities were calculated by adding the shaft and tip capacities for each pile. The restrike times of the piles varied from about 1.5 hours to about 170 hours. The length of the piles varied from 4.6m to 40.3m. The increase in capacity ranged from 6% to 167%; while the average for all 21 projects was 36%.

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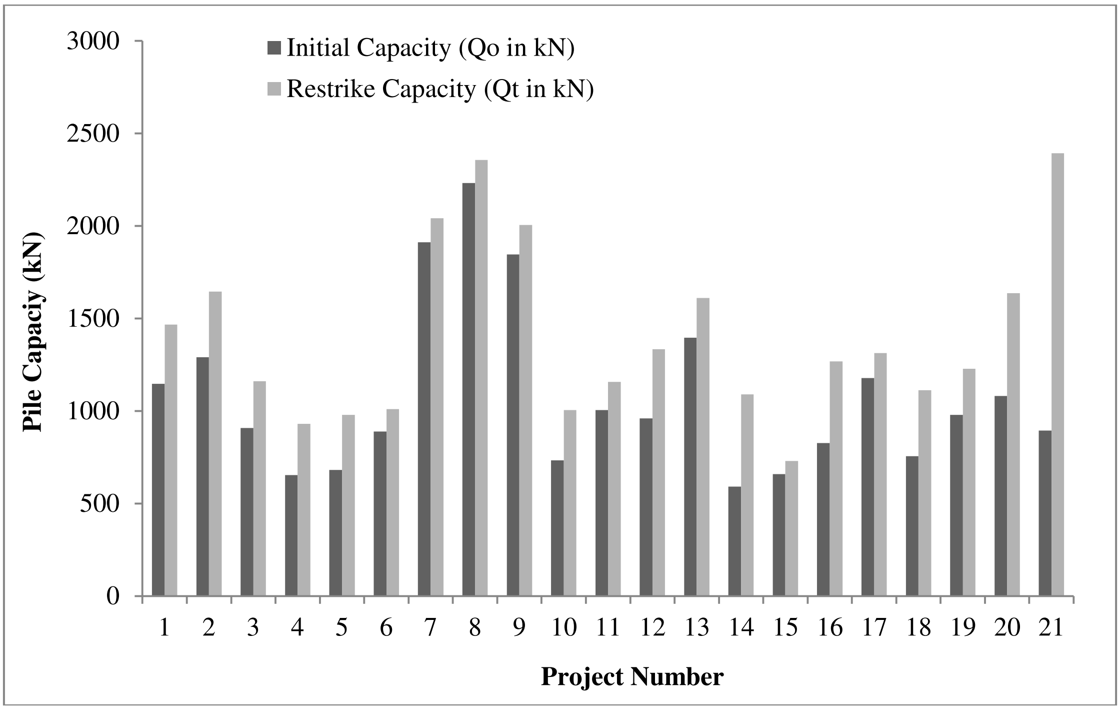

Figure-1. Comparison between Initial and Restrike capacities.

Figure-2 plots the percentage of capacity increase due to setup against the percentage of pile length reduction along with the regression equation. A very strong correlation with R^2 = 0.985 was obtained. A power function relationship to predict pile length percentage is proposed.

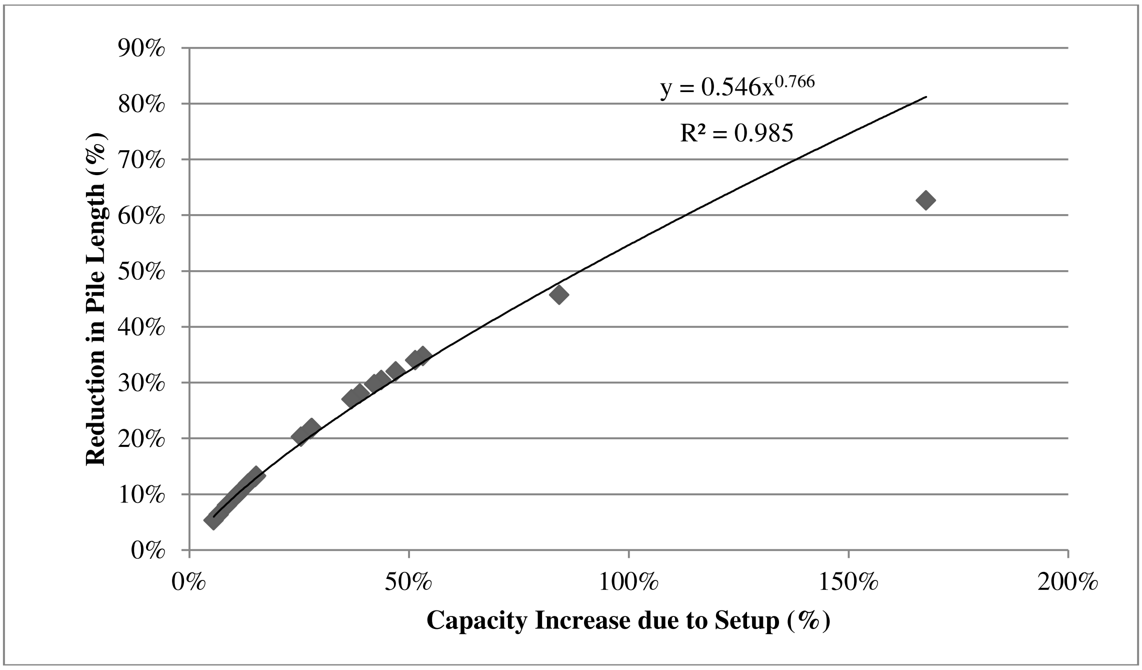

Figure-2. Variation of pile length reduction (%) with capacity increase due to setup (%).

4.1 Effect of Restrike time on setup

Dynamic load tests are often required for verification on driven pile projects, and unanticipated results such as large setup or unusually low indicated resistance can lead to project delays and/or additional testing requirements. This time affects the schedule and cost of the project as no other tasks are completed until the testing is performed. The restrike time is therefore an important factor that requires investigation.

The 21 pipe piles studied in this research varied in length and diameter. For the purpose of comparison, the ratio of strength gain (Q_t/Q_o) was divided by the aspect

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ratio (pile length (L)/ diameter (D)) and plotted against the restrike time (t). The best-fit regression curve along with the regression equation is shown in Figure-3. An acceptable correlation (R^2= 0.74) was achieved. It can be noted from Figure-3 that most of the setup was achieved within the first 96 hours of the pile installation.

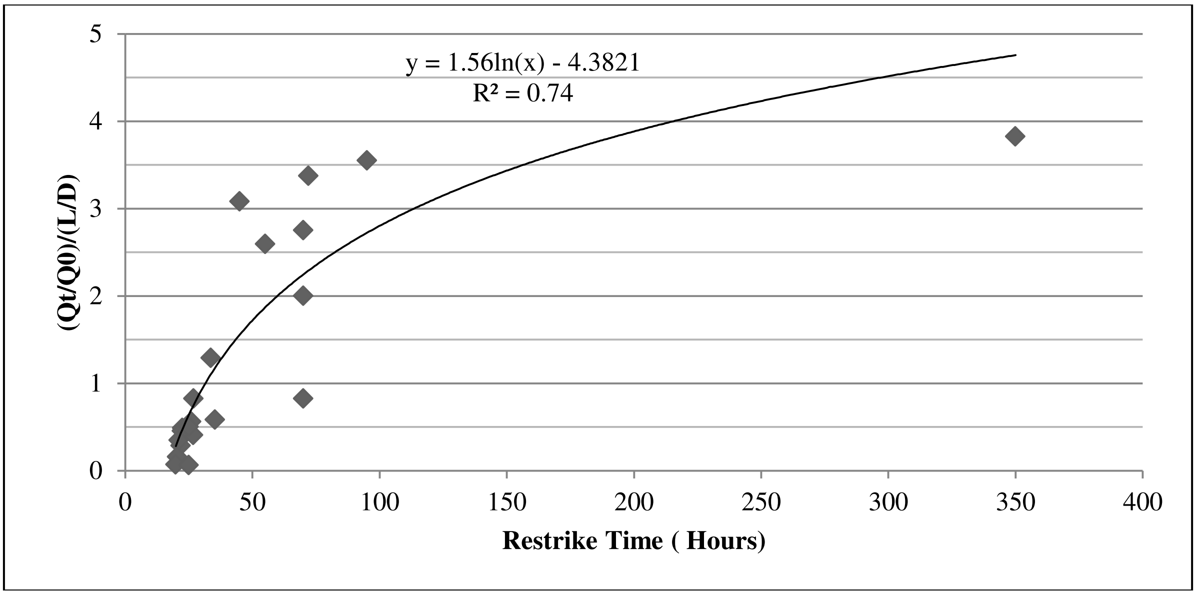

Figure-3. Pile strength gain per aspect ratio vs. time of Restrike.

4.2 Effect of soil type on setup

From the collected data, it was observed that clay content ranged from 5% to 45%, while silt content ranged from 5% to 56% along the length of the piles, as shown in Table-1. Analysis of the collected data showed that most of the studied piles were embedded primarily in soil with higher fine content (clay and silt). It was noted that piles with higher clay content needed more time (around 96 hours) to achieve higher setup as additional time is needed to dissipate the porewater pressure. On the other hand, soils with higher granular material content (sand and gravel) achieved significant setup during the first 24 hours because less time is needed to dissipate the porewater pressure. Piles driven into clay generally tend to experience greater setup than piles driven into sand and silt.

5. COST REDUCTION

Given the importance of pile foundations in supporting significant structures such as: bridges, high-rise buildings, power plant stations, off-shore platforms, and museums; it is necessary to consider foundation design economy. Foundation cost is usually about 20–25% of the whole structure cost (Tarawneh *et al.*, 2018). Letsios *et al.* (2014) also concluded that the pile foundation cost might exceed 20% of the construction cost of the superstructure in large projects, where the number of piles required might exceed several hundreds or even thousands.

The total final capacities were calculated by multiplying the restrike capacity of the individual pile (tip+ shaft) by the number of piles in each project. The new suggested pile length was calculated based on the final higher capacity to allow for cost saving. For the 21 pile projects investigated in this research, through the proposed incorporation of pile setup into the foundation design, the benefit in terms of foundation cost reduction varied from 5.3% to 62.6%. Nevertheless, in terms of total project construction the saving varied between 1.3% and 15.7%. Figure-4 presents the foundation cost reduction, and total project cost reduction for all 21 pile projects.

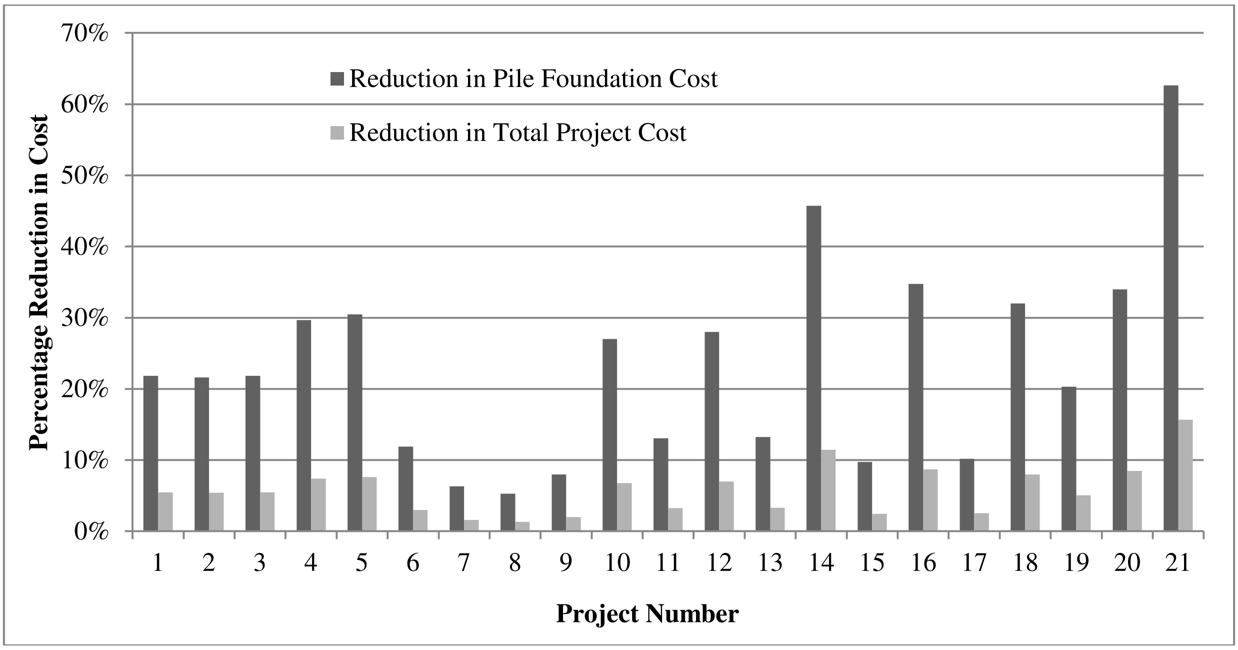

Figure-4. Percentage reduction in pile foundation cost and percentage reduction in total project cost.

6. CONCLUSIONS

As demonstrated earlier, the capacity increase due to setup is significant and worth including during the design stage of the project, the values of increase in capacity ranged from 6% to 167%; while the average for all 21 pile projects was 36%. As for the pile length reduction expected, from incorporating setup in the capacity calculations, it varied from 5% up to 67%. Another important factor that was investigated is the restrike time. It was found that there is no need to wait beyond 96 hours for restrike testing.

For projects with detailed soil testing or geotechnical exploration programs, it may be possible to use one of the proposed empirical relationships described in Section 2.1 to estimate pile setup during the design stage. For setup inclusion to be feasible there has to be an adequate number of piles on the project, so that the savings in pile length resulting from setup incorporation will be more than the cost of the pile testing.

In large scale projects, contractors can rely on pile setup in value engineering change proposals (VECP). This can be done either by performing extensive soil testing and using the empirical formulas to estimate setup or by demonstrating the amount of setup using dynamic load testing.

REFERENCES

Attwooll W.J., Holloway M.D., Rollins, K.M., Esrig M.I., Si, S. and Hemenway D. 1999. Measured Pile Setup during Load Testing and Production Piling: I-15 Corridor Reconstruction Project in Salt Lake City, Utah. Transportation Research Record 1663, Paper No.99-1140, pp. 1-7.

Axelsson Gary. 2002. A Conceptual Model of Pile Set-up for Driven Piles in Non-Cohesive Soil. Deep Foundations Congress, Geotechnical Special Publication. 1(116): 64-79.

Bullock P.J., Schmertmann J.H., McVay M.C., and Townsend F.C. 2005a. Side Shear Setup. I: Test Piles Driven in Florida. Journal of Geotechnical and Geoenvironmental Engineering ASCE. 131(3): 292-300.

Bullock P.J., Schmertmann J.H., McVay M.C., and Townsend F.C. 2005b. Side Shear Setup. II: Test Piles Driven in Florida. Journal of Geotechnical and Geoenvironmental Engineering ASCE. 131(3): 301-310.

Guang-Yu Z. 1988. Wave Equation Applications for Piles in Soft Ground. Proceedings of the 3rd International Conference on the Application of Stress-Wave Theory to Piles, Ottawa, Canada. pp. 831-836.

Holloway D.M. and Beddard D.L. 1995. Dynamic Testing Results, Indicator Pile Test Program, I-880, Oakland, California. In: Deep Foundations Institute, 20th Annual Members Conference and Meeting, South Carolina, USA. pp. 105-126.

Huang S. 1988. Application of Dynamic Measurement on Long H-Pile Driven into Soft Ground in Shanghai. Proceedings of the 3rd International Conference on the Application of Stress-Wave Theory to Piles, Ottawa, Canada. pp. 635-643.

Komurka V. E., Wagner A. B. and Edil T. B. 2003. A Review of Pile Setup. Proceedings of the 51st Annual Geotechnical Engineering Conference, Minnesota, USA. pp. 105-130.

Komurka V. E., Winter C. J. and Maxwell S. 2005. Applying Separate Safety Factors to End-of-Drive and Setup Components of Driven Pile Capacity. Proceedings of the 13th Great Lakes Geotechnical and Geoenvironmental Conference, Wisconsin, USA. pp. 65-80.

Khan L.I. 2011. Prediction of Pile Setup for Ohio Soils. Prepared for the Ohio Department of Transportation Office of Research and Development.

Letsios C., Lagaros N. and Papadrakakis M. 2014. Optimum Design Methodologies for Pile Foundations in London. Case Studies in Structural Engineering. 2, pp. 24-32.

Long J. H., Kerrigan J. A. and Wysockey M. H. 1999. Measured Time Effects for Axial Capacity of Driven Piling. Transportation Research Record 1663, Paper No. 99-1183, pp. 8-15.

Skov R. and Denver H. 1988. Time-Dependence of Bearing Capacity of Piles. Proceedings of the 3rd International Conference on Application of Stress-Waves to Piles, Ottawa, Canada. pp. 1-10.

Svinkin M. R., Morgano C. M., and Morvant M. 1994. Pile Capacity as a Function of Time in Clayey and Sandy Soils. Deep Foundations Institute Fifth International Conference and Exhibition on Piling and Deep Foundations, Section 1.11.1-1.11.8.

Svinkin M. R. 1996. Setup and Relaxation in Glacial Sand Discussion. Journal of Geotechnical Engineering. 122(4): 319-321.

Svinkin M. R. and Skov R. 2000. Setup Effect of Cohesive Soil in Pile Capacity. Proceedings of the 6th International Conference on Application of Stress Waves to Piles, Sao Paulo, Brazil. pp. 107-111.

Svinkin M. R. 1997. Time-Dependent Capacity of Piles in Clayey Soils by Dynamic Methods. Proceedings of the 14th International Conference on Soil Mechanics and Foundation Engineering, Hamburg, Germany. pp. 1045-1048.

Svinkin M. R. 2002. Engineering Judgement in Determination of Pile Capacity by Dynamic Methods. Deep Foundations Congress, Geotechnical Special Publication. 2(116): 898-914.

Tarawneh B. 2013. Pipe Pile Setup: Database and Prediction Model using Artificial Neural Network. Soils and Foundations. 53(4): 607-615.

Tarawneh B. and Imam R. 2014. Regression versus Artificial Neural Networks: Predicting Pile Setup from Empirical Data. KSCE Journal of Civil Engineering. 18(4): 1018-1027.

Tarawneh B., Nusairat J. and Hakam Y. 2018. Load Testing and Settlement of Shallow Foundation on Desert Sands. Proceedings of the Institution of Civil Engineers - Geotechnical Engineering. 171(1): 52-63.

Walton P.A. and Borg S. L. 1998. Dynamic Pile Testing to Evaluate Quality and Verify Capacity of Driven Piles. Transportation Research Board. 1633, pp. 117-119.