Identification and Application of Soil Strength Changes in Driven Pile Design and Construction

What are time effects?

By Patrick J. Hannigan, P.E.

Time effects are changes in pile capacity that occur over time. Soil setup is a time dependent increase in the static pile capacity. In clay soils, setup is attributed to increases in effective stress as large excess positive pore pressures generated during driving dissipate, as well as due to thixotropic effects. In sands, setup is attributed primarily to aging effects and/or release of arching effects with time. Soil setup frequently occurs for piles driven in saturated clays, as well as loose to medium dense silts and fine sands as the excess pore pressures generated during driving dissipate. The magnitude of soil setup depends on soil characteristics as well as the pile material and type. Incorporation of soil setup in a driven pile design facilitates an economical foundation design. A detailed overview of soil setup can be found in Komurka *et al.* (2003).

Relaxation is a time dependent decrease in the static pile capacity. During pile driving, dense soils may dilate, thereby generating negative pore pressures and temporarily higher effective stresses and soil resistance. Relaxation has been observed for piles driven into dense, saturated non-cohesive silts and fine sands. Relaxation has also been observed in some weathered shales and other weak laminated rocksFortunately, relaxation occurs much less frequently than soil setup. An overview of relaxation can be found in Thompson and Thompson (1985).

Methods to estimate time effects

An early method for estimating the capacity at a later time, "t," based on the capacity at a short time after initial driving was proposed by Skov and Denver (1988) and is presented below:

$$R_u = R_0 (1 + A \log [t / t_0]) \qquad \text{Equation (1)}$$

Where: R_u = the long-term capacity at time t.
R_0 = the capacity at time t0.
A = factor based on soil type (suggested 0.5 for sand, 1.0 for clay, 5.0 for chalk).
t_0 = time since initial driving where capacity is linear in log time.

Bullock (2008) modified the Skov and Denver expression to focus only on the change in shaft resistance as presented in Equation 2.

$$R_s = m_s \log [t / t_0] + Rs_0 \qquad \text{Equation (2)}$$

Where: R_s = the shaft resistance at time t.
R_{s0} = the shaft resistance at reference time t_0.
t = elapsed time in days since the end of driving in days.
t_0 = reference time in days (recommended to use one day).
m_s = semilog-linear slope of R_s versus log t.

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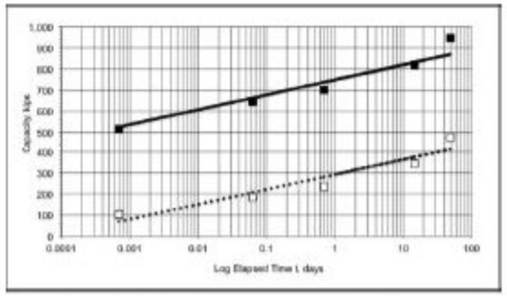
Table 1. Soil setup factors (after Rausche et al. 1996)

Predominant Soil Type Along Pile Shaft	Range in Soil Setup Factor	Recommended Soil Setup Factors*	Number of Sites and (Percentage of Database)
Clay	1.2 – 5.5	2.0	7 (15%)
Silt – Clay	1.0 – 2.0	1.0	10 (22%)
Silt	1.5 – 5.0	1.5	2 (4%)
Sand – Clay	1.0 – 6.0	1.5	13 (28%)
Sand – Silt	1.2 – 2.0	1.2	8 (18%)
Fine Sand	1.2 – 2.0	1.2	2 (4%)
Sand	0.8 – 2.0	1.0	3 (7%)
Sand – Gravel	1.2 – 2.0	1.0	1 (2%)

** Confirmation with local experience recommended*



An example of this approach is presented in Figure 1. In the project shown, dynamic test data was acquired and analyzed using signal matching software such as the CAPWAP program, Rausche *et al.* (2010), to determine the mobilized pile capacity as well as the shaft resistance. Dynamic test data was acquired at the end of initial driving as well as at 0.06, 0.69, 14.65 and 48.81 days after the end of initial driving. During this timeframe, the shaft resistance increased by a factor of 4.7 and the total capacity increased by a factor of 1.9. This magnitude of setup must be clearly utilized for economical foundation design. The derived capacity versus time trend lines were used to evaluate production pile acceptability in similar soil conditions based on select restrike tests performed one to three days after installation.

In recent years, numerous research efforts have been performed to improve soil setup predictions for various pile types and soil conditions, Khan and Decapite (2011), Ng *et al.* (2013), Reddy and Stuedlein (2014) and Haque *et al.* (2014).

General setup and relaxation factors

Rausche *et al.* (1996) calculated general soil setup factors based on the predominant soil type along the pile shaft. The soil setup factor was defined as the static load test failure load divided by the ultimate capacity determined from the end-of-drive wave equation analysis. These results, summarized in the Table 1, were based on 99 test piles from 46 sites. The percentage of the database in a given soil condition is also noted in the table. These soil setup factors are useful for preliminary estimates. However, site specific data gathered from pile restriking, dynamic measurements or static loading tests is preferable.

Similar to the setup factor, the relaxation factor is defined as the static load test failure load divided by the capacity at the end of initial driving. Published cases of the relaxation magnitude in various soil types are relatively limited. For piles driven into dense to very dense silts, relaxation factors ranging from 0.6 to 0.8 have been reported. Similarly, relaxation factors of 0.7 to 0.9 have been noted for piles driven into dense to very dense fine sands. A few published cases of relaxation in rock from Thompson and Thompson (1985) as well as Hussein *et al.* (1993) suggest relaxation factors for piles founded in some shales can range from 0.5 to 0.9. Hence, it is important to check for time dependent decreases in capacity for end bearing piles in the above noted soil and rock materials.

Quantifying time effects

There are several ways that time effects can be quantified, each with varying degrees of accuracy and cost. The cheapest but least accurate method to assess time effects is a non-instrumented restrike of a previously driven pile. Based on the observed changes in blow count between the end of driving and the time of restrike, the change in pile capacity can be assessed using a wave equation analysis or other blow count versus capacity relationship. Since the energy transferred to the pile in a non-instrumented restrike is unknown, some uncertainty exists in the assessment of the capacity change from blow count alone. This is because the blow count change could be caused by a change in hammer and drive system performance or by a change in the dynamic soil properties and not solely from a soil strength change.

An increased level of confidence in the capacity change can be obtained if dynamic measurements are acquired during the restrike event. Since the energy transfer is now quantified, the change in blow count can be better assessed and the resultant change in pile capacity more accurately quantified. The acquired dynamic measurements can also be evaluated using signal matching software to determine the mobilized capacity and the soil resistance distribution. Compared to a non-instrumented restrike, this approach has significantly increased accuracy at a modest increase in cost.

Instrumented restrike tests can also be used to assess the time rate of increase by restriking one pile at different elapsed times after the end of initial driving. The method can also be used to look at variations across a site or at variable pile penetration depths. Common restrike times used in various soil and rock materials from Hannigan *et al.* (2016) are provided in Table 2.

Table 2. Typical time delay for restrike test based upon soil type

Soil Type	Time Delay Until Restrike
Clean Sands	1 Day
Silty Sands	2 Days
Sandy Silts	3–5 Days
Silty Clays	7–14 Days*
Shales	10–14 Days*

** Longer times sometimes required*

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The most definitive measure of the change in pile capacity with time can be obtained from a static loading test taken to geotechnical failure. However, this is the most expensive method and is therefore generally only performed on one or a few piles at a site. It is important that the static test be performed after an appropriate time delay following driving to quantify the majority of the time dependent capacity change that will occur. The addition of strain gage instrumentation along the pile length increases the knowledge gained on the soil setup magnitude and its location from the static loading test. Depending on the site conditions, the load test may be performed from seven to 30 days after driving. Since this is the most expensive quantification method, longer wait times between the end of driving and commencing the static loading test are often specified in order to capture the greatest potential benefit.

Application of time effects in design and construction

In soil conditions with significant soil setup potential, larger projects can benefit greatly from a design phase or pre-production test pile program that quantifies the magnitude of soil setup, the time rate of soil setup, the setup profile versus pile penetration depth and the setup profile across the site. Komurka *et al.* (2017) presents a recent case history that documents the use of soil setup on a high-rise building project. For smaller projects, dynamic monitoring of a limited number of test piles during initial driving and again during short-term restrikes can often reduce driving criteria and pile length when setup is incorporated into the pile installation criteria.

When relaxation is encountered, driving piles to a capacity greater than that required can often be an effective means of overcoming the effects of relaxation. Initial drive and restrike tests that quantify the relaxation magnitude are beneficial in these cases to identify the amount of overdriving required.

Time effects are an important design and construction consideration for driven pile foundations. Relaxation, in the limited cases in which it occurs, must be addressed. Soil setup, which typically occurs, can yield substantial cost savings and construction schedule benefits where it is present in a significant magnitude. ▼

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