The Easy Button for Driven Pile Setup: Dynamic Testing

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ABSTRACT: Field inspectors often observe a dramatic increase in penetration resistance between initial driving and restrikes of driven piles, a result of additional static "setup" capacity. Designers often ignore setup when specifying pile lengths and blow count acceptance criteria, and pile capacity design methods, calibrated against static load tests, already incorporate some setup that occurs during the test preparation delay. Research indicates that setup results mostly from an increase in side shear and occurs in all soil types as a result of combined pore pressure dissipation, consolidation, and mechanical aging effects. Repeated static tests provide a reliable measurement of setup, but also delay construction. Penetration resistance (set per blow) does not reliably measure setup during isolated restrikes as it varies per blow due to inconsistent driving system performance and changing pile capacity. Instrumented dynamic tests, using strain gages and accelerometers, provide an "easy button" to verify hammer energy and pile capacity during all phases of installation. This paper reviews pile setup, its causes, and related properties. It presents a simple method, with examples, to measure and analyze setup from dynamic test results. An engineer may use these results to reduce the length, size, or number of production piles, and adjust the required set per blow. Caveats include staged testing effects and consideration of the setup contribution from different soil strata.

KEY WORDS: aging, driven pile, dynamic load test, end bearing, restrike, side shear, signal matching, time dependence, ultimate static capacity

INTRODUCTION

Field inspectors and engineers often observe a change from "easy" to "hard" driving during restrikes following the initial installation of driven piles, and possibly during brief driving interruptions for cushion changes, template removal, or equipment breakdowns. They may also measure unexpectedly high capacity during a static load test (typically 3 to 14 days after the end of driving) following low penetration resistance. Depending on site stratigraphy and pile type, this "setup" may increase the pile capacity by more than

100% over time. However, many engineers do not include setup in design calculations, or attempt to assess it during construction. Ignorance of time changes can also lead to foundation problems, as piles driven into some soil-rock profiles may actually decrease in capacity with elapsed time, or "relax". With the relative simplicity and widespread availability of dynamic testing methods (see equipment in Figure 1), engineers can now measure changes in static capacity through a series of restrikes specified in the project documents, benefiting the designer through capacity verification, the client through economy in the constructed foundation, and the contractor through reduced driving requirements and shorter pile lengths. This paper reviews when to expect setup (almost always), the causes of setup and relaxation, setup predictor tests, and staged testing effects. It presents a relatively simple method for measuring and analyzing side shear setup using dynamic tests, with numerical examples based on field data.

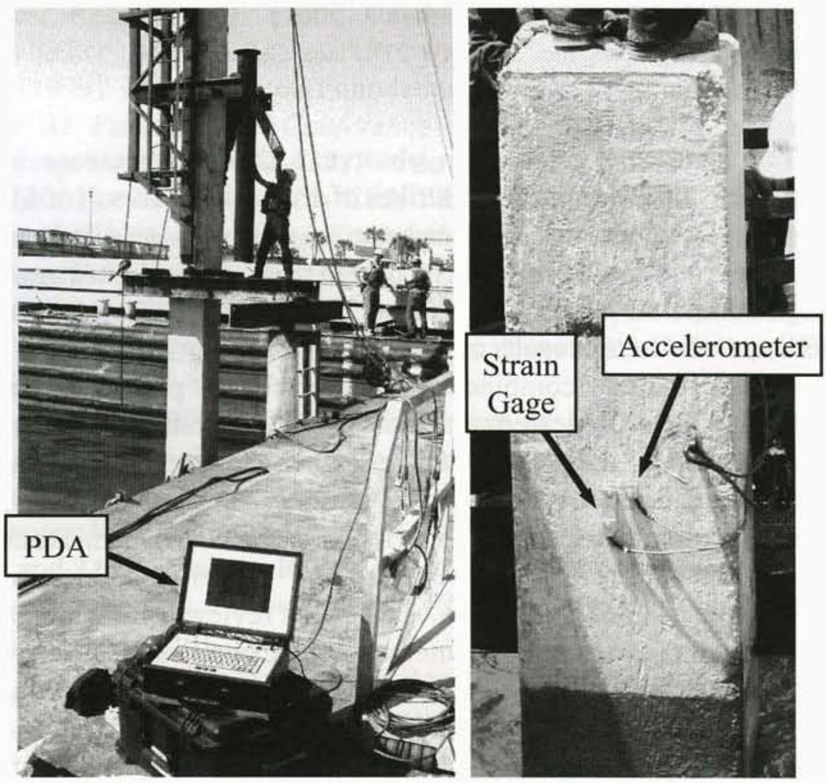

FIG. 1 Dynamic Test Equipment: Pile Driving Analyzer® (PDA) from Pile Dynamics, Inc.

SETUP OR RELAXATION?

Driven pile setup seems the rule rather than the exception, and it seems to occur in all soil types, including cohesionless soils. A few examples covering a variety of soil and pile types include (among many available):

- Bullock et al. (2005) - four Florida sites, ***sand, clay, mixed soils***, prestressed concrete piles, dynamic tests followed by three to six static tests over

16 to 1727 days elapsed time using Osterberg cell tests to separate side shear and end bearing, 12 to 32% side shear increase per log cycle of time.

- Fellenius et al. (1989) - Wisconsin, ***sandy clay and silty sand***, driven steel pipe and H-piles, static and dynamic tests, capacity increase averages 50% between 1 and 21 days.
- Karlsrud and Haugen (1985) - Norway, ***sensitive, overconsolidated clay***, jacked closed-end, pipe piles, static tests, side shear increase averages 30% between 6 and 30 days.
- Kehoe (1989) - two Florida sites, ***mixed cohesive soils***, driven square, prestressed concrete piles, static and dynamic tests, capacity increases average 58% and 200% within 11 days after driving (72% of increase within 100 min)
- Lukas and Bushell (1989) - five Illinois sites, ***soft to stiff clay***, driven steel pipe and H-piles, static tests, capacity increase averages 25% between 10 and 32 days in stiff clay and 50% between 10 and 82 days in soft clay.
- Seidel et al. (1988) - Australia, ***alluvial sands over limestone***, driven prestressed, concrete pile, static and dynamic tests, 80% capacity increase 535 days after initial driving (see Figure 3).
- Tavenas and Audy (1972) - Quebec, ***uniform medium sand***, hexagonal, reinforced concrete piles, static tests, average capacity increase of 70% between 0.5 and 15-20 days.

Foundation engineers also sometimes observe driven pile "relaxation", but fortunately much less often than setup (and than commonly feared). Some reports of this phenomenon, based solely on blow count, have less creditability due to changes in the driving system or inefficient hammer operation during restrikes. Relaxation may result from temporary confining effects, or from the creation of negative pore pressures that grip the pile during initial penetration and then later dissipate (see Chow et al., 1998). The following stratigraphy may raise these concerns:

- sands confined by a cofferdam, or closely spaced piles, in which lateral confining stresses may later relax
- strong soils that dilate during penetration (e.g. dense fine sands), creating negative pore pressures that later dissipate
- weak, foliated, sedimentary and metamorphic rock (e.g. shale), in which driving stresses may relax due to creep

Given the predominance of evidence suggesting setup (Bullock, et al., 2005, Chow, et al., 1998, etc.), the foundation engineer, after considering the above list, often may reasonably assume de facto setup for a given pile foundation. Of course, if lacking local experience, he or she will prudently require verification testing of this assumption via the relatively simple procedure provided below.

REVIEW OF SETUP BEHAVIOR

Side Shear Only: Bullock et al. (2005), Axelsson (1998a), and Chow et al. (1998) concluded that setup occurs primarily as a result of side shear increase, not end bearing. Penetration of the pile pushes soil outward and away from the pile, destructuring and shearing it to a greater extent adjacent to the side of the pile than at the pile tip, and thus reducing the side resistance during installation (and increased aging effects).

Conventional Pile/Soil Side Shear: Eq.1 provides a relatively simple and conventional estimate of side shear, which shows that setup could result from either, or both, an increase in the horizontal effective stress or an increase in the strength components.

f_s = unit side shear = $c'_a + \sigma_h'(\tan \Phi')$ ....(1)

where: c'_a = pile-soil adhesion
σ_h' = effective horizontal stress
Φ' = pile-soil drained friction angle

What Changes?: Bullock et al. (2005), Chow et al. (1998), and Axelsson (1998a), all concluded that the setup process initially increases the strength components of Eq.1 through consolidation and the effective stress as result of both consolidation and collapse of soil pushed away from the pile during installation. However, they postulate that later setup (after about 30 days) occurs as a result of mechanical aging increasing the friction angle, a process that Schmertmann (1991) identified as affecting soil behavior in many other situations as well. For cohesive soils, consolidation and aging effects seem to overlap, resulting in an apparently continuous setup process. However, pore pressures dissipate rapidly in well drained soils (sand), possibly resulting in a time gap between the two effects. Therefore, as found by Bullock et al. (2005), pile tests in clean sands often show no increase in side shear until aging effects begin, possibly one to two weeks after driving.

Continuing Process: The research literature indicates that side shear setup begins almost immediately after the end of driving (EOD), and continues for many years, though the rate of increase approaches zero over time. Initially the capacity increase may exceed 100% within the first 24 hrs after driving. A satisfactory mathematical model of setup should describe a continuing process. Of course at some point, typically in the range of 60 to 180 days after EOD, the foundation must bear a substantial portion of the design load (including construction loads), and later changes may not provide usable design capacity. Some engineers simply multiply the EOD capacity by a conservative constant, effectively ignoring later increases, e.g. Table 1 from Rausche et al. (1996). These factors generally underestimate the actual setup trend, but may prove useful for wave equation driveability studies to determine the reduced static resistance to driving from that calculated for various analytical methods (Hannigan, et al, 2006).

TABLE 1. Prescriptive Setup Factors from Rausche et al. (1996)

Soil Type Adjacent to Pile	Range of Setup Factor	Recommended Setup Factor
Clay	1.2 - 5.5	2.0
Silt - Clay	1.0 - 2.0	1.0
Silt	1.5 - 5.0	1.5
Sand - Clay	1.0 - 6.0	1.5
Sand - Silt	1.2 - 2.0	1.2
Fine Sand	1.2 - 2.0	1.2
Sand	0.8 - 2.0	1.0
Sand-Gravel	1.2 - 2.0	1.0

Whole-Pile Semilog-Linear Setup Factor, A: The total pile capacity (side shear plus end bearing) generally follows a linear increase versus the log of the time elapsed after the EOD. Figure 2 shows a best fit line through both static and dynamic test data from Seidel et al. (1988) illustrating this trend. Skov and Denver (1988) proposed the dimensionless setup factor, A, in Eq.2 to represent the relative increase in pile capacity per log cycle of elapsed time. The plot in Figure 3 shows the Figure 2 data with the resulting setup factor, $A = 0.10$ based on the best-fit line in Figure 2. Though sometimes useful, this approach incorrectly includes end bearing in the setup process and thus reduces the setup factor by increasing the reference capacity. Note that Eq. 2 proves less accurate early (<10 min) and late (> 3 years) in the setup process, but generally adequate within the range of practical application (15 minutes to 1 year).

$$\frac{Q}{Q_0} = A\log\left(\frac{t}{t_0}\right) + 1 = \left(\frac{m_Q}{Q_0}\right)\log\left(\frac{t}{t_0}\right) + 1 \quad \text{.......(2)}$$

where: A = Dimensionless setup factor
Q = Whole pile capacity at time t
Q_0 = Whole pile capacity at initial reference time t_0
t = Time elapsed since EOD
t_0 = Reference time at start of log-linear capacity increase
m_Q = Semilog-linear slope of Q vs. log t (see Figure 2)

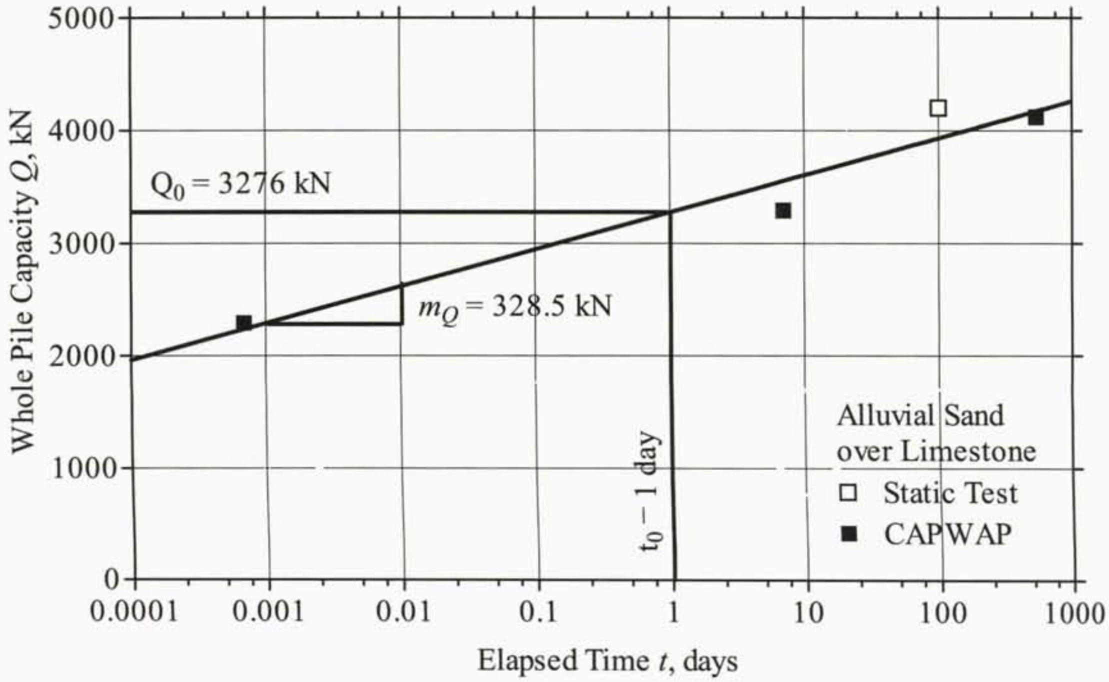

FIG. 2. Pile Capacity Data from Seidel et al. (1988)

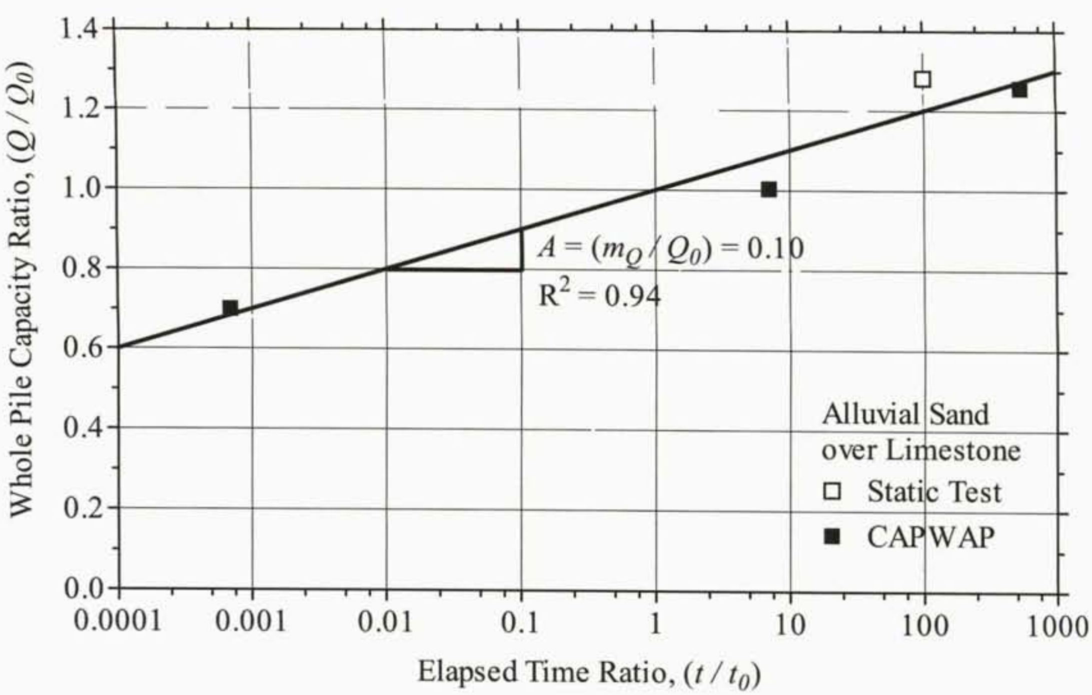

FIG. 3. Setup Factor for Data from Seidel et al. (1988)

Side Shear Semilog-Linear Setup Factor, A: Bullock et al. (2005) recommend three modifications of the analysis proposed by Eq.2:

- Use $t_0 = 1$ day as this removes the difficulty of finding the actual start of the semilog-linear setup process while providing a convenient global reference.

- Use A to describe the side shear component only, not the whole pile capacity, as the end bearing component may change in magnitude due to differing pile sizes or site variability and does not increase appreciably due to setup. Though the setup factor decreases when including end bearing, differences in bearing between piles may lead the engineer to over predict the total capacity using whole-pile setup factors.

- As an approximation based on experience, plot the EOD capacity (determined from dynamic testing) at 1 min elapsed time. Capacity measurements at fixed times should prove more reliable.

Setup factors based on side shear as shown in Eq.3 provide a more reliable comparison between test and production piles, for which the designer may expect $A = 0.1\text{-}0.8$ using $t_0 = 1$ day.

$$\frac{Q_S}{Q_{S0}} = \frac{f_S}{f_{S0}} = A\log\left(\frac{t}{t_0}\right) + 1 = \left(\frac{m_S}{Q_{S0}}\right)\log\left(\frac{t}{t_0}\right) + 1 \quad \text{...(3)}$$

where: A = Dimensionless setup factor
Q_S = Side shear capacity at time t
Q_{S0} = Side shear capacity at initial reference time t_0
f_S = Unit side shear capacity at time t
f_{S0} = Unit side shear capacity at initial reference time t_0
t = Time elapsed since EOD, days
t = reference time. recommended to use 1 day
m_S = Semilog-linear slope of Q_S vs. log t

Pile Size: Note that Eq.3 works equally well with either force or unit resistance as the ratio (Q_S / Q_{S0}) cancels the side area of the pile (perimeter times length). Figure 4, from data presented by Bullock (1999), shows dynamic test results from the Seabreeze site in Daytona Beach, FL for restrikes performed at 15 min to 4 days after the EOD of eighteen, 610-mm-square, prestressed concrete piles. These test piles produced a similar side shear setup factor, A = 0.18, to that found from the combined dynamic and static tests of a 457-mm-square, prestressed concrete, research pile, A = 0.21. The scatter of the data for the 610 mm piles in Figure 4 likely results from site variability and estimation of the side shear using the Case method capacity (not signal matching). Bullock et al. (2005) found that reducing the reference time of 1 day in proportion to the ratio of the squared, effective pile diameter produced similar setup factors for this same

457-mm test pile compared with torque tests on a 51-mm-diameter, driven sampler (see below). However, this effect may prove less important when comparing full-size piles, especially for incremental differences in pile size.

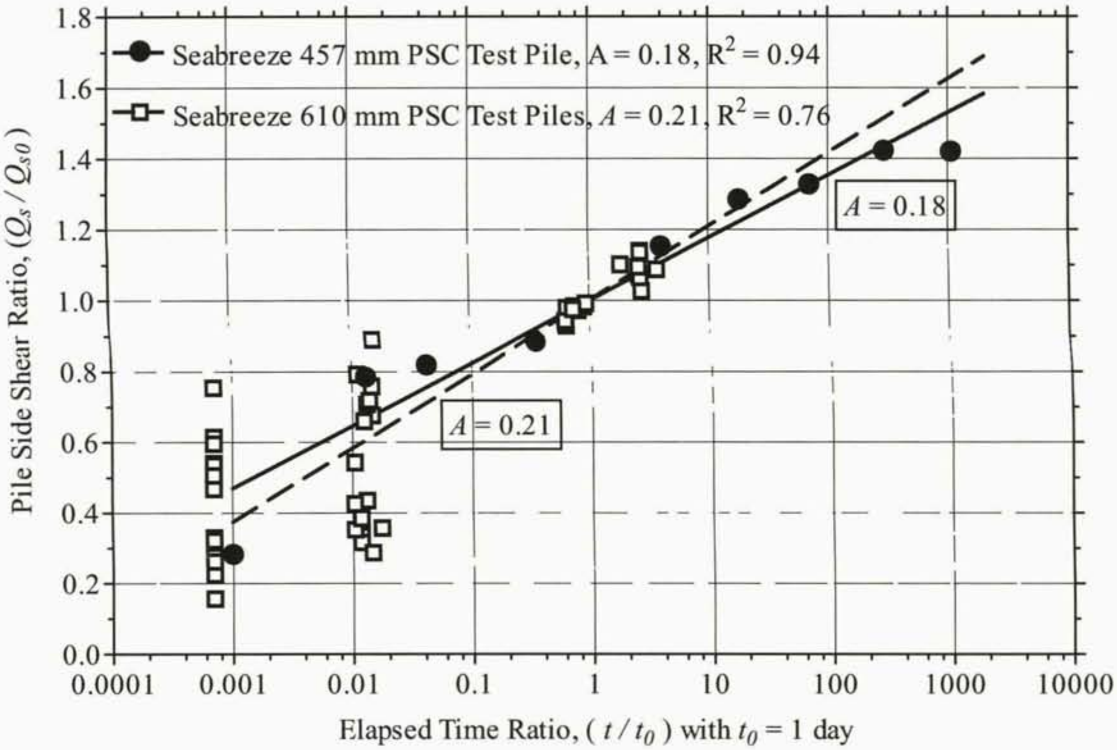

FIG. 4. Setup Factor from Bullock (1999) for Two Pile Sizes at FL Site

Setup Predictor Tests: While this paper focuses on dynamic tests of driven piles, predictor tests based on model piles may provide the designer an opportunity to assess pile setup from insitu tests such as: torque tests performed on the Standard Penetration Test (SPT) sampler by Bullock and Schmertmann (2003), uplift tests performed on the SPT sampler by Rausche et al (1996), or tests of driven rods performed by Axelsson (1998b).

Setup Reduction for Staged Testing: Engineers investigating setup routinely perform repeated, or "staged", tests of pile capacity on the same pile, typically resulting in small axial movements (< 50 mm) during each test (dynamic or static). The resulting pre-shearing effect of one test on the next does not remold the volume of soil that a larger penetration might affect, such as during initial driving. Staged testing apparently increases side shear at a quicker rate, and results in a higher setup factor than for piles tested only once, or "unstaged", at a specific elapsed time following the EOD. Research results reported by Karlsrud and Haugen (1985) for steel pipe piles, Miller (1994) for steel pipe piles, and Bullock and Schmertmann (2003) for torque tests of the SPT sampler show that staged tests significantly increase side shear capacity when compared to unstaged tests in clay soils. Although the range of soil types affected requires further research, Bullock et al (2005) recommend reducing the setup factor calculated from staged test results by 60%, or a factor of 0.4, when applying it to unstaged piles. This reduction factor does not apply to the staged test pile itself, as it develops and maintains the capacity actually measured.

DYNAMIC MEASUREMENT OF STATIC CAPACITY

Static load tests require time, money, manpower, and heavy equipment, all essential commodities on a construction site. Dynamic tests provide an attractive "easy button" alternative to static testing, mobilizing minimal test equipment and personnel on short notice with little impact to the construction schedule. Ground conditions around the test pile generally do not impede dynamic tests, and the engineer can test any accessible pile.

Dynamic measurements during driving require strain gages and accelerometers (see Figure 1) mounted near the top of the test pile to measure and record the instantaneous pile velocity and force generated in the pile by each hammer blow. Through advances in instrumentation, computer equipment, and user-friendly software, the effort required to obtain and analyze dynamic test data has decreased greatly during the last 25 years. Analysis of the test data, preferably with a signal-matching program such as CAPWAP®, separates dynamic and static resistance to estimate the overall static capacity, as well as the side shear and end bearing components. While estimation of the side shear and end bearing components has less reliability, analytical expertise and consideration of site stratigraphy can improve this.

For 303 comparisons up to a capacity of 36 MN, Likins et al. (2004) report 0.98 for the ratio of the CAPWAP® estimate to static load test measurement, with a 17% coefficient of variation. Site-specific calibration of dynamic test results using static tests may provide additional design confidence on sites with unfamiliar soil conditions, unusual piles, large projects, or heavy loads. Like a static load test terminated prior to failure, dynamic tests with less than about 1 to 2 mm penetration per blow may not fully mobilize, and therefore tend to under predict, the pile's static capacity. For best comparison, both tests should attain a failure load on the same pile, and the dynamic test should follow 12 to 24 hrs after the static test (not the reverse).

ASTM International provides a standard test method (D4945) for high strain dynamic testing, and Likins et al. (2000) indicate that many governmental and code organizations worldwide accept and encourage dynamic tests. Because of the wide acceptance and availability of dynamic testing, and the accuracy of static capacity estimates from signal-matching techniques, the foundation engineer has an ideal tool to quickly assess pile setup using restrike tests, preferably scheduled to minimize construction delays. Of course, for large projects, unusual soil profiles, and large setup factors, the prudent engineer will still require static tests to verify dynamic results.

WHEN TO RESTRIKE (EARLY AND OFTEN)

Possibly as a legacy from static tests that often require a week or more to prepare and perform, many engineers specify long restrike times to assess setup. Of course, when comparing dynamic test results to a static test, the engineer should request a restrike performed immediately following (not before) the static test. However, with the exception of piles driven in clean sand, restrike tests can provide considerable, and often dramatic, setup information as little as 15 min after the EOD.

Figure 5 shows a best-fit $A = 0.30$ with $R^2 = 0.99$ for the combined static and dynamic side shear capacity measurements from the Aucilla test pile reported by Bullock et al. (2005), with the EOD capacity plotted at 1 min elapsed time. The dynamic tests at the EOD, 15 min, and 60 min provided a best-fit $A = 0.28$ with $R^2 = 0.95$, and the static tests from 1 day up to 4.7 years later provided a similar best-fit $A = 0.32$ with $R^2 = 0.98$.

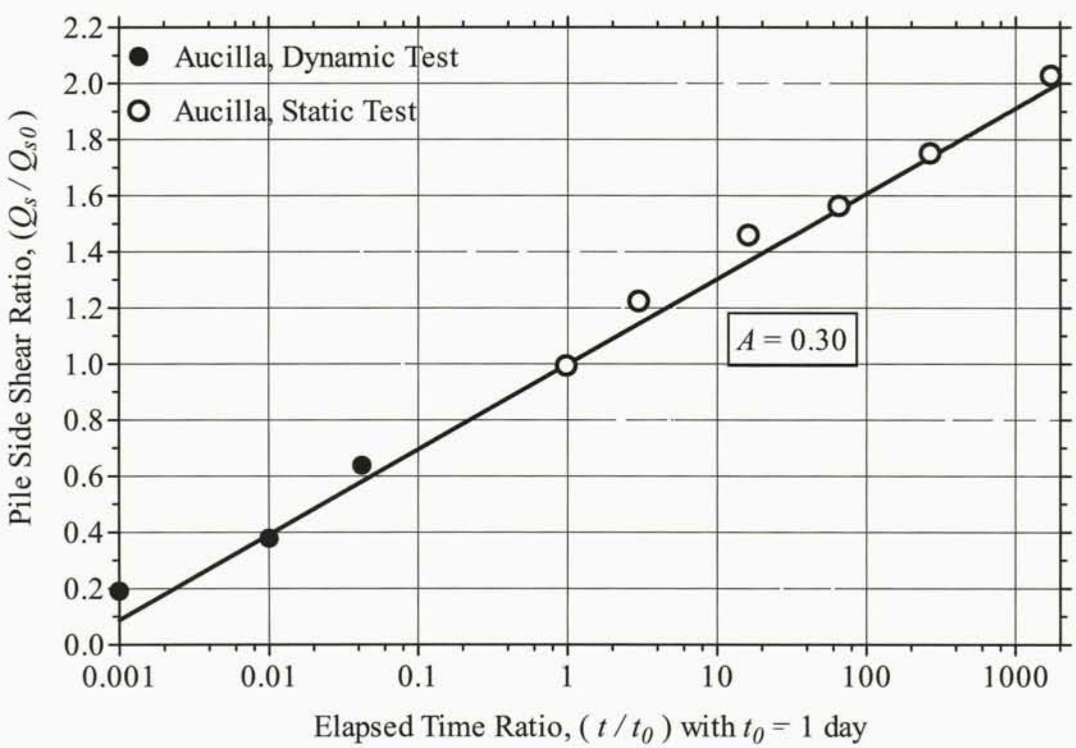

FIG. 5. Side Shear Setup for Florida Test Pile in Bullock et al. (2005)

The setup factor A describes the relative capacity increase with respect to the 1-day capacity, Q_{S0}, but a comparison with the EOD capacity proves much more remarkable. Table 2 shows the ratio of the setup capacity of the pile with both the EOD ($t = 1$ min) and 1-day reference. The results in Table 2 indicate that a restrike only 15 min after the EOD showed a dramatic increase of 97% of the EOD capacity, while restrikes at 1 hr and 24 hrs showed increases of 232% and 417% respectively.

TABLE 2. Side Shear Setup for Florida Pile (Aucilla) from Bullock et al. (2005)

Elapsed Time from EOD, t days	Time Ratio t / t_0 t_0 = 1day	Measured Side Shear Q_S kN	Q_S/Q_{S0} t_0 = 1day for Q_{S0} = 977 kN	Q_S/Q_{S1} t_1 = 1 min for Q_{S1} = 188 kN
0.0007	0.0007	188	0.19	1.00
0.010	0.010	370	0.38	1.97
0.042	0.042	624	0.64	3.32
0.98	0.98	972	1.00	5.17
2.97	2.97	1197	1.22	6.36
16.1	16.1	1427	1.46	7.59
65.1	65.1	1528	1.56	8.13
265	265	1712	1.75	9.11
1727	1727	1982	2.03	10.54

Therefore, while later restrikes provide greater reliability for setup trend analysis, early restrikes may provide adequate data without unnecessary delay to the project. For best results, obtain dynamic test results from the EOD and two or three restrike capacities at 15 min, 1 hour, and 1 to 3 days after the EOD. More data develops a better trend line, and the prudent designer will require that some restrikes verify the desired capacity. Note that if relaxation proves important, a 15 min restrike should quickly identify this problem as well. (Note that a geometric time progression for restrikes provides equally spaced data on a semi-logarithmic plot, though it may test a contractor's patience.)

ANALYSIS STEPS

The following examples illustrate the use of dynamic tests and restrikes to determine the setup factor and predict pile capacity. The basic steps include:

1. Perform dynamic tests (measure force and velocity in pile) during the EOD and a minimum of two restrikes, with accurate set per blow measurements (important for analyses).
2. Perform signal-matching analysis of an average blow at the EOD
3. Perform signal-matching analysis for an early blow of each restrike (typically second or third blow with adequate transferred energy to mobilize pile capacity)
4. End bearing typically does not change much during restrikes with only a few inches permanent set. Consider (don't force) this in signal-matching analyses.
5. Tabulate the estimated static capacity versus elapsed time since EOD for each blow analyzed. Use the time of first blow to calculate elapsed time from EOD for restrikes, and as a first approximation, use 1 min for the EOD capacity.
6. Plot side shear and total capacity versus the logarithm of elapsed time.

7. Find a best fit line through the side shear (slope m_S) and through the total capacity. They should have similar slopes with a relatively constant difference of the average end bearing. (If not, adjust as necessary, usually assuming the total capacity slope as more accurate unless the end bearing is suspected to increase.)
8. Using the adjusted best fit line (slope m_S), calculate the reference side shear capacity Q_{S0} at the reference time $t_0 = 1$ day.
9. Calculate the side shear setup factor $A = (m_S / Q_{S0})$
10. Calculate and plot the ratio of (Q_S / Q_{S0}) versus the time ratio (t / t_0). Add the setup line with slope A through the point $(Q_S / Q_{S0}) = 1$ and $(t / t_0) = 1$.
11. Use Eq.3 to estimate side shear at desired times. Add end bearing to obtain total pile capacity at these times. For reliability, perform at least some late restrikes to verify the desired capacity.

EXAMPLES FROM LOUISIANA AND THE RED SEA

The engineer can perform the above analyses quite easily in a spreadsheet program, such as Excel or Quattro. Figure 6 shows a spreadsheet analysis of static pile capacity (Class A prediction) for dynamic tests of a 762-mm-square, prestressed concrete pile driven 33 m into cohesive Louisiana soils at Rigolets Pass. The static test performed 14 days after the EOD agrees reasonably well with the Figure 6 trend line of predicted capacity based on restrikes at 15 min, 1 hr, and 1 day.

When possible, a comparison of setup results from multiple test piles at the same site provides additional confidence in the results. Figures 7 to 9 show setup results from six, 1372-mm-diameter, open-ended, steel pipe piles, driven near-shore on the Red Sea through 20 m of water and penetrating 31 to 40 m into calcareous sand, silty sand, and weak limestone to bear on competent limestone. Figures 7 and 8 respectively show the total capacity and side shear obtained from CAPWAP analyses. The setup factor for these piles ranged from 0.13 to 0.18 with an average of 0.15 as shown in Figure 9, or a side shear increase of 15% per log cycle of elapse time in days. This setup factor falls at the low end of the expected range, possibly as a result of the primarily calcareous soils and less soil displacement and destructuring caused by an open-ended pipe pile.

		Elapsed	CAPWAP Capacity				Capacity Estimate with Setup				
	Pile	Time	Shear	Ratio	Toe	Total	Setup	Shear	Ratio	Toe	Total
Blow	Penetr.	t	Q_S	Q_S/Q_{S0}	Q_B	Q	Time	Q_S	Q_S/Q_{S0}	Q_B	Q
Type	m	days	kN		kN	kN	days	kN		kN	kN
EOD	**13.46**	**0.0007**	**323**	0.164	**3156**	**3479**	0.0007	229	0.116	3172	3401
SC1	**13.46**	**0.0160**	**750**	0.380	**3281**	**4031**	0.0160	982	0.497	3172	4154
SC2	**13.58**	**0.0424**	**1301**	0.659	**3111**	**4412**	0.0424	1216	0.616	3172	4388
SC3	**13.69**	**0.924**	**2008**	1.017	**3166**	**5174**	0.924	1956	0.990	3172	5128
		(EOD plotted at 1 min)					2.0	2141	1.084	3172	5313
Average Q_B		3,172 kN		5463 kPa			4.0	2308	1.169	3172	5480
	t_0	1.0 day					8.0	2474	1.253	3172	5646
	Q_{S0}	1975 kN		(at t_0)			16.0	2641	1.337	3172	5813
	m_S	552.8 kN		(slope of Q_S)			30.0	2792	1.413	3172	5964
	A	0.280		(unitless setup factor)			**14.0**	**(Static Test)**			**6540**

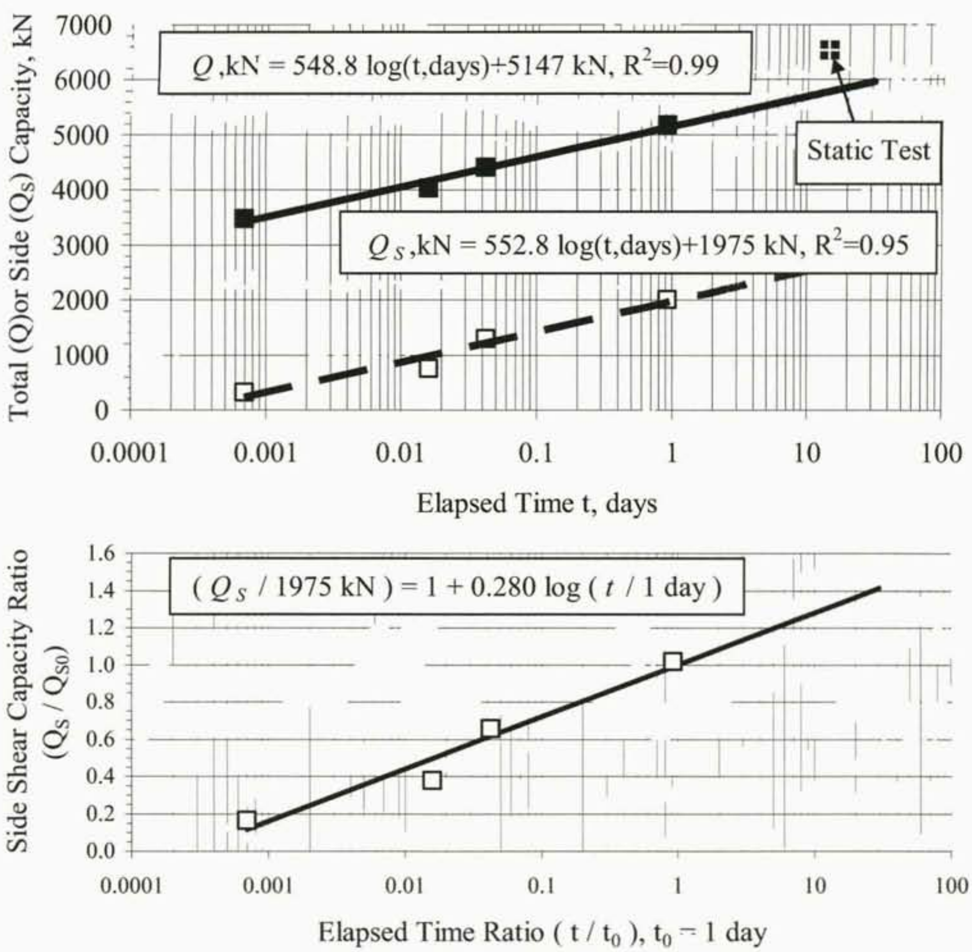

FIG. 6. Spreadsheet Analysis for Rigolets Pass Test Pile (required input in bold)

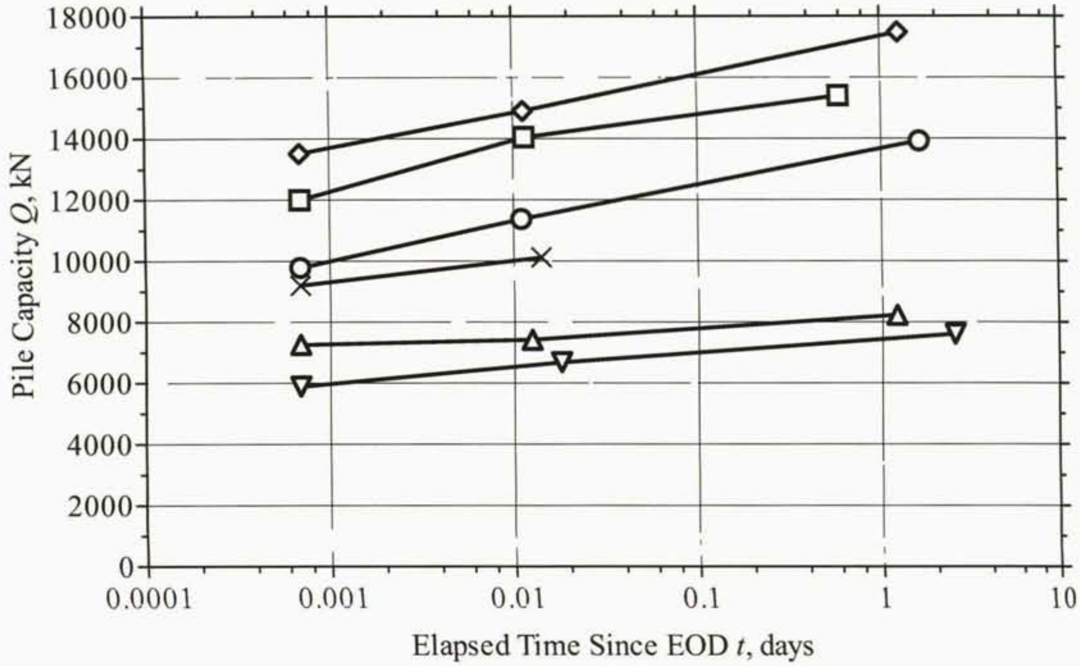

FIG. 7. CAPWAP Total Capacity from Restrikes of Six Red Sea Pipe Piles

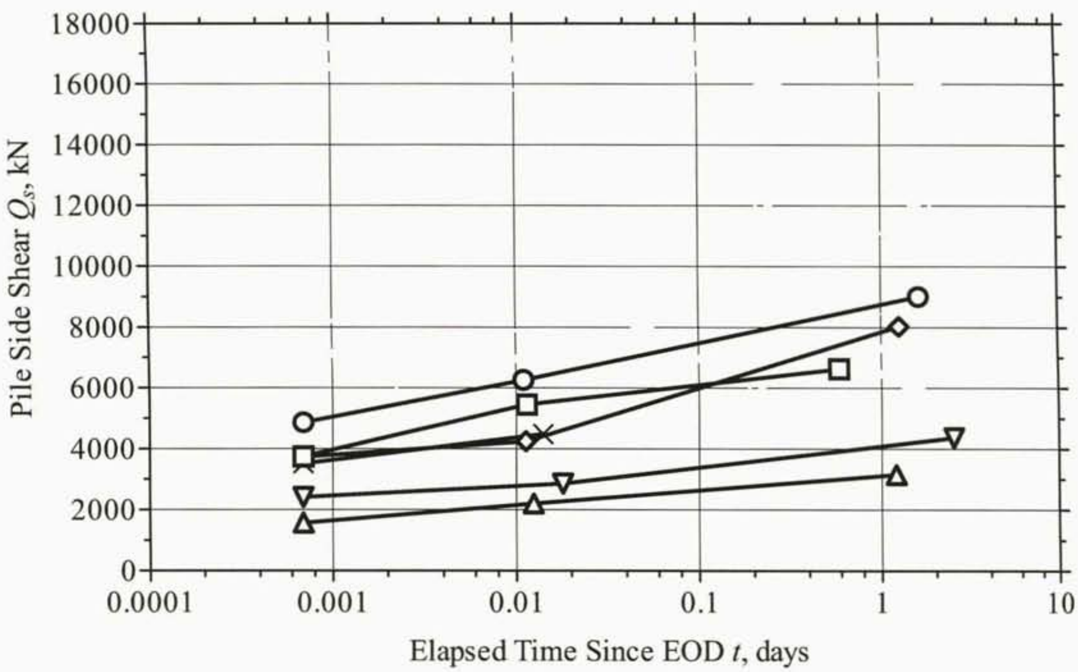

FIG. 8. CAPWAP Side Shear Capacity from Restrikes of Six Red Sea Pipe Piles

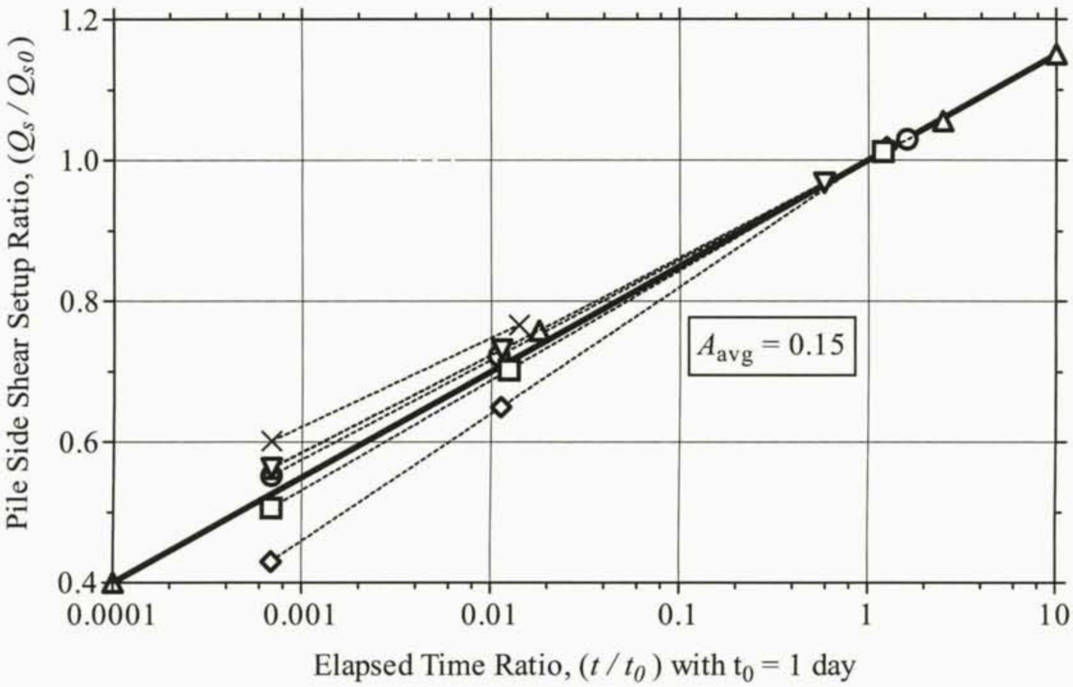

FIG. 9. Setup Factor from Restrikes of Six Red Sea Pipe Piles

APPLICATION OF SETUP FACTOR

After calculating a setup factor from the restrikes and analysis, what next? The list below provides a few possibilities:

- Estimate the static capacity of the pile at a future time (generally less than 90 days) to determine if it meets the design criteria. The engineer may specify additional restrikes to verify large extrapolations or estimates that barely comply. Foundations lacking redundancy and those with high capacity piles (especially offshore platforms) require greater conservatism, which may include testing of every pile, more tests per pile, or greater safety factors (lower resistance factors).
- Calculate an average setup factor from multiple test piles to validate the setup rate for the site. Apply this setup factor to production piles (after reduction for stage testing effects). Perform random restrikes during production driving to validate capacity.
- If the setup analysis of test piles indicates excess capacity, consider shorter, smaller, or fewer production piles. Some soil types provide a greater setup factor, and the designer should check the site stratigraphy to verify that a shorter pile does not eliminate too much of the setup. Also check that any design change does not result in undesirable settlement of the single pile or the pile group. Perform restrikes at the start of production driving to validate any changes in pile length or size.

- If the setup analysis of production piles indicates excess capacity, the engineer may reduce the blow count acceptance criteria and/or required penetration, possibly resulting in a foundation cost savings.
- Develop a database of setup factors for design use. Include location, geology, site stratigraphy, and pile type and size for future reference.

SUMMARY AND CONCLUSIONS

1. The published research shows that displacement piles exhibit side shear setup in most soil types, and that relaxation occurs with less frequency in relatively specific stratigraphy.
2. End bearing does not appear to contribute significantly to setup, and the engineer should avoid including it in setup calculations when possible.
3. Analysis of restrike capacity should generally result in constant end bearing so that the total and side shear capacity will have a similar slope versus the logarithm of elapsed time (unless stratigraphy indicates changing tip conditions).
4. Side shear setup follows a relatively continual process, with capacity increasing linearly versus the logarithm of time elapsed since the EOD, as a result first of pore pressure dissipation and consolidation, and then of mechanical aging. Pile capacity in clean sands may stabilize temporarily before the onset of aging.
5. Expect the setup factor A, describing the increase in side shear relative to the reference capacity at one day elapsed time since the EOD, in the range of 0.1 to 0.8.
6. Limited evidence of staged testing increasing the rate of setup for the tested pile suggests a 60% reduction of the setup factor before applying it to piles without staged tests.
7. Dynamic test measurements during restrikes provide a simple, cost-effective, means to establish a setup trend, with wide acceptance and reasonably accurate estimates of static capacity from signal-matching.
8. Use the estimated setup trend to validate design capacity, and possibly reduce the length, size, or number of production piles. (Provide static tests to verify dynamic estimates for unfamiliar soil conditions, large projects, or heavy loads.)
9. Early restrikes minimize project delay and provide adequate information to extrapolate capacity at later times. Except for piles driven in clean sands, the linear increase of capacity versus the logarithm of time results in rapid capacity gain, measurable and usable within 24 hours. Restrike times of 15 min, 60 min, and 1 day should normally prove adequate. Sands may require longer setup times to allow for mechanical aging effects.
10. Long-term restrikes provide verification of capacity estimates when extrapolating early restrikes to attain the desired capacity.

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