Set-up Factors for Driven Piles Through the Presumpscot Formation

Cameron J. Stuart, EIT
Golder Associates Inc. Manchester, New Hampshire

Thomas C. Sandford, PhD, PE
University of Maine, Orono, Maine

ABSTRACT: Clay adjacent to driven piles is remolded during driving causing loss of pile capacity due to loss of strength from generation of excess porewater pressure. With time after driving the clay regains strength, and thus pile capacity increases. Literature has shown that driven piles in clays, such as the Presumpscot Formation, can experience increasing capacity upwards of 250 days after installation with a set-up (time-dependent increase in pile capacity) exceeding 6 (the ratio of pile capacity with time/ pile capacity at the end of driving). However, current practice in Maine assesses pile capacity using dynamic load tests at the end of driving (EOD). Tight construction schedules for inclusion of piling into structures do not allow assessing pile capacity with significant time after driving. This means that designs based upon EOD dynamic load tests will not use the full capacity of the piles. Dynamic pile load tests on 27 piles with dynamic load tests at the EOD as well as at the later beginning of restrike (BOR) from Maine Department of Transportation (MaineDOT) bridge projects provided valuable set-up data for the Presumpscot Formation. The MaineDOT data was supplemented by data at Portland harbor on 11 pile tests having EOD dynamic load tests as well as BOR dynamic load tests conducted by the Federal Highway Administration (FHWA).

The MaineDOT data showed the set-up in Presumpscot Formation ranged up to 3.5 for one to two days after the end of driving. The data also showed that the set-up factors varied with the water content of the clay with the higher set-up factor occurring for higher water content clay. The FHWA data included a longer BOR waiting period (ranging up to eight days), and the set-up factor in Presumpscot Formation ranged up to 4.2. These measured set-up factors were used to calibrate the Skov & Denver (1988) method to determine set-up factors with time. The calibrated Skov & Denver method indicated at 270 days (maximum long term strength) a predicted set-up factor in Presumpscot Formation of 7.1 for a water content > 40% while predicting a set-up factor of 1.3 for a water content < 26%. The intent of the set-up factors presented in this paper is to assist design engineers in estimating pile capacities with time from capacity measured at the end of driving.

1 INTRODUCTION

1.1 *Project Background*

In 2011 the MaineDOT requested that the University of Maine examine and evaluate their current static pile capacity design methodologies using the results from dynamic load tests on piles as a standard. Current practice in Maine assesses pile capacity using dynamic load tests at the end of driving (EOD). Tight construction schedules typically do not allow time for assessing pile capacity with significant time after driving; thus, making it difficult to quantify pile set-up with time. This implies that designs based on dynamic tests at EOD will not use the full capacity of the piles and/or require pile lengths or diameters greater than necessary.

MaineDOT provided data from over 80 projects including 250 dynamic pile load tests for bridge projects throughout the State of Maine. Upon analysis of the data, 27 piles that were driven through the Presumpscot Formation and tested at end of driving and beginning of restrike (BOR) using a CAPWAP (CAse Pile Wave Analysis Program) analysis (Hannigan et al. 2006b) were selected for further analysis. The piles with CAPWAP analyses were specifically chosen because the CAPWAP analyses can estimate the contribution of side and end bearing resistance to total capacity. The MaineDOT data was supplemented by data at Portland harbor on 11 pile tests having EOD dynamic load tests as well as BOR dynamic load tests conducted by the Federal Highway Administration (FHWA 1990). These set-ups that were measured after waiting periods of primarily one day with a few ranging up to eight days were used as a basis to develop set-up factors applicable to the pile types and subsurface conditions at the subject MaineDOT and FHWA sites. The intent of the set-up factors presented in this paper is to assist design engineers in estimating pile capacities with time from resistance measured at the end of driving.

1.2 *Pile Set-up*

Piles are generally designed based on peak strength states of the soils along the sides and end of the pile. However, MaineDOT as well as many other design engineers typically use end of driving resistance measurements using dynamic tests to check that the piles have obtained the required capacity. The EOD capacities will be conservative especially in cohesive soils, since the pile is supported by lower remolded strength at EOD. The piles will gain capacity with time as the pore pressures from driving dissipate. If the design capacity of the pile has not been achieved at the EOD measurement, then increasingly higher resistance can be measured with time as pore pressures dissipate. Set-up is the ratio of the resistance at any time after driving compared to EOD resistance. The excess porewater pressures developed during driving will dissipate with time and typically correlate to larger pile capacities, however, the rate at which this dissipation occurs varies by site and subsurface conditions. Often construction schedules do not allow tests after the EOD, and thus guidance on estimated set-up for piles installed in the Presumpscot Formation and granular soils is important for the designer to evaluate capacity increases after EOD.

The amount of set-up experienced with time can be determined by conducting beginning of restrike (BOR) tests at various times after EOD. However, the amount of set-up experienced by piles driven through cohesive soil layers is expected to be greater than through granular soil layers. To provide more meaningful set-up parameters an effort has been made to estimate the effects of soil type, pile type and distribution of side friction and end bearing.

2 ANALYSIS OF RAW DATA

2.1 *MaineDOT Data*

The MaineDOT pile test data consisted of 250 dynamic pile load tests using data from Pile Driving Analyzer (PDA) testing (Hannigan et al 2006b) and in most cases a CAPWAP refinement. To analyze pile set-up, the data set was limited to piles with both BOR and EOD test data which can be separated into side and end bearing capacities. This limited data set, summarized in Table 1, consists of 27 piles from 6 different projects where piles were installed through Presumpscot Formation deposits to bear on a high strength underlying bearing stratum. The BOR data was collected between 1 hr to 2 days after EOD.

MaineDOT also provided geotechnical design reports (GDRs), when available, to accompany the pile driving data. The subsurface conditions assumed in the static capacity analyses were taken from laboratory testing data and assumptions made within reports. Effort was made to use only the water content values that applied to the clay strata, however, the separation of these values are only as good as the strata descriptions in the GDRs. Furthermore, the undrained shear strengths of the soils for both the undisturbed and remolded soil states were obtained from the geotechnical reports and boring logs where applicable. The values used in calculations were taken as the average strength for the layer. However, the undrained shear strengths were not always available from the project documents. In the cases when the measured undrained shear strengths were not available, representative values were estimated through correlations with the field corrected standard penetration number (N_{60}). These correlations were provided by Terzaghi, Peck, & Mesri (1996).

2.1.1 Set-up for End Bearing Resistance

The data in Table 1 was further analyzed in an attempt to assess set-up trends.

Table 1: List of Piles Tested at EOD and BOR

			Measured Side Friction Resistance		**Measured End Bearing Resistance**			
Location	**Pile Type**	**Days after EOD**	**EOD kips**	**BOR kips**	**EOD kips**	**BOR kips**	**Pile Length in Clay (%)**	**Clay Water content (%)**
Norridgewock	HP 14x73	1/24	210	180	450	430	0.0	N/A
Verona Island	HP 14x117	2	345	355	710	770	0.0	N/A
Verona Island	HP 14x117	1	314	362	726	660	3.5	?
Verona Island	HP 14x117	2	312	338	736	737	0.0	N/A
Verona Island	HP 14x117	2	346	429	935	950	0.0	N/A
Falmouth	HP 14x73	1	140	280	760	600	16.1	40.3
Falmouth	HP 14x73	1	110	190	310	270	47.3	42.8
Falmouth	HP 14x73	1	260	300	370	320	17.6	36.6
Falmouth	HP 14x73	1	230	240	170	150	17.4	36.6
Falmouth	HP 14x73	1	210	540	580	270	38.4	40.3
Falmouth	HP 14x73	1	250	520	440	220	38.3	40.3
Falmouth	HP 14x73	1	190	220	60	20	16.8	36.6
Portland	22" Pipe Open End	1	80	260	890	690	89.0	42.9
Portland	22" Pipe Open End	1	90	90	1160	1130	21.6	25.2
Portland	HP 12x53	1	10	10	530	560	23.5	36
Portland	22" Pipe Open End	1	190	250	1340	1290	77.0	36.4
Portland	HP 14x89	1	20	30	770	650	21.5	29.6
Portland	22" Pipe Open End	1	190	210	860	880	71.3	22.3
York	20" Pipe Closed End	1	300	340	940	910	26.7	35.5
York	20" Pipe Closed End	1	160	250	1110	1040	0.0	N/A
York	20" Pipe Closed End	1	100	120	900	1370	13.1	24
York	24" Pipe Closed End	1	510	660	930	810	14.0	31.6
Canaan	HP 14X89	1	71	108	465	475	19.5	32
Canaan	24" Pipe Closed End	1	100	120	1010	930	26.5	38.7
Canaan	24" Pipe Closed End	1	460	270	760	610	19.1	38.7
Canaan	24" Pipe Closed End	1	640	320	420	440	16.0	38.7
Canaan	24" Pipe Closed End	1	140	100	1130	990	7.5	38.7

Notes: 1) EOD = End of driving,
BOR = Beginning of Restrike,
HP = H-pile

The end bearing test data provided by MaineDOT did not specify end bearing conditions, therefore, end bearing conditions were assumed when sorting the data. The piles were separated into three categories: piles with less than 500 kips tip resistance were assumed to be bearing in till, piles greater than 800 kips tip resistance were assumed to be bearing on bedrock, and piles with between 500 and 800 kips tip resistance were ambiguous and could fall into either end condition. These categories were then subdivided by pile type (i.e. H-Pile, open-end steel pipe pile, closed end steel pipe pile). This data is presented in Table 2.

Table 2: End Bearing Set-up Factors for MaineDOT Test Data

End Bearing Resistance	Pile Type	Set-up Factor	Number of Piles
<500 kips	H-Pile	0.93	6
	Pipe Open	N/A	0
	Pipe Closed	1.05	1
500-800 kips	H-Pile	0.97	1
	Pipe Open	N/A	5
	Pipe Closed	0.80	0
>800 kips	H-Pile	1.02	2
	Pipe Open	0.94	4
	Pipe Closed	0.91	5

2.1.2 Set-up for Side Resistance

The MaineDOT piles in Table 1 generally experienced an increase in side resistance after EOD, although there was variability.

On initial review of Table 1, it is difficult to see a definitive trend in the side resistance set-up by soil type, but if the set-ups in side resistance for piles entirely in granular soils are isolated, it is possible to estimate set-up of cohesive soil layers. The first step was to determine the set-up for piles in granular soils.

There were five piles which had only granular soils along their entire length. Four of these piles were H-piles which had an average set-up of 1.07; the other pile was a closed end pipe pile which had a set-up of 1.51. These values are consistent with measurements by Long et al (1999). These values were then used to back-calculate set-up factors for the cohesive layers for piles driven through mixed soil strata.

When combined with the percentage of cohesive and granular soil along the side of the pile and the overall BOR/EOD ratio, the set-up of the cohesive layers could be estimated. On average the aggregate set-up for H-piles was 2.08, for open end pipe piles was 1.92, and for closed end pipe pile 2.31 based on 6, 4, and 3 piles respectively. In general, these set-up values correspond to a waiting period between EOD and BOR of about one day. It is important to note that some data points were omitted from the full dataset (27 piles) due to unusual subsurface or pile driving conditions.

The set-up data was analyzed to look for trends with index properties of the Presumpscot Formation, but only water content provided any definitive trend. The set-up factors for piles listed in Table 1 were calculated and sorted by water content in the cohesive soil layers. MaineDOT data with both EOD and BOR CAPWAP data shows the dependence of set-up on the water content of the Presumpscot Formation. The measured set-up is plotted versus water content in Figure 1 with a line of best fit. The Figure 1 plot assumes all pile set-up occurs within the cohesive layer.

Table 3: Table 3: Cohesive Setup Factors for Side Capacity from MaineDOT Test Data

Water Content	Pile Type	Setup Factor	Number of Piles
< 26%	H-Pile	N/A	0
	Pipe Open	0.69	2
	Pipe Closed	2.06	1
26-35%	H-Pile	2.62	2
	Pipe Open	N/A	0
	Pipe Closed	2.67	1
35-40%	H-Pile	1.28	2
	Pipe Open	1.39	1
	Pipe Closed	2.25	2
> 40%	H-Pile	2.92	4
	Pipe Open	3.52	1
	Pipe Closed	N/A	0

Note: * Set-up times for piles in this table are shown in Table 1 and range from 1 hour to 2 days after end of driving.

The set-up factors of cohesive side resistance (after granular set-up was removed) are shown in Table 3. These values are lower than measurements of set-up near 5 by Long et al (1999) and Attwooll et al (1999). However, the measurements in the literature were after 90 days while the measurements in Table 3 were primarily 1 day. The data indicates that the closed end pipe piles experienced greater set-up than low displacement piles, although the sample size is small. This occurrence is likely due to the larger end area disturbing more soil during driving.

Table 4: Fore River Bridge Test Piles (FHWA 1990)

Pile ID	Pile Type	Depth	Time to BOR	Side Friction Resistance		End Bearing Resistance		Length in Clay	Length in Ablation Till
				EOD	BOR	EOD	BOR		
		feet	days	kips	kips	kips	kips	%	%
A10	18" Pipe Closed	79	1	141	202	195	212	41.8	19.0
B17	18" Pipe Closed	71	1	267	380	157	146	0.0	81.7
B23	18" Pipe Closed	51	6	63	120	260	220	0.0	74.5
B22	18" Pipe Closed	71	3	221	297	196	139	0.0	81.7
A5	18" Pipe Closed	99	2	143	318	203	181	33.3	15.2
B14	HP 14x89	115	5	188	259	91	70	0.0	63.5
A8	HP 14x89	115	N/A	N/A	225	N/A	12	28.7	13.0
A6	HP 14x89	115	N/A	N/A	212	N/A	53	28.7	0.0
	HP 14x89	131	N/A	236	N/A	321	N/A	25.2	0.0
B21	HP 14x89	115	5	215	218	82	89	0.0	63.0
A4	HP 14x117	136	8	141	251	590	853	24.3	11.0
A9	HP 14x117	134	1	214	418	649	465	24.6	11.2

Note: * EOD = End of Driving, BOR = Beginning of Restrike, HP = H-pile

Table 5: Set-up for Piles Driven at Fore River Bridge (after FHWA 1990)

	Pile Type	**Set-up Factor**	**Number of Piles**
	Side Friction Resistance		
Ablation Till	H-pile	1.27	2
	Pipe Closed	1.59	3
Cohesive Soils	H-pile	4.24	2
	Pipe Closed	2.46	2
	End Bearing Resistance		
< 500 kips	H-Pile	0.92	2
	Pipe Open	N/A	0
	Pipe Closed	0.89	5
500-800 kips	H-Pile	1.06	2
	Pipe Open	N/A	0
	Pipe Closed	N/A	0

2.2 *FHWA (1990) Fore River Bridge Dynamic Test Data*

To supplement the findings in the data provided by the MaineDOT, test data from the State Highway 77 Fore River Bridge Replacement project (FHWA 1990) was analyzed. Table 4 summarizes the Fore River Bridge test data. There were 9 piles on the project that were tested at EOD and BOR. Only four of these piles were driven through clay layers. However, none of the piles were driven to bedrock or had end bearing in the clay. Table 5 displays the set-up factors for the piles on this project.

The closed end pipe piles experienced side resistance set-up in granular soils of 1.59 similar to the 1.51 in the MaineDOT data (Table 1). The side resistance set-up of H-piles in granular soils on the Fore River Bridge project was about 20% larger than the set-up factor on the MaineDOT projects. Additionally, the side capacities of piles in cohesive soils were also larger on the Fore River Bridge project. However, these piles were typically tested after longer periods of time, so the larger set-up factors indicate that the piles are continuing to gain capacity after one day. It is interesting to note that the side resistance set-up of H-piles in cohesive soils was significantly larger than the closed end pipe piles, but again the H-piles had greater set-up times than the closed end pipe piles which likely accounts for the difference.

In the Fore River Bridge data the average set-up factor of 0.92 for end bearing H-piles with capacities less than 500 k was similar to the average factor of 0.93 from the MaineDOT data. With a larger average time of 4 days from EOD to BOR at the Fore River Bridge compared to close to 1 day for the MaineDOT data, indicates that there is practically no resistance change beyond 1 day. The average set-up factor of 1.06 for end bearing H-piles with capacities of 500 - 800 k compared to 0.97 from the MaineDOT data indicates that the combined factor is close to 1.0. The average set-up factor of 0.89 for 5 closed end pipe piles with capacities below 500 k was lower than the set-up factor of 1.05 (1 closed end pipe) in the MaineDOT data. This set-up factor of 0.89 reflects similar behavior to the H-pile at this load level.

3 DETERMINATION OF SET-UP FACTORS FOR DESIGN

The limited amount of substantial long term set-up data in the Presumpscot Formation inhibits designers from making estimates of ultimate capacity for piles installed through the formation. As evident in the MaineDOT test data, pile set-up is variable by pile type as well as the water content of the supporting cohesive layer.

The MaineDOT test data (Table 3) combined with the Fore River Bridge data (Table 5) were used to estimate pile set-up with time for side friction. The set-up values at one day for each of the H-piles entirely in granular soil (4 piles) from Table 1 were averaged to calculate a typical set-up BOR/EOD ratio for granular soil.

3.1 *Method Projecting Long Term Set-up Factors*

The most widely used method for calculating pile set-up as a function of time in soil is the method proposed by Skov & Denver (1988). The Skov & Denver method allows for the capacity to be calculated at any time after installation. This method is shown below:

$$\frac{Q_t}{Q_0} = 1 + A \log\left(\frac{t}{t_0}\right) \tag{1}$$

Where:
Q_t = Pile capacity at time t
Q_0 = Pile capacity at time t_0
A = Dimensionless coefficient
t = Time of interest
t_0 = Elapsed time after driving for initial capacity

The Skov & Denver method (1988) was used by both Camp & Parmar (1999) and Long et al (1999) to analyze pile set-up with time. However, there does not appear to be a consistent method for determining the t_0 and A parameters for use in the equation. The appropriate values vary among users. Long et al (1999) reported that the reference time (t_0) that they used was 0.5 day and 1.0 day for sands and clays respectively. The reference time used by Camp & Parmar (1999) was 2 days. Since the initial PDA capacity measurement was taken close to EOD, values of t_0 greater than 0.5 days were not appropriate. In this study, the elapsed time from EOD to the initial PDA measurement (t_0) for use in Equation 1 was taken to be 20 minutes (0.014 days). This value was based on typical dynamic testing procedure outlined by Hannigan et al (2006).

The dynamic test reports generally report that the BOR test was conducted the following calendar day from the EOD. The elapsed time to BOR (t) for calculations was taken to be 19 hours rather than 24 hours. It was considered that the pile was likely tested at EOD in the afternoon (the office of the testing company is 3 to 5 hours from most Maine locations). The technician came back in the morning to conduct the BOR test and returned to his office (3-5 hours) following the test.

Using the available MaineDOT and FHWA data, an A parameter for granular soil can be calculated with Skov & Denver's (1988) relationship (Equation 1). From these datasets, the Q_t, t, Q_0, and t_0 values are known, or estimated as described previously, allowing for the A parameter to be calculated. These A parameters were then sorted by pile type, high displacement (CEP) and low displacement (H-pile and open end pipe), and to obtain average A values of 0.29 and 0.042 respectively.

The A parameters suggested in the literature review did not include correlations to specific types of cohesive soils, so the A parameter for the Presumpscot Formation was also back-calculated. By back-calculating the A factor from data specific to the Presumpscot Formation, then material specific properties including dissipation rates, consolidation, and mineral composition are incorporated into the A factor. Furthermore, there was not sufficient data to determine trends in cohesive set-up by pile type. Instead, these A parameters were calculated for various clay water contents. From the available MaineDOT test data and the set-up trend shown in Figure 1 the back-calculated clay A parameters were sorted into three ranges of water content with the clay layer: water contents < 26%, water contents 27-39%, and water contents > 40%. This resulted in average A parameters for each water content group of 0.061, 0.38, and 1.42 respectively.

3.2 *Time for Full Dissipation of Pore Pressures Caused by Driving*

The first step to estimate set-up versus time for side friction in cohesive soils is to assess the expected time for full dissipation of pore pressures caused by driving. Orrje & Broms (1967) indicate the assumed time at which the pore pressure had fully dissipated for Swedish glacial clays is 270 days, and that the clay had reached the long term strength state. Swedish glacial clays have a similar geologic history and Atterberg limits to Presumpscot Formation. Long et al (1999) and Attwooll et al (1999) found that set-up was increasing to 100 days and perhaps beyond. Although pore pressure dissipation for large layers of clay can take much longer, for piles it is just pore pressure dissipation within the disturbed zone (i.e. 2 radii thick or about 1 ft thick around the pile) into the surrounding clay. Also there are silt laminae in the Presumpscot Formation which allow horizontal movement of porewater. These are not measured in the usual consolidation test where the flow is vertical.

Using a time rate of consolidation analysis with the following equation (Poulos & Davis 1980) and typical data for Presumpscot Formation, then an estimate of dissipation rate can be made.

$$T = \frac{tC_h}{a^2} \tag{2}$$

Where:

T = time factor
a = pile radius (feet)
C_h = coefficient of horizontal consolidation (ft^2/day)

The time factor can be found from the above equation for various elapsed times. A C_h value of 0.15 ft^2/day was used and was obtained from a C_v average of 0.10 ft^2/day (Andrews 1987) with a C_h/C_v = 1.5 (Poulos & Davis 1980). The relation between the time factor (T) and percent consolidation ($\bar{U}_p$) for a ring of soil with a radius 3 times the radius of the pile was determined from relationships published by Poulos & Davis (1990) and shown in Figure 2. These relationships were used to estimate consolidation for each time period shown in Table 6. It was determined that at 289 days the pore pressure was 96% dissipated. This indicated that the Orrje & Broms (1967) suggestion was a reasonable range for set-up.

3.3 *Set-up Factors with Time*

Using the Skov & Denver (1988) relationship and the calculated A parameters, set-up factors were calculated at 0.8 days (1 day BOR), 1 day, 2 days, 3 days, 5 days, 6 days, 8 days, 14 days, 90 days, and 270 days. The resulting set-up factors (Q_t/Q_0) from Equation 1 are shown in Table 6 for various elapsed times.

Table 6: Estimated Side Friction Set-up Factors vs Time for Piles Driven in Presumpscot Formation and Granular Soils

Time (days)	**Cohesive Soil Set-up Factors** w > 40% Qt/Qo	w = 26-39% Qt/Qo	w < 26 % Qt/Qo	**Granular Soil Set-up Factors** HP & Open Pipe Qt/Qo	CEP Qt/Qo
0.8	3.49	1.67	1.11	1.07	1.51
1	3.63	1.70	1.11	1.08	1.54
2	4.06	1.82	1.13	1.09	1.62
3	4.31	1.89	1.14	1.10	1.68
5	4.63	1.97	1.16	1.11	1.74
6	4.74	2.00	1.16	1.11	1.76
8	4.91	2.05	1.17	1.12	1.80
14	5.26	2.14	1.18	1.13	1.87
90	6.41	2.45	1.23	1.16	2.10
270	7.09	2.63	1.26	1.18	2.24

Note: * w = water content, HP = H-pile, CEP = closed end pipe pile, Qt = Capacity at time (t), Qo = Capacity at reference time (EOD)

The end bearing set-up factors in Table 2 for MaineDOT data and in Table 5 for FHWA data were synthesized into Table 7. The set-up factor of 0.92 for glacial till (<500 kips) indicates relaxation consistent with negative pore pressures from dilation during driving dissipating rapidly in more free draining till. For H-piles on bedrock (>800 kips) no change with time was considered. All CEP piles were considered to be bearing on till with perhaps partial bearing for >800 kips on bedrock. Thus there was relaxation for all CEP piles.

Table 7: Final Bearing Resistance Set-up Factors

EOD Bearing Resistance	**H-Pile & Open Pipe Pile** Q_{BOR}/Q_{EOD}	**CEP Piles** Q_{BOR}/Q_{EOD}
< 500 kips	0.92	0.92
500-800 kips	1.00	0.91
> 800 kips	1.00	0.91

Note: *EOD = End of Driving, Q_{BOR} = Capacity at Beginning of Restrike, Q_{EOD} = Capacity at End of Driving

4 CONCLUSIONS

The increase in driven pile capacity with time (set-up) in Maine depends upon the soil type, pile type and the time after pile driving. The findings from this study further indicate the set-up value depends upon the water content, i.e. the sensitivity to disturbance, of the clay for the side of piles within the Presumpscot Formation. It is the opinion of the authors that there is much higher sensitivity when the water content exceeds the liquid limit. This leads to loss of strength upon remolding and thus a great percentage increase in setup as it recovers. The set-up factors within clays with water content greater than 40% are approximately 3 times greater than those with lesser water contents. Piles driven into granular materials will also have set-up, although the set-up value for granular materials will be less than for the Presumpscot Formation. At many locations in Maine, the profile consists of layers of granular and Presumpscot clay. When finding the net set-up for the pile, the set-up for the granular layer must be evaluated separately from the set-up for the Presumpscot Formation.

Based on data correlations with the empirical set-up relationship developed by Skov & Denver (1988), the majority of the set-up for side friction in Presumpscot Formation is estimated to occur in the first two weeks after driving. However, measurements cited in the literature and analytical methods for estimating pore pressure dissipation indicate that set-up will continue to develop at decreasing rates for 90 to 270 days, or longer, after driving.

Pile foundations in Maine are typically driven to bedrock, glacial till or granular glacial outwash end bearing strata. The data set evaluated did not include end bearing conditions in clay.

The end bearing set-up data indicates that piles can expect an initial reduction in end bearing resistance of roughly 8% when bearing on till. This relaxation of the soil after driving could occur if the side resistance had significant set-up for which the designated pile driving hammer could not deliver enough energy to fully mobilize the end bearing resistance at the tip during testing.

The data indicated that bearing on bedrock does not have an appreciable change in bearing resistance with time.

5 RECOMMENDATIONS AND LIMITATIONS

The pile installation data provided by the MaineDOT generally lacked sufficient waiting periods between EOD and BOR to establish a measured relationship between set-up and the time duration that set-up is expected to occur. The set-up data was primarily for one day. Since the majority of set-up occurs within two weeks, more testing between one day and two weeks should be conducted.

The long term set-up factors presented in this paper rely on extrapolated trends from short term set-up data. The authors of this paper believe that it would be beneficial to conduct some long term (up to 270 days) dynamic pile testing to further refine the A parameters used in the Skov & Denver analyses as well as the resulting set-up factors presented in this paper. It is important to note that the A parameters used by the authors for the Skov & Denver analysis are related to the estimated t_0 (0.014 days) and should not be mixed with other reference times. However, it is anticipated that modeling with other reference times will still yield similar set-up rates with time as given in Table 6.

More comprehensive long term pile capacity testing for various pile sizes and types would help further refine set-up predictions. Furthermore, the cohesive setup factors provided in this paper were derived with the assumption that the Presumpscot layer was uniform along each pile. In reality the properties of the Presumpscot (i.e. water content and strength) will vary along the side of the pile. If desired, a more detailed analysis could be completed by dividing the Presumpscot component of side capacity into more discrete layers to make a more refined set-up prediction.

6 REFERENCES

Andrews, David W. 1987. "The Engineering Aspects Of The Presumpscot Formation." *Proceedings of Geologic and Geotechnical Characteristics of the Presumpscot Formation Maine's Glaciomarine "Clay."* Maine Geological Survey, Morrison Geotechnical Engineering, University of Maine Civil Engineering Dept., University of Southern Maine Geosciences Dept., Augusta, ME, 1-15.

Attwooll, William J., Holloway, D. Michael, Rollins, Kyle M., Esrig, Melvin I., Sakhai, Si, and Hemenway, Dan. 1999) "Measured Pile Set-up During Load Testing and Production Piling: I-15 Corridor Reconstruction Project in Salt Lake City, Utah." *Transportation Research Record*, Transportation Research Board, (1663), 1-7.

Bjerrum, L. 1954. “Geotechnical properties of Norwegian marine clays,” Geotechnique, vol. IV, no. 2, pp 49-69.

Camp III, William M., and Parmar, Harpal S. 1999. "Characterization of Pile Capacity with Time in the Cooper Marl Study of Applicability of a Past Approach To Predict Long-Term Capacity." *Transportation Research Record*, Transportation Research Board, (1663), 16-24.

Federal Highway Administration. 1990. *“Dynamic Pile Monitoring and Pile Load Test Report:* Federal Highway Administration, Washington, D.C. *State Highway 77 Fore River Bridge Replacement.”*

Hannigan, P. J., Goble, G. G., Thendean, G., Likins, G. E., and Raushe, F. 2006a. "Design and Construction of Driven Pile Foundations- Volume I." FHWA-HI-97-013, Federal Highway Administration, Washington, D.C.

Hannigan, P. J., Goble, G. G., Thendean, G., Likins, G. E., and Raushe, F., 2006b. "Design and Construction of Driven Pile Foundations- Volume II." FHWA-HI-97-013, Federal Highway Administration, Washington, D.C.

Long, J., Kerrigan, J., and Wysockey, M. 1999. "Measured Time Effects for Axial Capacity of Driven Piling." *Transportation Research Record,* Transportation Research Board, (1663), 8-15.

Orrje, O. and Broms, B. B. 1967, "Effects of Pile Driving on Soil Properties." *Journal of Soil Mechanics and Foundations Division*, ASCE, 93 (SM5), 59-73.

Poulos, H. G., and E. H. Davis. 1980. *Pile Foundation Analysis and Design*. Wiley, New York.

Skov R, and Denver H. 1988. “Time-Dependence of Bearing Capacity of Piles.” *Proceedings 3rd International Conference on Application of Stress-Waves to Piles*, 1-10.

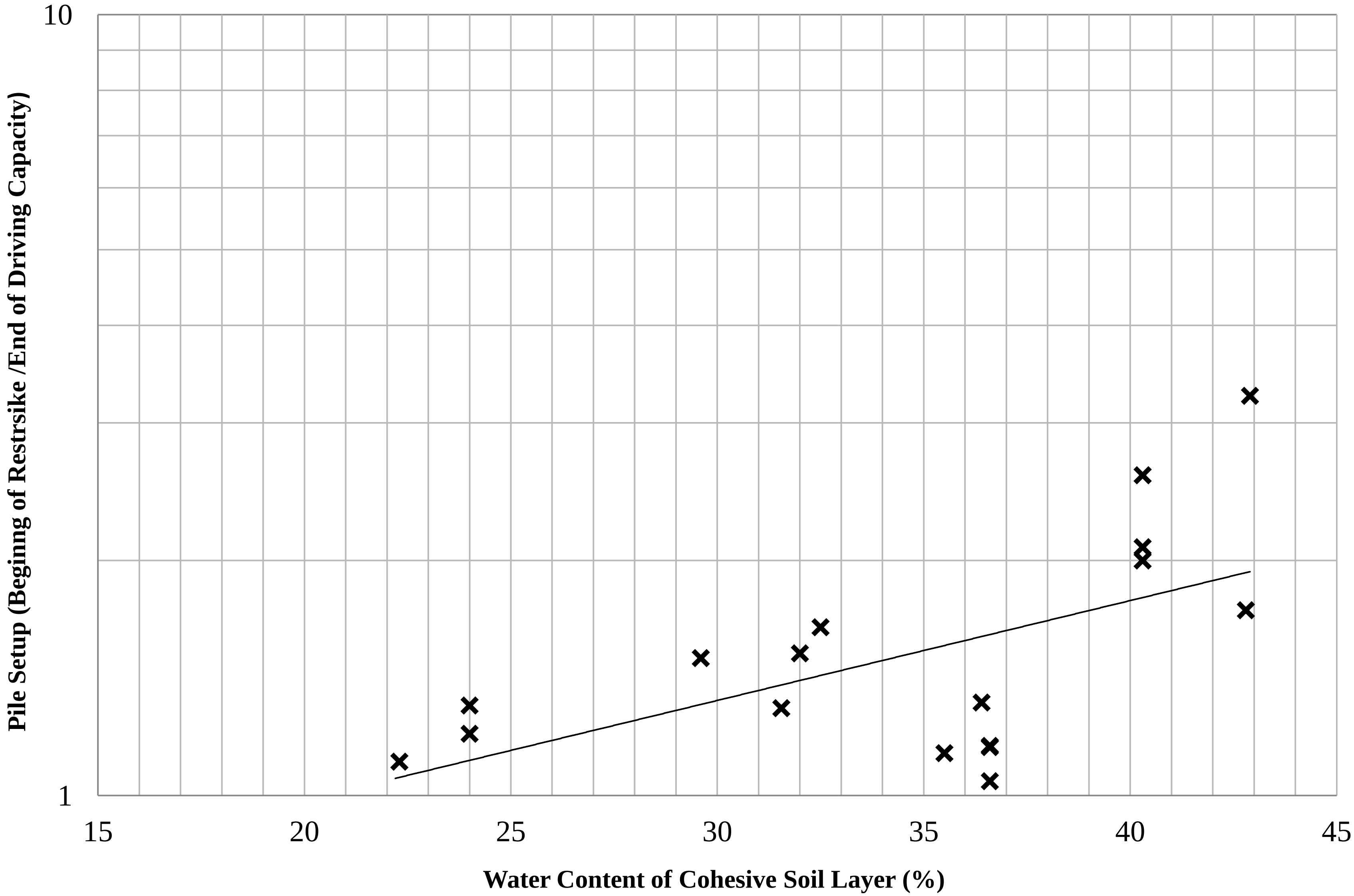

Figure 1: Pile Setup as a Function of Cohesive Soil Water Content

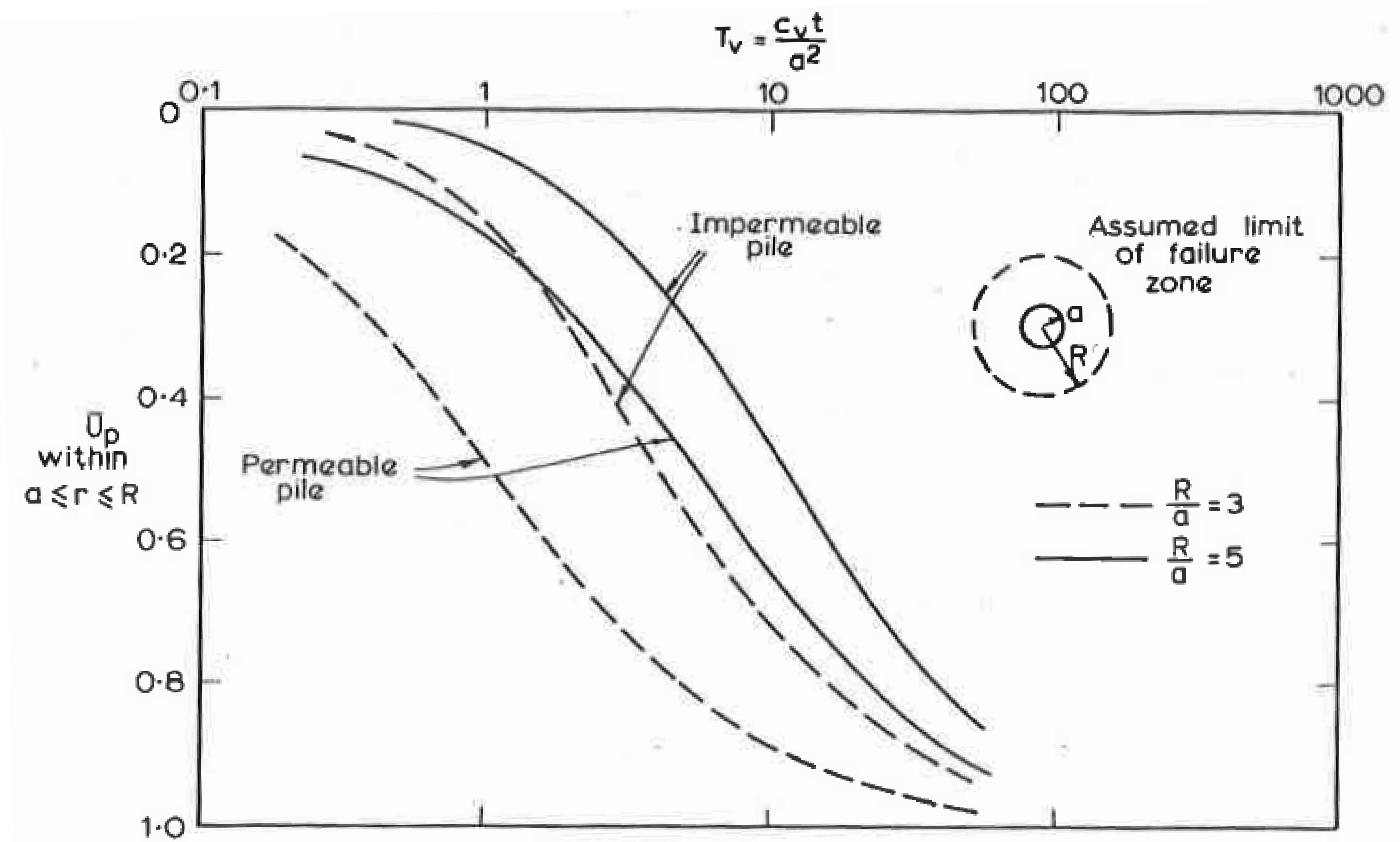

Figure 2: Percent Consolidation for Driven Piles from Poulos & Davis (1980)