"This technical note was originally published in the *DFI Journal*, Vol. 3 No. 2 November 2009. DFI is an international technical association of firms and individuals involved in the deep foundations and related industry. *DFI Journal* electronic and print subscriptions are available at www.dfi.org/dfijournal.asp."

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DEEP FOUNDATIONS INSTITUTE

DFI

Vol 3, No. 2 November 2009

DFI JOURNAL

The Journal of the Deep Foundations Institute

PAPERS:

Deep Foundations Institute is the Industry Association of Individuals and Organizations Dedicated to Quality and Economy in the Design and Construction of Deep Foundations.

TECHNICAL NOTE

Evolution of Top of Pile Measurement Techniques in Deep Foundation Static Load Testing

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ABSTRACT

Ensuring the accuracy of collected data during deep foundation static load tests is of paramount importance. Typically, pile head displacements are measured relative to a purpose-built reference system, which is assumed to be fixed. This study presents a simplified error analysis of this assumption, illustrates the potential magnitude of these errors, and proposes an improved method of pile head displacement monitoring.

INTRODUCTION

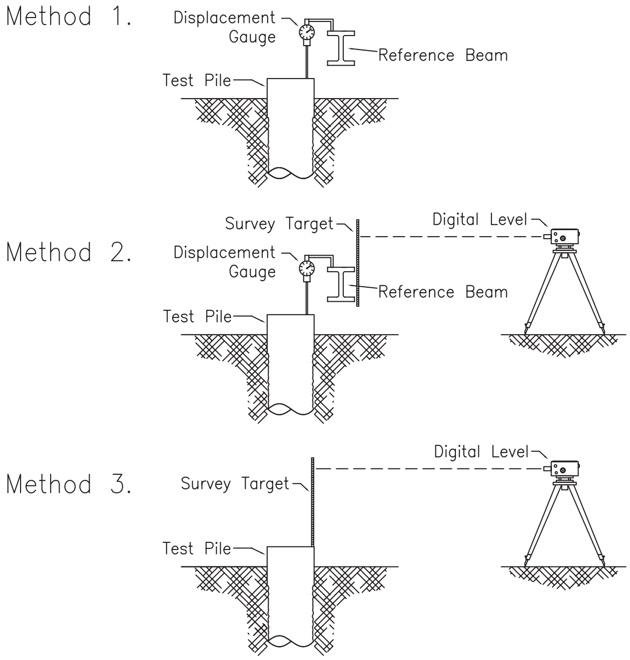
Current practice in full scale static deep foundation testing is to set up one or more reference beams next to or over the pile head, in general accordance with ASTM D1143/D1143M - 07 (ASTM, 2007). Electronic and/or dial gauges are mounted to the beam(s) and used to monitor pile head displacement during application of test loads. In order to mitigate the influence of downdrag or heave of the soil around the pile, the beam supports are placed five pile diameters (or further) away from the center of the test pile. However, with increasing pile diameter, this creates a long span for the reference beam, which can result in non-trivial vertical displacement of the beam due to thermal strains and other factors. On the other hand, the zone of influence of the pile under load can be greater than many engineers estimate, and ground movement can cause displacement of the reference beam supports even if they are located several diameters away from the test pile. A solution to this problem is to monitor the reference beam itself for displacement using a remote device and correct the gauge readings accordingly. This procedure has been the authors' standard practice for over 12 years for all reference systems used in pile testing. A simplifying alternate method of pile head displacement measurement is to use the remote device directly, and eliminate the reference system altogether. This study presents a comparison of the potential measurement errors associated with these three methods. It is not the authors' intent to examine all possible sources of error in detail, but rather to make a qualitative comparison of the measurement methods described herein.

MEASUREMENT OF PILE HEAD DISPLACEMENT

Fig. 1 illustrates the evolution of the pile head displacement measurement system used by the authors.

1. The first method, which is still used in common practice in the industry, assumes that the reference beam remains fixed during the course of the test.
2. The second method monitors the reference beam for displacement (to the same level of precision as the pile head displacement gauges), and adds or subtracts any recorded reference beam deflection from the gauge reading to arrive at a total pile head displacement.
3. The third method eliminates the reference beam altogether and instead uses the beam-monitoring equipment (precision level) to directly measure pile head displacement. This non-traditional method of pile head displacement measurement is addressed in ASTM D1143/D1143M – 07 sections 7.2.4 and 7.2.5.

Note that for illustration purposes, only one displacement gauge and one digital level are shown. In practice, all pile and reference beam displacements are computed by averaging multiple gauges as per ASTM D1143/D1143M – 07. The precision levels can be any leveling type instrument which can optically and/or digitally read a target which is mounted on the reference beam and/or pile head, from a sufficient distance so as not to be in the zone of influence of testing and on the same schedule as the head displacement gauges are read. Examples of such devices include digital



[FIG. 1] Schematics of Pile Head Displacement Measurement Methods

levels and total stations, the Samsung SPI line-scan camera system (Se-Na Lee et al., 2002) and precision laser leveling systems. The system used by the authors of this study is the Leica NA3000 Digital Level, with associated invar staff bar-code target, which has a specified precision of a single measurement of 0.01 mm with a standard deviation of 0.03 mm at a range of 60 m (200 ft). To compensate for relatively high-frequency disturbances such as wind-induced vibration, multiple readings are taken which are then averaged for each desired time interval. To check for static displacement such as ground settlement under the level supports, a fixed backsight (second target mounted on a fixed object such as a neighboring structure or pile head) is utilized.

NUMERICAL COMPARISON OF THE THREE METHODS

The basic equation for the measured Top of Pile displacement using Method 1 ($\mathbf{TOP}_1$), assuming no measurement error, is:

$$\mathbf{TOP}_{1\ (\text{nominal})} = \mathbf{PH}_{\text{gauge}} \tag{1}$$

where $\mathbf{PH}_{\mathbf{gauge}}$ is the average of 2 or more reference-mounted-gauge measured Pile Head displacements of Top of Pile. The full equation for Top of Pile displacement using this method, with all random and systematic errors, is given below:

$$\mathbf{TOP}_{1\ (\text{actual})} = \mathbf{PH}_{\text{gauge}} + \partial\mathbf{Gauge} + \partial\mathbf{RB} \tag{2}$$

where ∂**Gauge** is the sum of all random and systematic errors associated with the displacement gauge and its mounting system and ∂**RB** is the error associated with the unmonitored deflection of the reference beam.

From Equations 1 and 2, the error in Method 1 ($\partial\mathbf{TOP}_1$) is:

$$\begin{aligned}\partial\mathbf{TOP}_1 &= |\mathbf{TOP}_{1\ (\text{actual})} - \mathbf{TOP}_{1\ (\text{nominal})}| \\ &= |\partial\mathbf{Gauge} + \partial\mathbf{RB}|\end{aligned} \tag{3}$$

The basic equation for the measured Top of Pile displacement using Method 2 ($\mathbf{TOP}_2$) is:

$$\mathbf{TOP}_{2\ (\text{nominal})} = \mathbf{PH}_{\text{gauge}} + \mathbf{RB}_{\text{level}} \tag{4}$$

where $\mathbf{PH}_{\mathbf{gauge}}$ is defined as above and $\mathbf{RB}_{\mathbf{level}}$ is the average of 2 or more remote level measured Reference Beam displacements. The full equation for Top of Pile displacement using this method, with all random and systematic errors, is given below:

$$\mathbf{TOP}_{2\ (\text{actual})} = \mathbf{PH}_{\text{gauge}} + \mathbf{RB}_{\text{level}} + \partial\mathbf{Gauge} + \partial\mathbf{Level} \tag{5}$$

where $\partial_{\mathbf{Gauge}}$ is defined as above and $\partial_{\mathbf{Level}}$ is the sum of all random and systematic errors associated with the remote level instrument, for both the level and the target.

From Equations 4 and 5, the error in Method 2 ($\partial\mathbf{TOP}_2$) is:

$$\begin{aligned}\partial\mathbf{TOP}_2 &= |\mathbf{TOP}_{2\ (\text{actual})} - \mathbf{TOP}_{2\ (\text{nominal})}| \\ &= |\partial\mathbf{Gauge} + \partial\mathbf{Level}|\end{aligned} \tag{6}$$

The basic equation for the measured Top of Pile displacement using Method 3 ($\mathbf{TOP}_3$) is:

$$\mathbf{TOP}_{3\ (\text{nominal})} = \mathbf{PH}_{\text{level}} \tag{7}$$

where $\mathbf{PH}_{\mathbf{Level}}$ is an average of 2 or more remote level measured Pile Head displacements. The full equation for Top of Pile displacement using this method, with all random and systematic errors, is given below:

$$\mathbf{TOP}_{3\ (\text{actual})} = \mathbf{PH}_{\text{level}} + \partial\mathbf{Level} \tag{8}$$

where ∂**Level** is defined as above. From Equations 7 and 8, the error in Method 3 ($\partial\mathbf{TOP}_3$) is:

$$\begin{aligned}\partial\mathbf{TOP}_3 &= |\mathbf{TOP}_{3\ (\text{actual})} - \mathbf{TOP}_{3\ (\text{nominal})}| \\ &= |\partial\mathbf{Level}|\end{aligned} \tag{9}$$

By definition, the magnitude of the ∂**RB** error in Method 1 for a given test is unknown. However, a statistical analysis of reference beam movement data from 100 separate load tests (Fig. 2) yields an average maximum reference beam displacement of 1.6 mm. Given that the precision of the instrumentation used is typically 0.05 mm or better, it is therefore assumed that ∂**RB** is statistically greater than either ∂**Gauge** or ∂**Level**.

If the setup and environmental conditions for the precision level (target mounting, distance to target, level & tripod shading, etc.) are similar for Methods 2 and 3 the magnitude of **∂Level** is assumed to be equivalent for both Methods 2 and 3. Thus, by comparing Equations 3, 6 and 9, it follows that:

$$|\partial \mathbf{Level}| < |\partial \mathbf{Gauge} + \partial \mathbf{Level}| < |\partial \mathbf{Gauge} + \partial \mathbf{RB}| \quad (10)$$

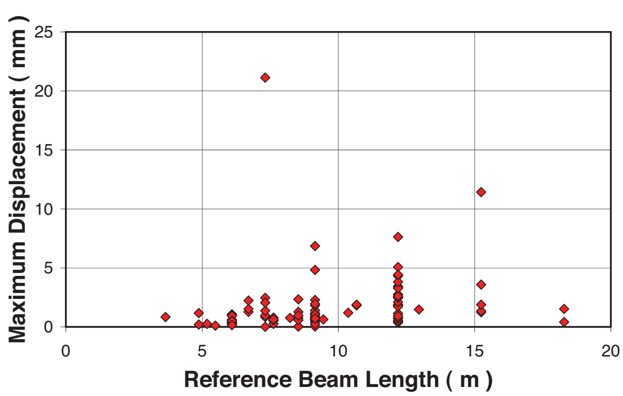
and thus:

$$\partial \mathbf{Top}_3 < \partial \mathbf{Top}_2 < \partial \mathbf{Top}_1 \quad (11)$$

As noted above, per ASTM D1143/D1143M – 07 section 7.2.4, the levels used in either Method 2 or Method 3 are either checked for stability using a backsight and/or mounted on a rigid platform (e.g. adjacent pile).

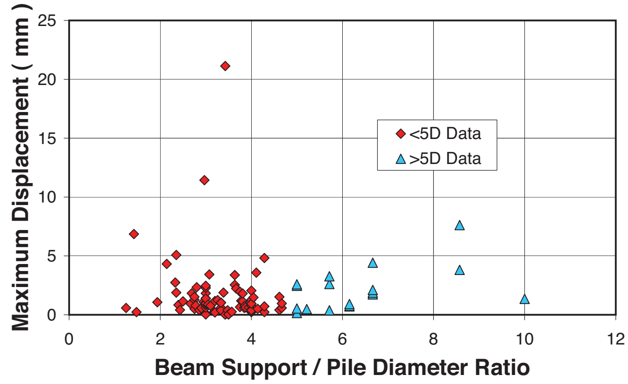
MAGNITUDE OF REFERENCE BEAM DISPLACEMENT

It is often assumed that a heavy steel beam, wooden beam or purpose-built steel truss reference system, supported five pile diameters from the test pile and shaded by a tarp, has negligible vertical displacement. However, it has been the authors' experience, based on a practice for over 12 years of monitoring the reference system with automated precision levels, that more often than not significant displacement of the beam occurs. Below is a scatterplot of the maximum measured beam displacement, taken randomly from 100 O-cell test data reports, plotted vs. beam length (Fig. 2), and vs. the ratio of beam length to pile diameter (Fig. 3).



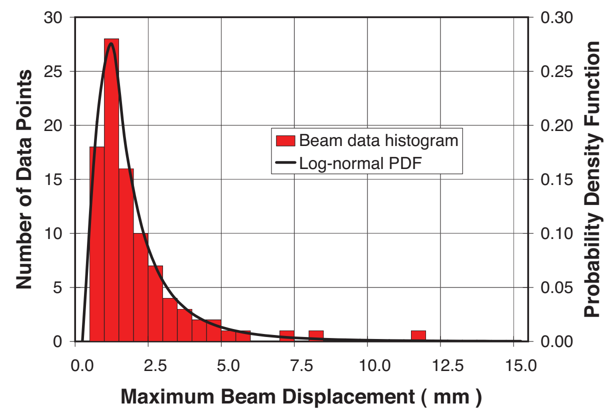
[FIG. 2] Maximum Reference Beam Displacement vs. Beam Length (LOADTEST Database, 1995-2004)

Note that most of the data was collected in general compliance with ASTM D1143 (1994) and hence the beam support to pile diameter ratio is less than five in many cases. The data in Fig. 3 has been separated into two subsets, with the ratio less than five diameters ("**<5D**", red diamond data points) and equal to or greater than five diameters ("**>5D**", blue triangle data points). Both a visual inspection of Fig. 3 and a probabilistic analysis of the **>5D** data subset (see below) indicates no significant difference in the distribution of maximum displacements.



[FIG. 3] Maximum Reference Beam Displacement vs. Support/ Diameter Ratio (LOADTEST Database, 1995-2004)

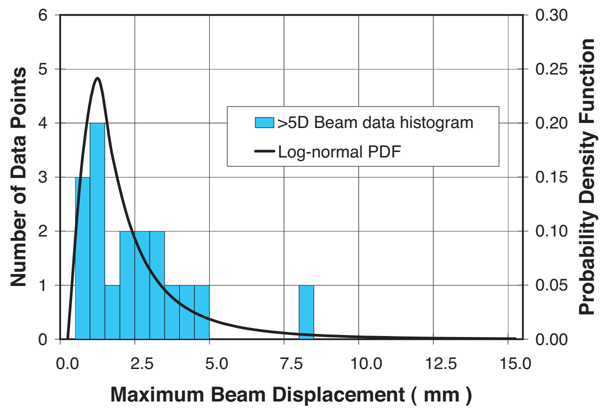
A probabilistic analysis of the data presented in Fig. 2 (excluding the extreme event data point of 21 mm displacement) indicates that the distribution of the maximum beam displacement may be approximated by a log-normal probability density function, as illustrated in the plot below.



[FIG. 4] Probability Density Function (PDF) of Max. Beam Displacement (LOADTEST Database, 1995-2004)

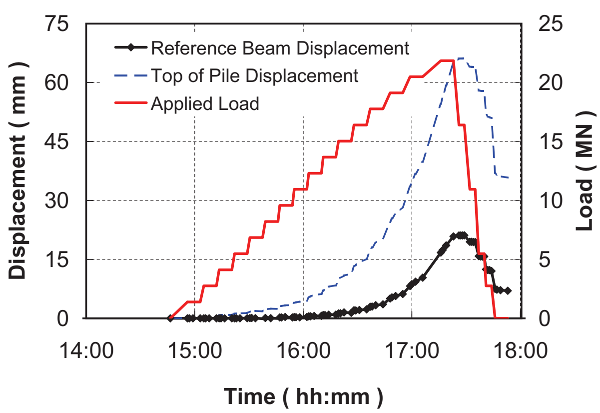
This probability distribution yields an average maximum reference beam displacement of 1.6 mm with a standard deviation of 1.7 mm, and indicates that 20% of beam movements can be expected to be greater than 2 mm, 10% greater than 3 mm and 5% greater than 4.5 mm. A parallel analysis of the **>5D** subset of the data yields very similar results (1.9 mm average beam displacement, 2.3 mm standard deviation, Fig. 5).

Two of the primary sources of the measured beam displacements are most likely ground movement below the beam supports, due to the influence of the pile test, and thermally-



[FIG. 5] Probability Density Function (PDF) of Max. Beam Displacement (>5D Subset) (LOADTEST Database, 1995-2004)

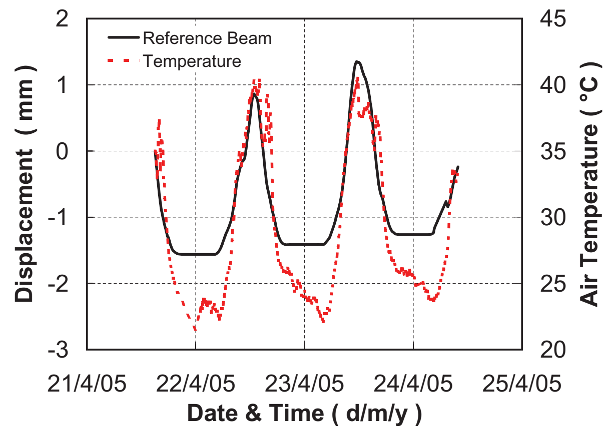
induced transverse strains of the beam. There is publicized evidence that the zone of influence (that is, the radius of the ground around the pile which heaves or settles along with the pile, due to radial transmission of shear stresses and strains) around a vertically loaded pile is greater than five pile diameters. For example, both Randolph and Wroth (1978), and Fleming et al. (1992) propose that the zone of influence of soil displacement around a pile extends radially outward to a magnitude equivalent to the pile length. Atkinson (2007) presents a nomograph suggesting that the pile group effect only dissipates at a pile spacing of approximately ten diameters. Any reference system supports which are located within this zone of influence are subject to vertical motion. This source of error can be quite significant, as illustrated in Fig. 6.



[FIG. 6] Reference Beam Displacement Compared with Applied Load (LOADTEST Project Reference No. 620, 2004)

The reference beam displacement of 21 mm in Fig. 6 represents a potential 50% error in the uncorrected maximum measured pile head displacement of 45 mm (the corrected displacement, with a maximum of 66 mm, is plotted).

ASTM D1143/D1143M – 07 makes reference to shading reference beams and supporting them on a pin-roller system. However, in the authors' experience, these measures can mitigate but not eliminate temperature-induced strains. While an idealized pin-roller system should in theory negate any vertical beam displacement due to thermal strains, in practice it is more often the case that some movement occurs. This is possibly due to field-assembled rollers which do not permit truly friction-free beam expansion. Ambient temperature of the reference beam fluctuates regardless of direct exposure to sunlight, and this can induce vertical beam motion, as illustrated in the plot of a shaded reference beam in Fig. 7.

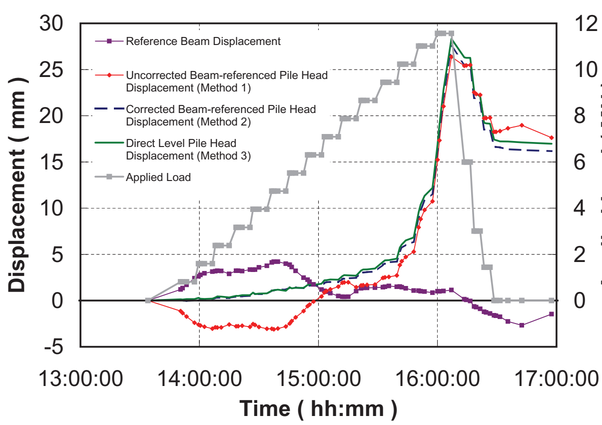


[FIG. 7] Shaded Reference Beam Displacement Compared with Temperature Variation (LOADTEST Project Reference No. 213-3, 2005)

For clarity, the pile head movement is omitted in Fig. 7. The maximum (corrected) pile head displacement for the test presented in Fig. 7 was 13.7 mm, and the 2.5 mm range of measured reference beam displacement represents a potential error of 18% if not corrected.

The two effects described above are both influenced by beam length. All else being equal, a longer beam (supports placed further away) will have less displacement due to ground heave in the immediate vicinity of the pile. However, the longer free span is subject to greater thermally-induced displacement. The inverse, that a relatively short beam will experience less thermally-induced displacement but greater ground settlement, is also true. This may explain the statistical similarity of the full data set and the >**5D** subset noted above. While an average reference beam movement of the order of 2 mm may not seem very significant, it should be noted that 20% of reference beam displacements in the random sample presented herein were greater, some by an order of magnitude. If not monitored, this displacement introduces an unquantifiable uncertainty into the test results. Also, 2 mm represents an error two orders of magnitude greater than the typical precision of modern measurement devices, and one which can be easily mitigated using the techniques described herein.

The authors have conducted several direct comparisons of the three methods described herein to verify that Methods 2 and 3 produce equivalent results. Fig. 8 illustrates one such direct comparison, wherein pile head displacement was measured independently using Methods 2 and 3 during a single pile test (Method 1 is implicit in the data, by not adding the reference beam correction). Methods 2 and 3 yield very similar results, and are not influenced by the reference beam displacement which is apparent in Method 1.



[FIG. 8] Direct Comparison of Results of Method 2 and Method 3 (LOADTEST Project Reference No. 539, 2005)

CONCLUSION

The analysis of the data presented in this study indicates that for any given test, there is a statistically significant possibility of non-trivial beam displacement. From the available data, it does not appear that setting the beam supports outside of 5 pile diameters results in any significant decrease in the maximum beam displacement, probably because a longer span is proportionally more susceptible to thermally-induced displacements. If the beam is not monitored during testing, there is no way to account for such displacement. Therefore, the current practice of measuring pile head displacement relative to a reference beam should in all cases be augmented by monitoring the displacement of the beam itself.

Once the beam monitoring equipment is going to be set up, the beam itself becomes extraneous, since the same equipment can monitor the pile head directly, with comparable or even slightly more precise results. It has been the authors' experience that setting up a pair of digital levels on tripods is easier, quicker and cheaper than constructing a reference frame, supports and tarps. It should also be noted that monitoring the pile head from a distance is, in the case of top-down testing, an improvement in safety.

While all of the data presented in this study was collected in the course of conducting bi-directional O-cell testing (i.e. without the presence of external reaction systems), it is the authors' opinion that the conclusions drawn herein apply to any type of deep foundation static load test.

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DFI JOURNAL

The Journal of the Deep Foundations Institute

International Standard Serial Number (ISSN): 1937-5247

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