Testing of Bored Pile Inclination

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ABSTRACT:
The allowable deviation from of piles from verticality is mentioned in practically all piling specifications, with typical values ranging from 1.33 to 2 percent. Similarly, specifications also limit the tolerance of raked piles from their specified inclination. While this restriction seems critical for piled retaining walls, the reasoning behind this restriction for piled foundations is not well understood. Finite element simulation we carried out has shown that exceeding the above limits can introduce large bending moments and shear forces in piles designed strictly for axial loads and may even lead to structural failure. Still, the above specifications are seldom enforced due to the lack of convenient testing apparati. In this paper, we describe the BIT (Borehole Inclination Tester), present its details and calculation method, and show initial field results.

1 INTRODUCTION

Probably all piling specifications prescribe the tolerances for both centricity and verticality of piles. The following examples demonstrate common values for allowable deviation:

"Verticality – the maximum permitted deviation of the finished pile from the vertical at any level is 1 in 75. Rake – the maximum permitted deviation of any part of the finished pile from the specified rake is 1 in 25 for piles raking up to 1 in 6 and 1 in 15 for piles raking more than 1 in 6" (ICE 1996).

"The vertical alignment of a vertical shaft excavation shall not vary from the plan alignment by more than 20 mm per meter (1/4 inch per foot) of depth. The alignment of a battered shaft excavation shall not vary by more than 40 mm per meter (1/2 inch per foot) of the distance along the axis of the shaft from the prescribed batter" (O'Neill and Reese 1999).

The importance of controlling the verticality of a contiguous piled retaining wall is clear: piles protruding excessively into an excavation for a parking basement, for instance, may cause the loss of parking spaces and hinder the granting of a building permit. Strict verticality is even more important in secant pile walls, where misalignment can make the wall non-watertight (Fleming et al. 1994). The questions we set out to answer were twofold.

- Why is verticality important for single foundation piles?
- How can we quickly check conformance of bored piles to the specifications regarding inclination?

In the following, we shall use finite element simulation to prove the importance of complying with such specifications. Later on we shall present a brief overview of existing devices which can measure pile verticality and then describe the system which we developed specifically for testing pile inclination. Initial field results which we have obtained demonstrate the viability and accuracy of this technique.

2 TERMINOLOGY

Borehole axis – The trajectory the Kelly bar tip follows when lowered into the borehole.

Inclination – the angle, in either degrees or percent, between the vertical and the borehole axis at any given depth.

Battered pile or *raking pile* – a pile purposely constructed at an inclination.

Stop – a depth in the hole at which stabilized inclination readings are taken.

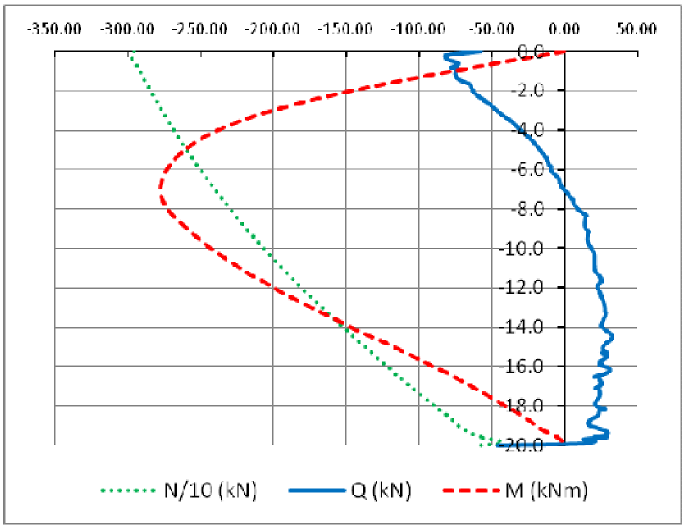
Depth interval – the mean distance along the borehole axis between two consecutive stops.

Deviation – the vector, measured in the horizontal plane, from the planned borehole axis to the actual one.

3 FINITE ELEMENT SIMULATION

To get a better understanding of the effect of excessive inclination, we ran a two-dimensional Plaxis simulation of a diaphragm wall 600 mm thick and 20 m deep, embedded in soft clay. The wall inclination was 2.5 percent from the vertical, a mere 0.5 percent above the typically acceptable value. We checked two cases: a free wall and a horizontally-restrained one.

The results (Figure 1) show the distribution of normal force N, shear force Q and bending moment N down the element for both a free-headed and a fixed-headed element. It shows clearly that even a small excessive deviation can introduce large, not-accounted for, shear forces and bending moments in free walls. In restrained walls, e.g. those connected by beams, this effect is minimal. Although this two-dimensional simulation is not fully-valid for three dimensional piles, the results are at least qualitatively applicable.



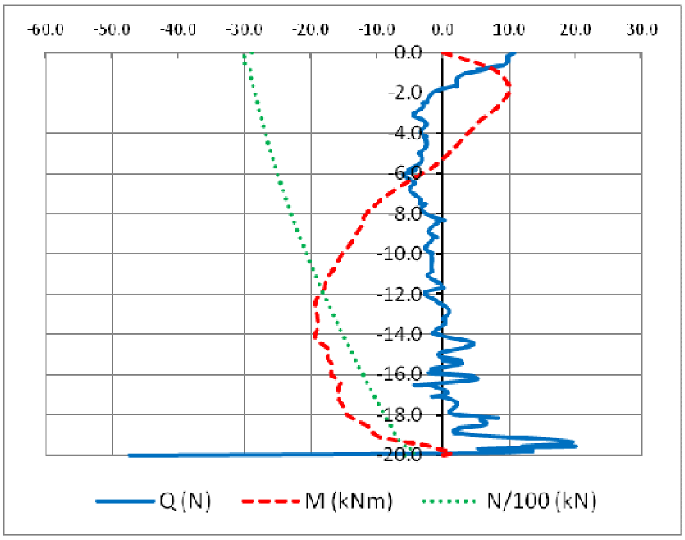


Figure 1: Effect of vertical load on inclined pile

4 EXISTING SYSTEMS

Present methods for measuring the inclination of bored piles are invariably based on the plumb bob principle: the instrument is hung down from the planned center of the pile, and the distance to the sidewalls is measured by ultrasonic sensors (Bruce et al. 1989, Kort and Kostaschuk 2007). The sensors are arranged in either of two fashions:

- Four transceivers in two mutually -perpendicular sets, providing four readings per every depth
- One rotating transceiver, giving 360° coverage.

Once the hole is completely logged, the sidewall profile is drawn and, provided it is relatively regular, the pile axis can be plotted and compared to the vertical. A bonus of this approach is that it enables the calculation of the bore volume, an item of special interest to contractors.

An interesting and simple method, described by Bruce et al. (1989), is the inverted pendulum in which a buoy floating on the slurry replaced the plumb bob.

The above systems have several drawbacks:

- They can be used only in slurry-filled holes
- They cannot be used in slender piles (when the slenderness ratio L/d exceeds 25, a deviation of 2% or more from the vertical cannot be measured)
- They cannot be used to measure the inclination of raked piles
- They cannot be used to measure the inclination of finished piles
- Some of these systems are cumbersome and need a dedicated crane to move around the site and an AC generator to power them.

5 THE PROPOSED SYSTEM

5.1 *Description*

The BIT system is dual purpose:

- During drilling, it can be mounted on the drilling bucket that acts as centralizer.
- In the finished pile, it can be lowered inside the access tubes which are routinely installed for crosshole ultrasonic testing (ASTM 2008).

The system consists of four main units (Figure 2).

1. The upper unit which contains the electronic circuitry and is mounted inside a 100 m. cable-reel
2. The lower unit, containing a bi-axial (X-Y) MEMS inclinometer, a MEMS gyro and a thermometer, all packaged in a compact waterproof housing. For drilling monitoring, the lower unit is rigidly mounted on the drilling bucket crossbar while for finished pile testing it is mounted on a stabilizer that acts as both a centralizer and a rotation-suppressor.
3. A wireless depth meter
4. A hand-held computer for recording and presenting data

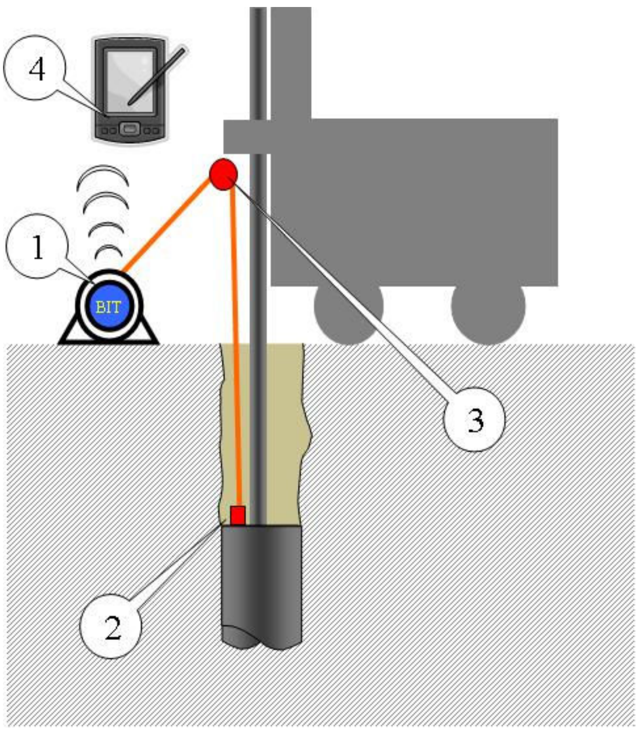


Figure 2: Schematic drawing of the system components

The lower unit transmits the data to the upper one via a cable that runs over the depth meter wheel and operates it. The upper unit uses wireless communication to both the depth meter and the computer.

The actual system components are depicted in Figure 3.

5.2 *Operation - Drilling configuration*

After the hole is drilled to the desired depth, the lower unit is fixed on the bucket cross bar and inserted into the hole while pointing to the reference north. The inclination and azimuth are measured at ground level and then at predetermined stops until the drilling bucket reaches the bottom of the hole. The procedure is then repeated on the way up, with readings taken at the same stops as before. During the whole procedure, the rig operator should keep Kelly bar rotation to a minimum (although some degree of unavoidable rotation is tolerable). When the bucket returns to the surface, it is aligned back with the reference north, and a final reading taken. Typical test duration is in the order of 10 to 15 minutes.

5.3 *Operation - Access tube configuration*

The lower unit with the stabilizer is inserted into the access tube pointing to the reference north. The inclination and azimuth are measured at pile head level and then at predetermined stops until the unit reaches the bottom of the tube. The procedure is then repeated on the way up, with readings taken at the same stops as before. When the unit returns to the surface, it is aligned back with the reference north, and a final reading taken.

Figure 3: The BIT system

5.4 *Calculations (Figure 4)*

1. For each stop numbered [n], with sensor heading h, the inclinations in the X-Y

directions are transformed to inclinations in the N-E directions by the following relationships.

$$\text{IncEast}_n = +X_n \cdot \cos(h_n) - Y_n \cdot \sin(h_n) \quad (1)$$

$$\text{IncNorth}_n = -X_n \cdot \sin(h_n) - Y_n \cdot \cos(h_n) \quad (2)$$

2. For each stop numbered [n] at depth = D_n, the deviations of the pile axis in the N-E directions are calculated as follows.

$$\text{DevEast}_1 = 0 \quad (3)$$

$$\text{DevNorth}_1 = 0 \quad (4)$$

$$\text{DevEast}_n = \text{DevEast}_{n-1} + (D_n - D_{n-1}) \cdot \tan\left(\frac{IncEast_n + IncEast_{n-1}}{2}\right) \quad (5)$$

$$\text{DevNorth}_n = \text{DevNorth}_{n-1} + (D_n - D_{n-1}) \cdot \tan\left(\frac{IncNorth_n + IncNorth_{n-1}}{2}\right) \quad (6)$$

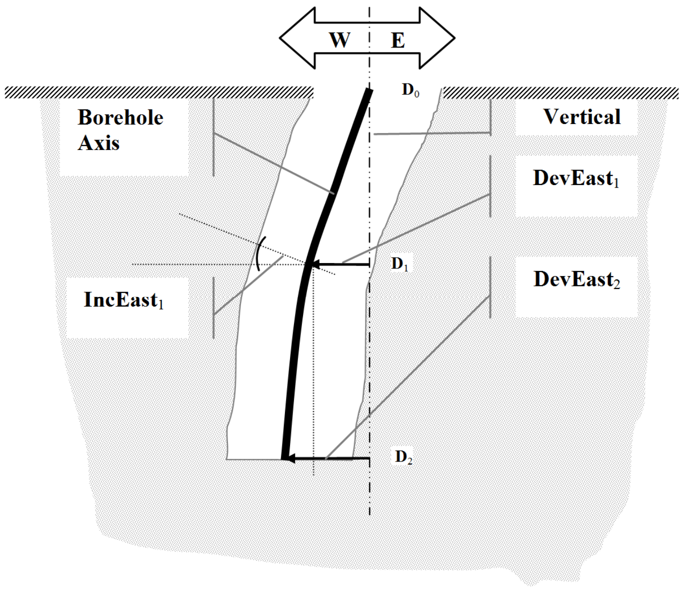


Figure 4: Inclination and deviation explained

And the combined deviation expressed as a polar vector is:

$$Dev_n = \langle r_n, \angle\theta_n \rangle \quad (7)$$

where

$$r_n = \sqrt{DevNorth_n^2 + DevEast_n^2} \quad (8)$$

$$\theta_n = \arctan\left(\frac{DevEast_n}{DevNorth_n}\right) \quad (9)$$

3. Ideally, for the final surface reading N, the total calculated deviation r_N should be zero.

4. If the closure error r_N is less than a pre-determined threshold value (expressed as a fraction of pile length), it is proportionately distributed among all stops.

5. If the closure error r_N exceeds the threshold value the operator receives a warning and may decide to repeat the test.

6. For each stop, the corrected downward and upward deviations are averaged and transformed to polar coordinates.

5.5 *Calibration*

Since the specifications typically allow a deviation in the order of only 1 to 2 percent, the system accuracy should be at least one order of magnitude smaller or better than 0.1%.

MEMS components are generally sensitive to temperature changes. To achieve the required accuracy, these components should be carefully calibrated before the test, as follows:

Inclinometer calibration: The lower unit is placed on a hard, smooth, horizontal surface and stabilized inclination readings for both axes taken. The lower unit is then rotated 180^0 and the procedure repeated. The mean X and Y readings, respectively, are the level (or zero inclination) readings.

Gyro calibration: MEMS gyro devices tend to drift at a fairly constant rate. To compensate for this drift the lower unit is laid stationary until the rate of drift is constant, at which time it is recorded.

Depth meter: A typical distance of 5 to 10 m is marked on the cable and pulled over the depth meter wheel.

5.6 *Reporting*

In addition to project and pile identification, the report typically includes graphic presentation of the results in two forms (Figure 5).

1. Top view of the pile axis superimposed on a number of concentric circles showing the radii in meters
2. Side view in which the maximum deviations measured in all stops are connected by straight lines on the background of a funnel depicting the allowable deviation

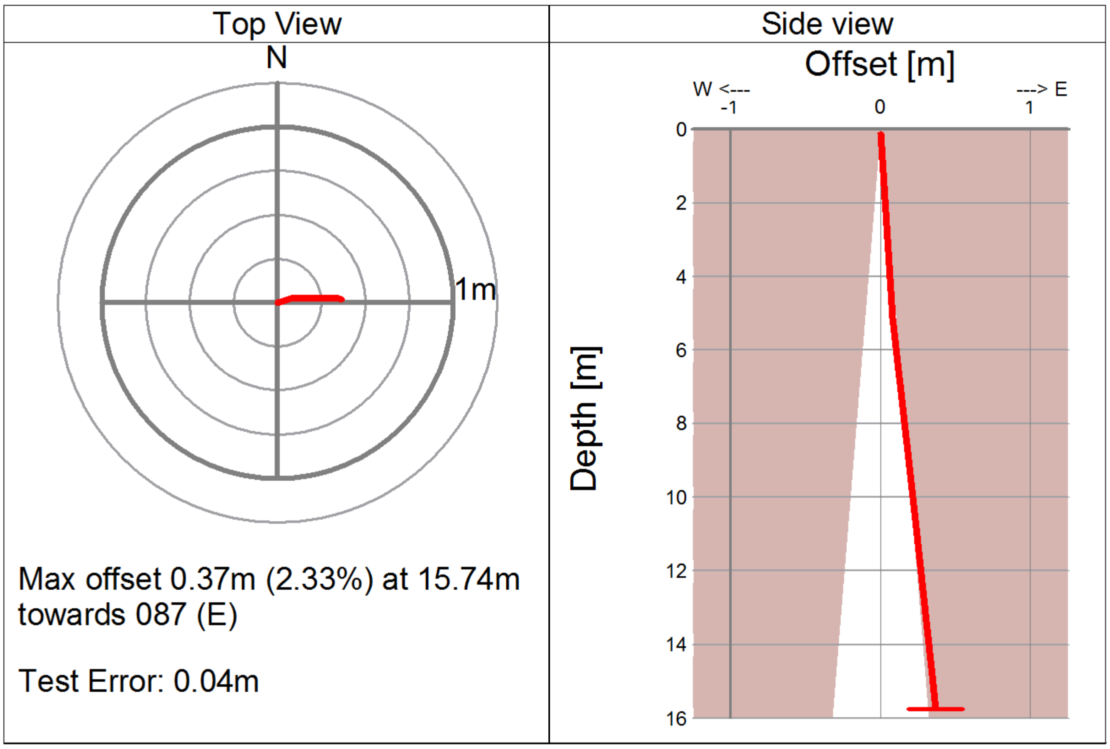


Figure 5: Typical results

6 CONCLUSIONS

Excessive inclination can be detrimental to piles which were planned to be vertical, by introducing large bending moments and shear forces. This effect is much more prominent when the piles heads are free to move.

The system presented is a portable instrument for measuring the deviation of bored piles from the vertical with accuracy within 0.1%. It may therefore assist the geotechnical engineer to enforce the specification for pile verticality. The system may also serve piling contractors who have to meet strict verticality tolerances in contiguous and secant piled walls. In addition, it can help the contractors to evaluate the suitability of specific rigs to difficult site conditions, such as the presence of boulders or rock.

7 REFERENCES

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