Discussion of “Distribution of residual load and true shaft resistance for a driven instrumented test pile”1

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Introduction

The authors have presented a well-documented case study of the load test interpretation of prestressed high-strength concrete (PHC) piles, which are very popular in the Far East and are often favoured over steel piles on the basis of cost. Despite their popularity, well-analyzed load test case histories are rare and hence the authors’ paper is a valuable contribution to the technical knowledge base. Although the authors have considered the geotechnical aspects in detail, the discussers believe that this case study also would benefit from a fuller analysis of the structural conditions of the piles. This is because the authors have identified that the key design aspects for this site are actually the maximum load in the pile and the pile structural strength, but not the pile capacity. Based on the load test results, the authors concluded that the long-term maximum load in the pile will approach the pile structural strength and hence grouting the central void should be considered. The discussers have carried out an assessment of the pile strength using a different approach and compared the results with the current design guidelines. It was found that even with the central void grouted, the PHC piles are still not sufficiently robust and a different pile size or type may need to be considered. The discussers’ assessment and, where appropriate, comparisons with the authors’ results are described as follows.

Ultimate pile strength

The authors estimated the ultimate compressive strength of the PHC pile by using a composite pile modulus of 30 GPa and assuming the ultimate strength is reached at a strain level of 0.15%. It follows that the ultimate strength is about 6.0 MN for the ungrouted pile (used at the Myeongji site) and 12.0 MN for the grouted pile (used at the Shinho site). While the results appear to correspond well with the observed ultimate strength of 6.4 MN for the Myeongji pile, they are actually highly dependent on the choice of the modulus and strain values. For example, the authors reported that the back-calculated secant modulus of the pile ($E_c$) can be expressed as 29.0–0.003 $\mu e$ for the Myeongji pile. If a moderate strain level of, say, 800 $\mu e$ is substituted into this equation, then the pile modulus will be 26.6 GPa. If this value is used instead, then the calculated pile strength will be 11% lower than the given estimated value. The strain level used is also subject to debate, as in reinforced concrete design the concrete is commonly assumed to crush at a strain level of about 0.2% (see, e.g., Wight and MacGregor 2009). If this value is used, the calculated pile strength will increase by more than 30% to well over the observed ultimate strength. As noted by the authors, the pile design for this site is governed by the structural strength of the pile. A more detailed analysis therefore seems necessary.

The discussers have carried out an assessment of the ultimate strength of the PHC piles using the conventional prestressed concrete design method. The equations used are given in Gilbert and Mickleborough (1990). In essence, for a prestressed concrete member subject to pure compression, the ultimate strength can be expressed by the following equation:

\[ N_u = C_c - T_p \]

where $N_u$ is the ultimate strength, $C_c$ is the compressive force in the concrete, and $T_p$ is the tension in the prestressed steel. The first term, $C_c$, is given by

\[ C_c = 0.85 f_{cy}^3 A_c \]

where $f_{cy}^3$ is the compressive cylinder strength of concrete ($\approx 0.8 f_{cy}^2$) and $A_c$ is the cross-sectional area of concrete. The factor 0.85 accounts for the difference between the actual and idealized stress block, and the strength difference between the cylinder specimen and the actual member. The second term, $T_p$, is given by

\[ T_p = \varepsilon_{pu} E_p A_p \]
where $\varepsilon_{pu}$ is the strain in the prestressed steel at ultimate, $E_p$ is the elastic modulus of the prestressed steel, and $A_p$ is the cross-sectional area of the prestressed steel. The values of these parameters have been given by the authors except for $\varepsilon_{pu}$, which needs to be calculated using the effective prestress ($f_{pe}$), which is 8 MPa for the piles concerned. Using eqs. [1] to [3], the ultimate strength, $N_u$, is estimated to be 6.9 MN for the ungrouted Myeongji pile and 9.2 MN for the grouted Shinho pile. For the estimation of the latter, eq. [1] was extended to include the strength contribution of the grout, $C_g$ (= 0.85 $g_c A_p$). The authors state that the grout was of strength about 18 MPa, but do not say whether this was a cube or cylinder strength. The discussers have assumed it to be a cube strength and thus the equivalent cylinder strength could be about 80% of 18 MPa. However, the in-pile strength of the grout will be increased as it is confined and the overall effect may be that the actual strength of the grout in the pile was about 80% of 18 MPa. Therefore, for the calculations of $C_g$, the discussers have taken $f_c$ as 18 MPa.

It can be seen that by using this approach the calculated $N_u$ for the ungrouted Myeongji pile (6.9 MN) is similar to the actual observed value of 6.4 MN and is not far from the authors’ value of 6.0 MN. The discussers’ overestimation (8% of true value) is probably due to the fact that the Myeongji pile has a hollow core, but the above calculations do not take into account the effect of reduced internal confinement (see, e.g., Dilger et al. 1996 for experimental evidence of the hollow core effect).

Unlike the case of the Myeongji pile, the calculated $N_u$ for the grouted Shinho pile (9.2 MN) is considerably lower than the authors’ prediction of 12.0 MN. If the discussers’ prediction is correct, then it would appear that the maximum test load applied to the Shinho pile ($\approx$ 9.0 MN) was already very close to its ultimate strength. As the Shinho pile was not loaded to structural failure, the actual ultimate strength is not known.

**Allowable pile load**

By comparing the estimated ultimate strength with the maximum load in the pile (6.0 MN for the Shinho site and 4.3 MN for the Myeongji site), the authors suggested grouting the central void of the pile to increase its structural strength. Although this suggestion is a reasonable one, the discussers believe that, for the actual design, it is should be the allowable pile load that is used for such comparison. This is because in the previous calculations the pile is assumed to be under pure compression and no factor of safety was applied, while in reality the pile could also be subject to lateral force and could be damaged during and (or) after installation (Gerwick 1993). In North America, the following equation is commonly used for the design of prestressed concrete piles (Gerwick 1993; PCI Committee on Prestressed Concrete Piling 1993; Hannigan et al. 2006):

$$ N = (0.33 f_{cy}' - 0.27 f_{pe}) A_c $$

whereas in the UK and in some Commonwealth countries, the following equation is used instead (BSI 1986):

$$ N = 0.25 (f_{cu}' - f_{pe}) A_c $$

As can be seen, both equations take into account the effect of effective prestress and limit the compressive stress in the concrete to below a certain level. If these equations are used, then the allowable load for the ungrouted pile will be 2.6 MN (eq. [4]) and 2.5 MN (eq. [5]). By assuming strain compatibility and taking force equilibrium into account, for the same concrete stress level ($N/A_c$), the allowable load for the grouted pile has been estimated to be about 4.5 MN. It can be seen that this value is just above the maximum load of 4.3 MN for the Myeongji site, but is considerably lower than the maximum load of 6.0 MN for the Shinho site.

**Conclusions**

Based on an assessment of the structural strength of the PHC piles, it appears that even with the central void grouted the piles are still not sufficiently robust for the Shinho site if the maximum pile load is to be kept below the allowable load as required by the North American or British design standards. To tackle this problem, it may be necessary to consider using a grout with a higher compressive strength (>18 MPa) and probably also steel reinforcement in the grout. If these measures are not sufficient, a different pile size or type may have to be considered.

**References**


**List of symbols**

- $A$ cross-sectional area
- $C$ compressive force
- $c$ subscript meaning concrete
- $E$ elastic modulus
- $f_{cu}'$ compressive cube strength of concrete
- $f_{cy}'$ compressive cylinder strength of concrete
- $f_g'$ compressive cylinder strength of grout
- $f_{pe}$ effective (net) prestress
- $g$ subscript meaning grout
- $N$ allowable axial strength of pile
- $N_u$ ultimate axial strength of pile
- $p$ subscript meaning prestressed steel
- $s$ subscript meaning secant
- $T$ tension
- $\varepsilon_{pu}$ strain in the prestressed steel at ultimate