Challenging the Perception of Precast Piles

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Precast, driven pile groups represent a robust and cost-effective piling solution for many civil engineering and infrastructure projects. When appropriately applied, these foundations can offer a number of benefits over existing methods currently used in bridge abutment design (e.g. large diameter cast in situ concrete piles).

This article outlines the benefits, challenges and ongoing research into the use of precast, driven piles as part of pile groups in bridge abutment design where complex loading conditions arising from construction on compressible soils are encountered. Issues surrounding installation, ultimate capacity, of both vertical and inclined piles, and long-term serviceability are addressed.

Initial studies indicate that pile groups combining both raking and vertical precast piles can require beneficially lower amounts of natural resources over traditional design methods for a range of scenarios offering both commercial and carbon benefits. However it is recognised that concerns remain in the engineering community over the use of precast, driven piles in particular design scenarios. These concerns are explored herein.

An Engineering Overview

The complex loading configurations placed on bridge abutments, coupled with earth movements taking place within the compressive stratum beneath, need to be effectively and efficiently managed by the foundation solution. Whilst the UK construction industry defaults to large diameter vertical bored piles (in the region of 900 to 1200mm nominal diameter), in Europe and beyond, the use of precast concrete driven piles are often the norm. Using a combination of vertical and raking piles, a solution can be provided that efficiently caters for the vertical and horizontal actions associated with bridge abutments, piers and many other structures.

Precast concrete piles come in a number of different section sizes (up to 450 mm square), with reinforcement arrangements available to satisfy a range of design requirements. Their offshore manufacture provides a number of benefits with respect to QA, reduced energy and carbon consumption, durability and low waste, while their installation benefits from no spoil production.

An industry survey carried out by the authors indicates that historically, precast piles were a normal accepted solution for bridge abutments, as well as a number of other applications. However reduced numbers of recent installations in the UK, and thus lack of experience and knowledge of their capability, in particular when installed at an inclination, has led to a change in philosophy with precast driven piles rarely being considered in design today. One of the reasons for this can be attributed to the uncertainty over interactions of the piles with displacing and consolidating soil highlighted by statements in standard references such as: “...raking piles should be avoided in situations where significant consolidation settlement of the soil may occur” (Fleming et al., 2008).

However the same authors also state “where ... raking piles derive their axial capacity from strata that are ... non deformable, they provide a stiffness in terms of laterally applied forces which can be very desirable. The main issue in design is to avoid large and unquantifiable secondary stresses and provided this can be achieved all will be well.”

To better understand the issue of secondary stresses, it is useful to outline the key challenges facing a foundation engineer considering the design and reliability of a larger pile group. Figure 2 illustrates these for a typical bridge abutment design, where piles are driven through a soft, compressive clay layer. Design requires that (i) vertical, horizontal and moment loading from the embankment fill is taken by the piling system through to the bearing stratum, (ii) the piles can resist vertical and horizontal flow of soft soil around them, (iii) the effects of end fixity conditions on the piles are correctly accounted for, (iv) installation and construction sequence are considered.

![Figure 1](image1.png)

**Figure 1.** Precast piles can be deployed for a range of applications

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![Figure 2](image2.png)

**Figure 2.** Geotechnical challenges facing a foundation engineer

Driven Pile Installation

The nature of pile driving installation allows immediate collection of in situ pile capacity data for each pile installed. Much like a standard penetration test (SPT), blow count data upon each pile installation can be easily determined, and compared against specific static and dynamic pile load test results, to give individual pile capacity with high confidence levels. The designer can then employ reduced values of correlation factors, $\xi_1$, $\xi_2$, $\xi_3$ and $\xi_4$, in Eurocode 7 ultimate compressive resistance calculations given the amount dynamic load test data made available during installation across the full project.
According to BS EN 12699-2015 displacement pile execution documentation (British Standards, 2015), driven piles are to be installed with geometrical deviations of just 1 in 75 for vertical and 1 in 25 for raking piles. The inclination of a raking pile is also to be within 2° of the designed angle. Given the sensitivity of raking pile design to ultimate inclination angle, allowing for tolerances in design calculations of 2° of error may lead to a particularly over-conservative design. Historically pile deviation is an industry-wide concern and is not without reason, given the possibility for piles to move out of alignment during installation due to obstructions in the ground. This may contribute to a raking pile solution being overlooked. That being said, increased driving efficiency as well as accuracy of raking pile installation using state-of-the-art hydraulic installation rigs (Fig. 1) has resulted in improvements to these tolerances. Ongoing research is also being performed into robustly determining and understanding the progression of inclination angle beneath the ground surface as the pile is driven through the soil.

Ultimate Pile Group Capacity
The calculation of the ultimate capacity of a pile group loaded at the surface comprising both vertical and raking piles is straightforward. Basic hand calculations can be executed such that the vertical and longitudinal actions and bending moments are resolved axially along the length of each individual vertical and raking pile. In accordance with guidance from Tomlinson (1977), horizontal loads are carried axially in the inclined pile; vertical piles do not carry any horizontal load. Commercially available pile group software packages, such as Repute (GeoCentrix, 2009), can also be employed to perform these calculations and are particularly useful for more complex pile group configurations. As illustrated in Figure 3, raking piles as part of a wider pile group provide much greater efficiency in the management of horizontal loads in comparison to a large diameter vertical pile solution (the same total section area of pile is adopted for a direct comparison of efficiency). For the vertical solution, classical $p - y$ curve analysis (Matlock, 1970) as applied in LPile computer software is adopted using an $\varepsilon_{soil}$ value of 0.02. The above calculations conservatively assume similar bearing capacities for precast and cast-in-situ piles. However, it is known that driven piles often have greater shaft and end bearing capacities due to the compaction and densification of displaced surrounding soil during driving. Pile capacities of up to three times greater can be developed for the same section area.

Transverse Loads from Compressible Stratum
In bridge abutments, loads from approach embankment fill can induce transverse movement within deeper compressive strata, both immediately after embankment placement and in the long term due to ongoing consolidation. This can induce notable lateral loads along the length of a pile. In current TRL design guidance documentation (Springman and Bolton, 1990), a formula, derived from a combination of soil stiffness, pile spacing and pile-soil bending rigidity, is used to predict the lateral loads on a vertical pile when subject to asymmetric embankment loading. This approach assumes plastic limit analysis and can also be used to predict the maximum vertical load that an embankment can take. The German EA-Pfähle Piling Recommendation (DGTT, 2013) presents a similar, simpler method.

One issue surrounding this method is that it assumes sufficient soil displacement to mobilise a full plastic load. This in turn is dependent on the soil stiffness and embankment surcharge loading. However for loads in the elastic range, it can be suggested that the transverse loads are over estimated (Poulos and Davis, 1980). It is here where an alternative calculation which takes into account only these elastic deformations is required.

Several models have been proposed in the literature. Here, a basic stress-strain based soil numerical model is used to estimate the magnitude of elastic 2D settlement experienced within the compressive strata; this is then coupled with soil-pile load-displacement interaction curves to predict the load applied normal to a pile. This load is a function of the relative displacement of the pile and surrounding soil; in some locations the soil applies load, whereas in others, it provides restraint. Figure 4 illustrates an example estimation of the ground movements within the compressive layer as a result of the immediate embankment loading.

From here, pile deformation as well as associated bending moments and shear forces can be evaluated using the fundamental Euler-Bernoulli beam approximation. Noteworthy results from model sensitivity analyses indicate maximum pile bending moment is directly related to pile inclination, head restraint conditions and pile stiffness.

Long Term Pile Reliability
In addition to the transverse ground movements taking place immediately after embankment placement, it is necessary to evaluate the long-term settlement that may occur as a result of ongoing consolidation. This is not considered in current design guidance and as shown below can significantly increase bending moments. Terzaghi’s theory of 2D consolidation coupled with element compressibility strain estimations has therefore been introduced into the numerical approximation to predict the long-term movements. Figure 6 presents the progression of pile bending moment with time. The additional moment is directly related to the soil’s coefficient of compressibility. Given the non-linearity of the adopted soil-pile load-displacement interaction model, a limit on the applied load normal to the pile is reached at a specified magnitude of relative ground displacement. This value relates to the development of a full plastic soil flow condition. Interestingly, pile installation after embankment placement and the realisation of a degree of consolidation significantly reduces maximum pile bending moment. It is admitted, however, that this is not always achievable given piles are often driven first and designed into embankment stability.
Factored Loads (EC 7 DA1/1 – A1 + R1 + M1):
\[ V_0 = [1.35, 1.0]; V_0 = [1.5, 0] \]
\[ V = 24244 kN; H = 5832 kN; M = 11664 kNm \]

Vertical load taking into account self-weight of abutment (6 x 2.5 x 15 m = 5625 kN). K taken as 1.0 for simplicity and to approximate the effects of fill compaction. The loads presented above are for the full width of bridge, W = 15m. Individual pile loads are obtained by dividing by the number of piles required.

Figure 5 presents a worked example comparison using Eurocode 7 DA1/1 – A1 + R1 + M1:

**Large diameter bored pile solution (5 No.):**

- Pile properties:
  - D = 950 mm; L = 13 m.

  **Bending moment per pile within from bridge loads:**
  \[ M_{\text{max}} = 2333 \text{ kNm} \]

  **Load from transverse soil movement:**
  \[ M_{\text{max}} \text{ after 120 years} = 2333 \text{ kNm (same magnitude given the large pile head design moment from bridge loads)} \]

  Using design \( N - M \) charts, for concrete with strength \( f_{c} = 50 \text{ MPa} \), 5 piles with 10H40 bars provides sufficient reinforcement, equating to total volumes:
  \[ V_c = 54 \text{ m}^3; V_i = 0.94 \text{ m}^3 \]

  Raking pile alternative (10 pairs):

  Model experiments are being carried out to provide further clarification of these issues.

**Conclusions**

Scoping calculations indicate that the deployment of precast, driven concrete piles as part of a bridge abutment solution on soft soils can present a beneficial solution in terms of materials usage for a range of site scenarios when compared to traditional vertical large diameter cast in situ pile foundations. This is in addition to other established advantages of pre-cast piles, which include increased quality management at fabrication stage, generally simpler on-site installation, no arisings to dispose of and the wider sustainability benefits such as reduced raw materials and ultimately reduced project carbon emissions.

The controlling factor in the design is the anticipated soft soil displacement around the piles. Further research is therefore in progress utilising analytical and physical models to enhance understanding, verify analytical models and clarify the optimal parameter range of precast pile deployment with the aim of providing enhanced design guidance for pre-cast piles in these scenarios.

**References**