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 a compressible 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 600mm square), with reinforcement arrangements available to satisfy a range of design requirements. Their offsite manufacture provides a number of benefits with respect to QA, reduced energy and carbon consumption, durability and low waste, while their installation incurs no spoil production.

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

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 fall from favour is 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, compressible 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. With respect to (ii), the paper focuses on in-plane movement. Small out of plane loading would be anticipated due to consolidation/squeezing, but this should be taken by the normal lateral capacity of the piles.

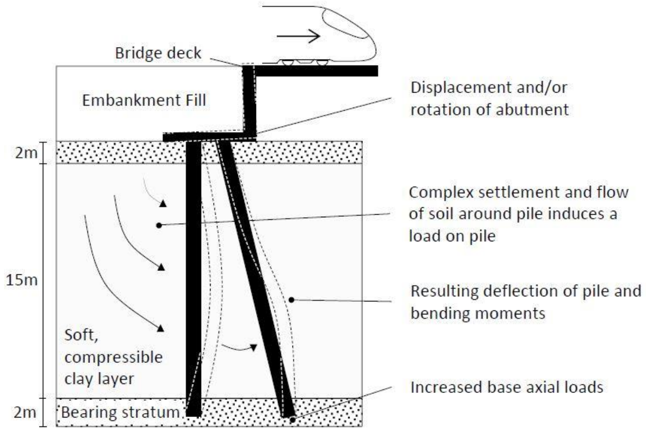


Figure 2. Geotechnical challenges facing a foundation engineer

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, ξ_1,ξ_2, ξ_3 and ξ_4, in Eurocode 7 ultimate compressive resistance calculations given the large amount of 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. Pile deviation is an industry wide concern and is not without reason, given the possibility for driven piles to move out of alignment during installation due to obstructions in the ground. That being said, increased driving efficiency as well as accuracy of raking pile installation using state-of-the-art pneumatic 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 the *LPILE* computer software is adopted using an ε_{50} value of 0.02.

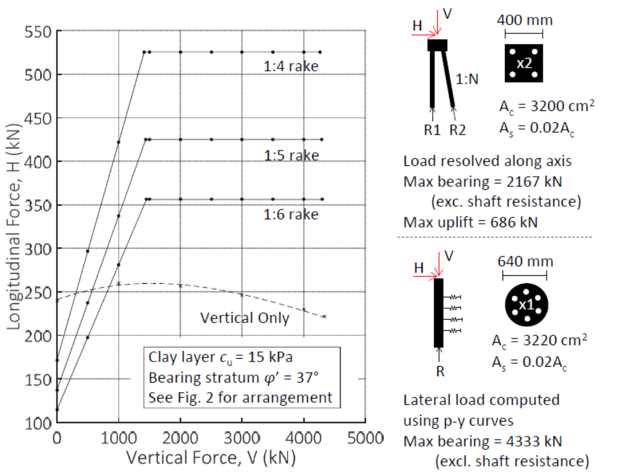


Figure 3. **Comparison between precast pile group and bored solutions**

The above calculations conservatively assume similar bearing capacities for precast and cast in-situ piles. However, it is known that driven piles can develop 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 compressible 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 apply. 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 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.

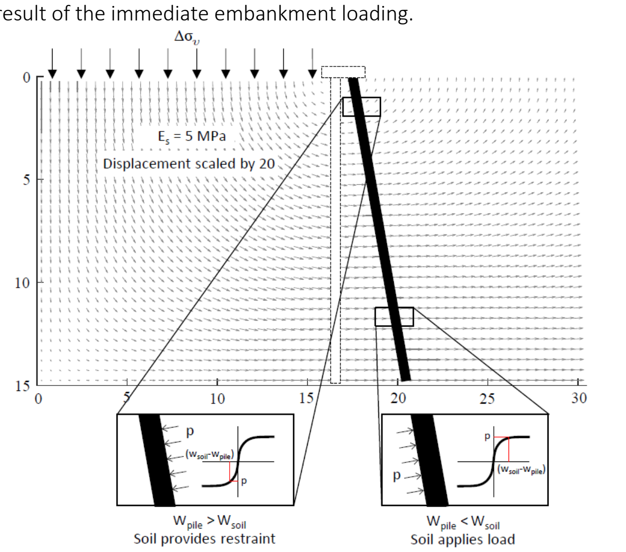


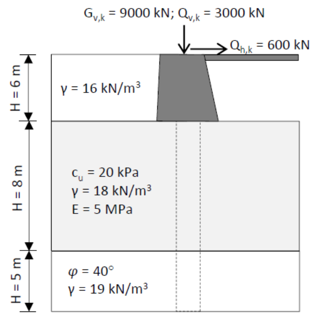
Figure 4. **Ground movement immediately after embankment loading**

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 placing, 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.

Design loads at pile top (bridge width 15 m):

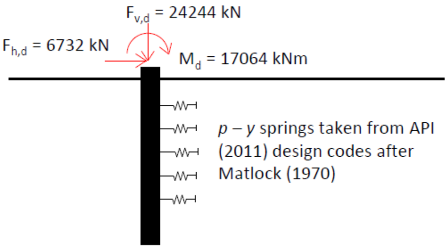


Factored Loads (EC 7 DA1/1 – A1 + R1 + M1):
γ_G = [1.35, 1.0]; γ_Q = [1.5, 0]
$F_{v,d}$ = 24244 kN; $F_{h,d}$ = 6732 kN; M = 17064 kNm

Vertical load taking into account self-weight of abutment (6 x 2.5 x 15 x 25 = 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 piles loads are obtained by dividing by the number of piles required.

Large diameter bored pile solution (5 No.):

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

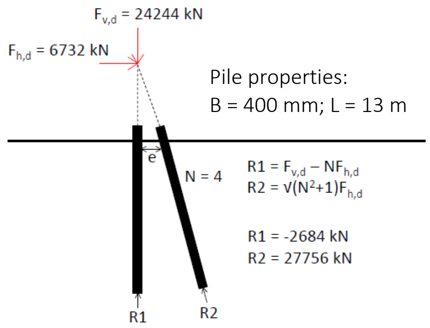


Bending moment per pile within from bridge loads:
$M_{d,max}$ = 3413 kNm

Load from transverse soil movement:
$M_{d,max}$ after 120 years = 3413 kNm (same magnitude given the large pile head design moment from bridge loads)

Using design *N – M* charts, for concrete with strength f_{cu} = 50 MPa, 5 piles with 18H40 bars provides sufficient reinforcement, equating to total volumes:
V_c = 54 m^3; V_s = 1.47 m^3

Raking pile alternative (10 pairs):



Pile properties:
B = 400 mm; L = 13 m

(R1 and R2 are totals over the full span; divide by 10 pairs for individual pile loads)

Load from transverse soil movement:
$M_{d,max}$ after 120 years (P1) = 170 kNm
$M_{d,max}$ after 120 years (P2) = 186 kNm

10 pairs of *Centrum* precast piles type 20 plus additional reinforcement (4H32) provide sufficient reinforcement to resist the consolidation induced bending for both compressive and tensile loadings in the piles. Total volumes:
V_c = 48 m^3; V_s = 1.40 m^3

Figure 5. **Worked Example**

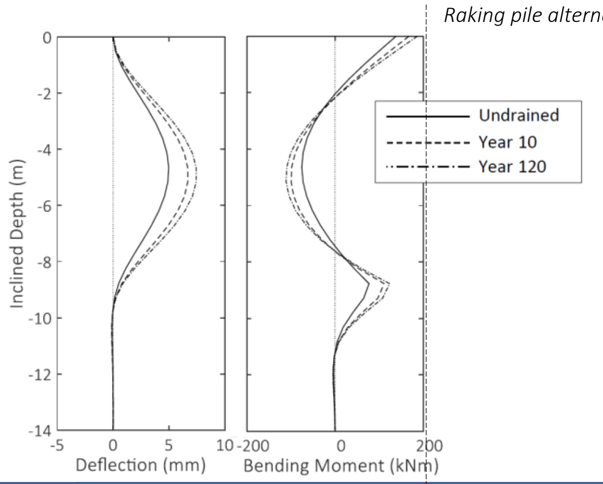


Figure 6. **Additional bending from ongoing consolidation**

Illustrative Worked Example

Figure 5 presents a worked example comparison using Eurocode 7 DA1/1 of a traditional vertical bored pile solution with a proposed, precast concrete pile solution. Outlined is a basic level of engineering calculation to offer an insight into the typical design process, size and number of members required. It should not be taken as detailed design. The example considers a single span road bridge with typical bridge end support loads of 12,000 kN and a 600 kN longitudinal live load with left to right taken as the more adverse loading condition. It adopts the elastic based model of ground movements discussed previously and an assumption of full pile end fixity at the surface.

It can be seen for cast *in situ* piles, the secondary effects of soft soil movement is typically a small contributor to the overall moment loading which is dominated by the surface loads. For the more slender pre-cast piles which deal with surface loading differently, the secondary effects are a more important issue and will typically control the pile section selected. Overall for this scenario, it is seen that the pile group combining raking and vertical precast piles offers a beneficial improvement on foundation efficiency over the cast in-situ vertical pile option (approximately 10% less concrete and 5% less steel). However, this is likely to depend on the overall geometry of the system, in particular the depth of the soft soil stratum and the efficiency gain could be significantly larger.

While this is a simple calculation, the potential benefits indicate a need for improved understanding of secondary effects in terms of soil flow and end fixity in order to provide confidence in design. Ongoing analytical and centrifuge scale 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.

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