AARSLEFF GROUND ENGINEERING & COWI PRESENT...

RAKED PILES FOR ABUTMENT AND THE BENEFITS OF DRIVEN PRECAST CONCRETE PILES FOR LOW CARBON INFRASTRUCTURE.

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ABSTRACT

Precast driven piles offer a robust and effective piling solution for a variety of civil engineering and infrastructure projects. They are widely used in Northern Europe as opposed to the United Kingdom. Here, traditionally bored piles are more common. However, the prevailing installed pile type in different countries is often based on local traditions supported by local standards. This paper demonstrates based on a case study that precast driven piles are a good technical alternative to bored piles. An abutment at the newly established Victoria & Widnes viaduct, part of the Mersey Gateway Project, constitutes the case investigated.

The UK has a legally binding commitment to achieve an 80 per cent reduction in carbon emissions by 2050. Furthermore, the Government has also committed to halving UK emissions during the 2023 to 2027 carbon budget period (relative to 1990). The second paper demonstrates the low carbon credentials of driven precast concrete piles and highlights a number of other key benefits that can be realised from adopting a precast pile solution.

CONTENTS

2. INTRODUCTION

RAKED PILES FOR ABUTMENTS

Large infrastructure projects such as the Mersey Gateway bridge are often complex structures in term of geometry, loading and soil conditions; hence the necessity of having robust foundations often resulting in piled solutions.

Different types of piles exist but they can generally be divided into two groups based on installation method (In the UK, cast-in-place is officially known as displacement piles: precast driven piles as non-displacement piles). The pile type chosen for a given project should be based on soil conditions, geometry of the structure, loading conditions, site constraints, project specific requirements, available equipment, traditions. Ecological, environmental and economic considerations should also be considered, as well as advantages and disadvantages of the different pile types, where the latter has been extensively discussed in this literature. However, often the pile type chosen is entirely based on local traditions.For example, in Northern Europe the prevailing pile type is precast driven concrete piles, while, in contrast, bored cast-in-place piles are very common in the United Kingdom.

The purpose of this paper is to demonstrate from a technical viewpoint that precast driven concrete piles are a robust alternative to a bored pile solution for a bridge abutment in the United Kingdom and by extension, other solutions.

Besides technical considerations, a thorough comparison between a bored and a precast driven piled solution also demand reflections on the project economy and the construction process, including time schedule and logistics.

The case investigated is an abutment at the newly established Victoria & Widnes viaduct, part of the Mersey Gateway Project, southeast of Liverpool in the western and north-western part of England. The viaduct is a multi-span bridge with 9 m high embankments at the abutments (See Figure 1).

Figure 1 Model picture of Victoria & Widnes Viaduct from the Mersey gateway project (from www.merseygateway.co.uk)

Two pile solutions are compared in this paper; a precast driven pile solution and cast-in-place bored pile solution. Due to the complicated geometry, loading scenario, soil conditions, pile-pile interaction and displacement pattern (soil, piles and abutment), the analyses have been undertaken using 3D Finite Element software. The two pile solutions are compared and discussed based on pile dimensions, displacement field (soil, piles and abutment), sectional forces in the piles and reinforcement.

2.1 CASE - VICTORIA & WIDNES VIADUCT

Increased pressure on the infrastructure across Europe has resulted in the need for upgrading existing and building new roads and bridges. A typical medium sized multi-span bridge is the Victoria & Widnes Viaduct from the Mersey gateway project. The abutments are founded on piles, which is common. Piled foundations for abutments are often subject to lateral loading due to the volumes of backfill behind the abutment and lateral soil displacements originating from compressible soils below the abutment. Use of vertical bored piles is a solution that sustains the complex loading and the lateral soil displacements. The alternative, precast driven pile solution utilises a combination of both vertical and raked piles. The purpose of the raked piles is to sustain the majority of the horizontal loads. The potential lateral soil displacements demand focus on the lateral behaviour of the soil-structure interaction and the actual behaviour of the piles to fully utilise the benefits of the precast piles. Hence, the abutment case constitutes a good basis to explore differences in the technical performance of bored and precast driven concrete piles.

2.2 GEOMETRY AND LOAD FROM BRIDGE SET

The bridge has 7 Nr spans with a span length of 22-32 m, a width of 23.7 m and a clearance of 5.5-6 m. The bridge deck consists of eight precast girders and an in-situ casted crossing beam at each supporting column, cf. Figure 2.

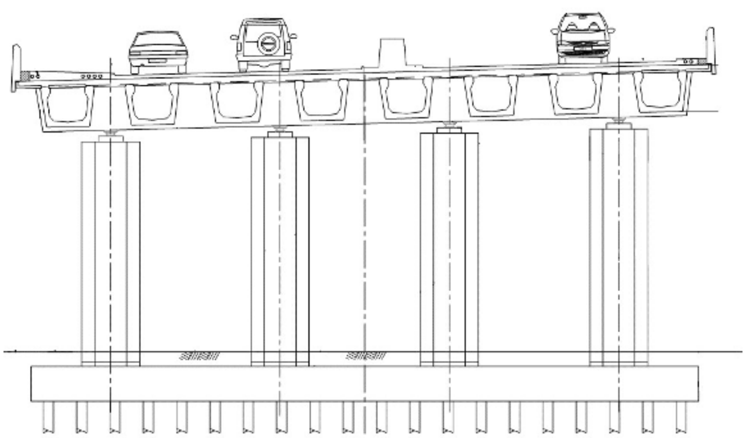

Figure 2 Cross section of Victoria & Widnes Viaduct.

The abutment is constructed in-situ by reinforced concrete supported by piles. The embankment at the abutment has a height of 8.8 m and the base of the abutment is 1.7 m below ground level (See figure 3). The base of the abutment has as width (across the bridge) of approximately 25.5 m. The weight of the bridge deck supported by the abutment is 5650 kN, whereas the characteristic traffic load on the abutment is 2250 kN.

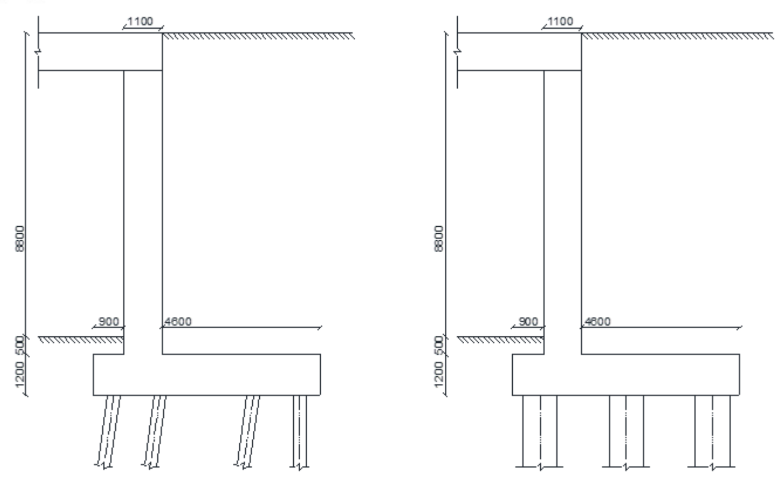

Figure 3 Sketch of abutment (left: driven piles, right: bored piles)

2.3 SOIL CONDITIONS

The ground consists of made ground (various composition) with a thickness of 3 m. This is followed by 15 m of cohesive glacial deposit, (firm to stiff slightly sandy/gravelly clay) and a 5 m thick bed of granular glacial deposit (medium dense to very dense slightly clayey/gravelly sand). The embankment is made of well-compacted granular material.

The applied characteristic soil parameters are given in Table 1:

Soil Layer	Thickness	Unit Weight	Strength	Stiffness
Embankment fill	8.8m	22 kN/m^3	φ’=35°	E =25.0 MPa
Made ground (MG)	3m	19 kN/m^3	φ’=35°	E =11.1 MPa
Cohesise Glacial Deposit (GD-C)	15m	19 kN/m^3	s_u=70+5.8z	E =17.8 MPa
Granular Glacial Deposit (GD-G)	5m	19 kN/m^3	φ’=34°	E =26.7 MPa

Notes:

z is the depth from top of actual layer

Unit weights are total bulk unit weights

φ’ is the internal angle of friction

s_u is the undrained shear strength

E is the soil stiffness

2.4 PILE LAYOUT

Two different pile layouts are analysed, one with ø1000 mm cast-in-place bored concrete piles and one with 350x350mm squared precast driven concrete piles. (See Figure 4)

The medium to very dense granular Glacial provides a large end bearing resistance compared to the adjacent cohesive Glacial layers, hence a pile with toe in the granular layer has a risk of punching through into the underlying cohesive layer. Calculation of the end bearing of a pile with the toe in a relative thin competent layer is based on the ratio between pile size and thickness of the layer in question. The driven piles for the present case can be therefore terminated in the medium to very dense granular Glacial deposit, whereas it is necessary to extend the bored piles into the deeper firm to stiff cohesive Glacial deposits.

The pile layout for the driven piles solution are provided in figure 4. There are four rows of piles resulting in a total of 61 nr piles. 55 nr piles in the foremost three rows consist are raked 1:8, whereas the back row consists of 6 nr vertical piles (Length of each pile is 18 m).

The pile layout for the bored piles solutions are given in figure 4 (right). There are three rows of piles resulting in a total of 26 nr vertical piles (Length of each pile is 36 m).

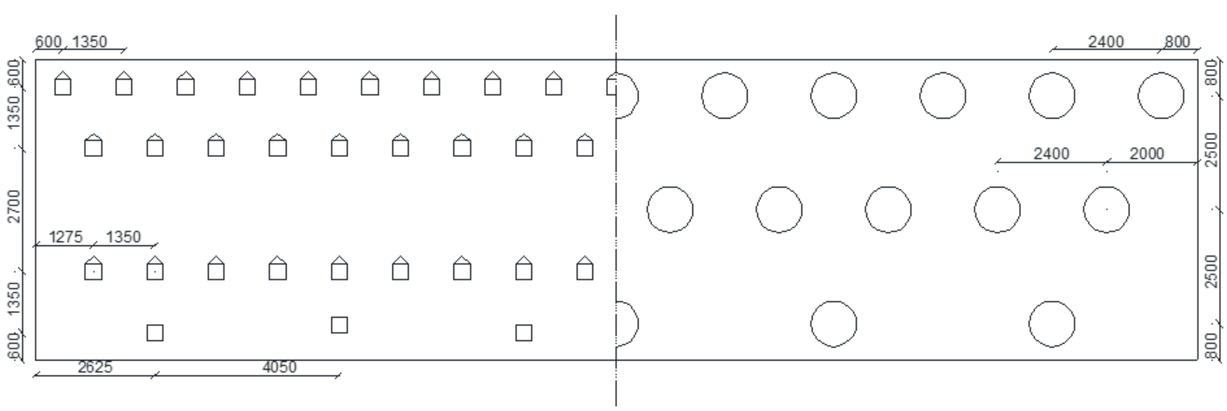

Figure 4 Pile layout. Left : driven piles and right : bored piles

3. MODEL

A combination of traditional analytical calculations for a single pile and numerical modelling have been used to determine the general pile layouts. The designs were undertaken in GROUP v2016 (Ensoft 2016) The software uses t-z and Q-z curves for axial pile-soil response and p-y curves for lateral response. However, the abutment structure or effects from the embankment on the piles cannot be modelled in the software.

The finite element program PLAXIS3D has been utilised to analyse in details the different aspects such the influence from the embankment on the piles and the distribution of forces from the bridge deck through the abutment structure and to the piles and hence include everything in a single analyse. A sketch of the 3D FEM is shown in Figure 5.

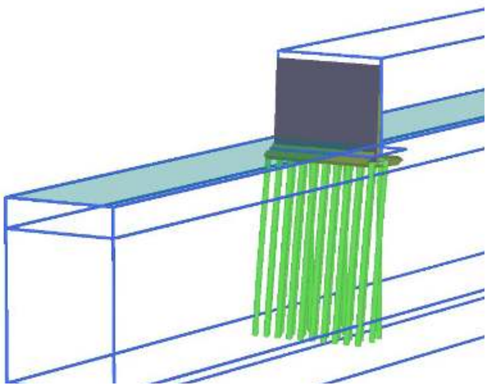

Figure 5 FE model of abutment with precast driven piles.

The main elements of the FE-modelling are:

- A section symmetrically around a vertical plane through the centre of the abutment has been modelled. The width of the section is 12.15 m in case of driven piles and 14.4 m for the case with bored piles. This is shown in Figure 4. The model domain perpendicular to the face of the abutment is 100x68.8 m (width x height).
- Plate elements situated at the centre of the wall and base are used to model the abutment, while the piles have been modelled using embedded beam elements with stiffness similar to piles they represent.
- Soil layers are modelled as Mohr-Coulomb soil with the parameters given in section 2.2. The stratigraphy consists of horizontal layers.
- The shaft friction of the piles is calculated based on the FE-model and the applied soil parameters with an interface roughness of 0.63 and 0.47 for the driven and bored piles, respectively. The maximum base resistance of the piles is determined analytically and given as input to the numerical model.

The FE analyses have been divided into multiple stages representing the construction phases. The main stages are:

- Generation of initial stress state

The abutment and piles are wished in place and the initial stress state is generated based on K0-procedure and subsequent nil-step to ensure equilibrium.

- Establishment of embankment

The embankment behind the abutment is activated through a plastic loading phase.

- Consolidation of embankment

The pore pressure generated through the establishment of the embankment is dissipated through a consolidation phase.

- Loading

The load on the abutment and the surcharge on the embankment are applied in a plastic loading phase.

4. RESULTS

4.1 SETTLEMENTS DUE TO CONSOLIDATION AND LOADING

The height and placing of the abutment backfill result in immediate and consolidation settlements of the embankment fill and the underlying natural deposits, which are shown in Figure 6 for the precast driven pile solution and the bored pile solution. The colour code goes from zero (dark blue) to 770 mm (dark red). In both cases, the total (the resultant of the vertical and horizontal components) displacements are largest away from the abutment on the embankment side. Hence, the abutment with the piles prevents displacements to some extent and the piles act as stabilizing elements (dowels) and they transfer the loads, due to the soil movements, to deeper lying layers. This is most pronounced for the bored piles where the displacement isochrones have a significant bending at the pile toe. The settlements of the abutment originate, in general, from the consolidation of the soil below the pile toe.

For both piled solutions, the settlements away from the abutment on the embankment side are predominantly vertically whereas there is a significant horizontal component when approaching the abutment. Since the abutment is stiff compared to the soil, the abutment undergoes a more or less stiff body movement. Hence, the vertical and horizontal displacements as well as the rotation of the top of the abutment can be used as a measure of the performance of the two piled solution. The horizontal displacements (positive towards embankment), the vertical settlements and the rotation (positive clockwise) of the top of the abutment for the driven and bored solutions due to consolidation settlements are 89 mm, 280 mm, 0.5° and 34 mm, 198 mm, 0.3°, respectively. Hence, the bored pile solution results in less movement compared to the precast driven pile solution. However, both pile solutions behave in the way expected.

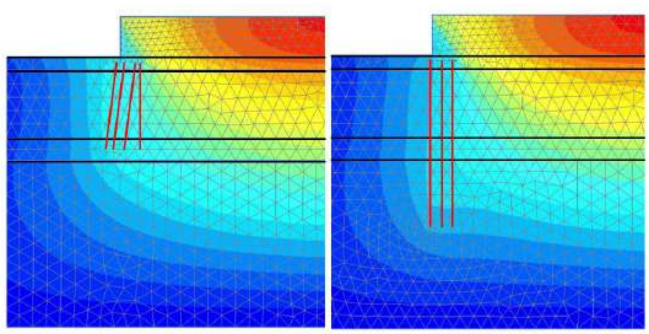

Figure 6 Displacement field (displacement isochrones) due to immediate settlements from placing the embankment fill and consolidation hereof. Left driven piles and right bored piles. Colours ranging from blue to red represents displacements from 0 to 770 mm. Layer boundaries are marked with black lines and piles are marked with red lines.

The displacements pattern are further illustrated in Figure 7 and Figure 8, which include, besides the consolidation settlements and the immediate settlements from the weight of the embankment fill, the movements due to the loading on the bridge and embankment. The general deformation patterns are similar to what is described for the case where only the consolidation settlements and the weight of the embankment fill were considered.

There is a basic difference in how the piles perform in the two pile solutions. The short, however many, precast driven piles undergo primarily a stiff body rotation, except for row four. This is due to a combination of the stiff body rotation of the abutment itself, the vertical settlements of the abutment, the axial stiffness of the piles and not least the lateral resistance exhibited by the lower glacial deposit layer. In contrast, the long, however few, bored piles behave more like flexible piles embedded in the deeper cohesive glacial deposit. Hence, the largest lateral deflections do not occur at the pile toe.

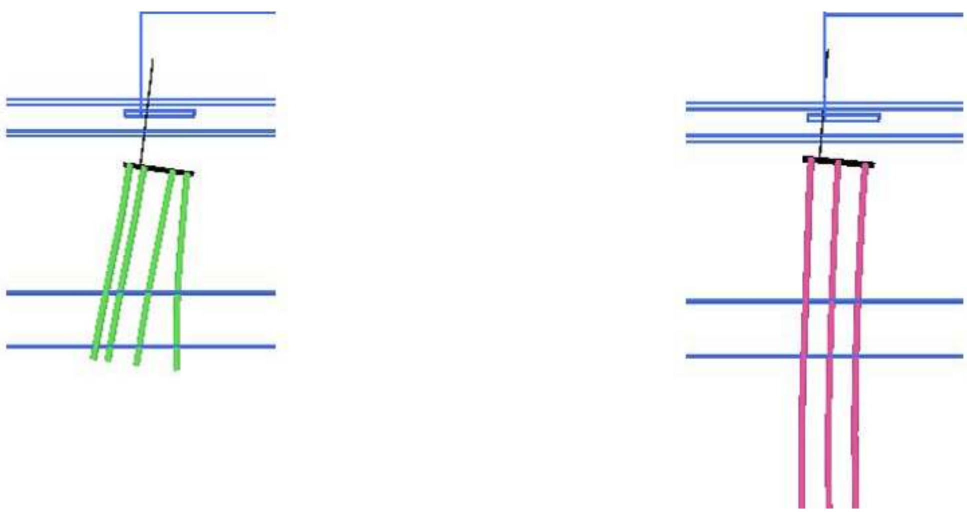

Figure 7 Behaviour of piles at loading from bridge beck. Left driven piles and right bored piles. Note the deformations of piles and mesh are scaled up.

This is further illustrated in Figure 8, which show the lateral displacements as function of depth. The pile position in the initial configuration (before any loading and consolidation settlements) corresponds to zero lateral displacements and a level -1.7m (denoted abutment), which corresponds to the base of the abutment measured from front of the abutment, see Figure 3. Negative displacements implies that the piles move away from the embankment. For the precast pile solution the piles in rows one to three (originally raked) undergo predominantly a stiff body movement whereas the piles in row 4 (originally vertical) behave more flexible. Furthermore, the deflections become larger towards the embankment. For the bored pile solution all pile rows experience a maximum horizontal displacement at a depth of approximately 24 m below the abutment whereas the pile toe experience less deformation; hence this "boomerang-shaped" deflection pattern. This is due to the facts that the piles are extended (in contrast to the precast pile solution) below the zone where the primary horizontal soil movements occur, and is fixed by the relative large resistance in the lower glacial deposit layer.

The vertical displacement of the pile top is 200-240 mm for the bored piles and 290-340 mm for the driven piles. This is due to the fact that the former involves longer piles (i.e. larger total shaft resistance), larger end bearing and higher axial stiffness (in excess of 3.0), which counteract the larger amount piles (factor of approximately 2.3) and the higher unit skin friction (factor of 1.3 in comparable layers) associated with the precast driven pile solution. Furthermore, the settlements due to the loading of the bridge abutment are negligible compared to settlements from immediate settlements from the construction of the embankment and consolidation process.

In general, the precast driven pile solution exhibits less horizontal deflection compared to the bored pile solution as function of depth. However, due the pile head fixity, the location of the vertical piles under the abutment and the pronounced bending originating from the horizontal displacement of the soil volume, the vertical piles in both configurations experience the largest horizontal deflections.

The contrary between less horizontal displacement of the driven piles compared to the bored solution and larger lateral displacements of the abutment for the driven solution is attributed to the rotation of the abutment for the driven pile solution that is approximately the double of the rotation of the bored pile solution.

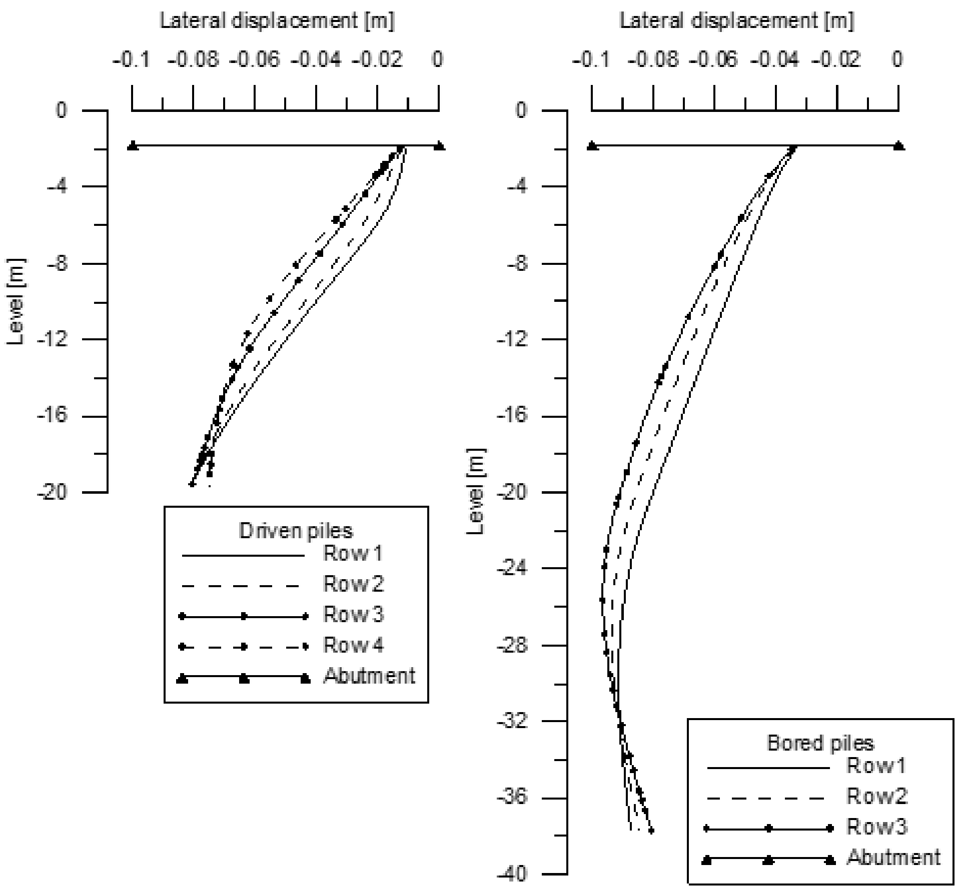

Figure 8 Displacement of piles from construction of embankment, consolidation and loading from bridge deck. Left driven piles and right bored piles, row numbers are from front to back, cf. Figure 3.

4.2 STRUCTURAL EFFECTS IN THE PILES

The entire loading scenario introduces forces in the piles, cf. Figure 9 and Figure 10. The forces reflect the deformation pattern shown in Figure 7 and Figure 8.

The structural effects in the three raked driven pile rows have similar shapes. The axial force is constant in the upper part and hereafter decreases with depth. Furthermore, due to the fixity of the piles in the abutment relative large bending moments occur at the pile heads; however, the moment decreases to approximately zero at a depth of 4-6 m below the abutment base. The same pattern is observed for the shear force. The axial force in row 4 increases with depth to approximately half-way down the pile from where it decreases linearly. The variation in sectional forces complies with the observed behaviour of the abutment, where the vertical and horizontal displacements imply axial loading in the raked piles. The settlements of the embankment induces a general horizontal displacement resulting in additional bending, which due to the pile configuration predominantly introduces axial loads in the piles. The vertical piles are additionally subjected to vertical soil movement (settlement) of the embankment leading to an increased axial force in the upper part of the pile. In summary, due to the pile configuration the relative complicated loading scenario results in predominantly axial loads in the piles. Hence, bending is limited and the potential of the driven piles are exploited.

The structural effects in the three rows of vertical bored piles vary to some extent. The axial forces in Row one are approximately constant in the upper 5 m where after it decreases. In contrast, the axial forces in Rows two and three increase to approximately half-way down the pile from where it decreases. All three rows are subject to relative large bending moments at the pile head (again due to the fixity of the piles in the abutment). They decrease over the upper 5 to 7 m, whereas there is an additional "bump" at approximately level -24 m. This is due to changes in the curvature indicated in Figure 8. The shape of the shear force curve is similar to what is observed for the bending moment. As mentioned, the observed variation of the structual effects with depth complies with the observed behaviour of the embankment and abutment. The piles of Row one sustain a large vertical load, corresponding to a part of the rotational behaviour of the abutment, whereas the settlement of the embankment tends to pull down the piles in Row two and Row three resulting in an increased axial force to a given level. The general horizontal displacements of the embankment and abutment result in bending at the pile head where the piles are fixed and bending in depth where the piles are fixed, acting as dowels.

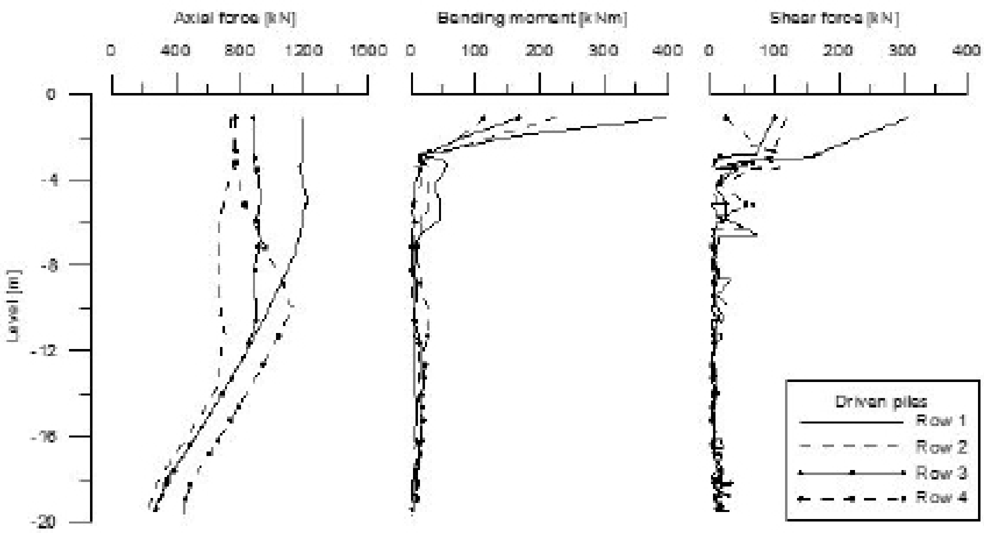

Figure 9 Structural effects for the driven pile solution. The resulting moments and shear forces are

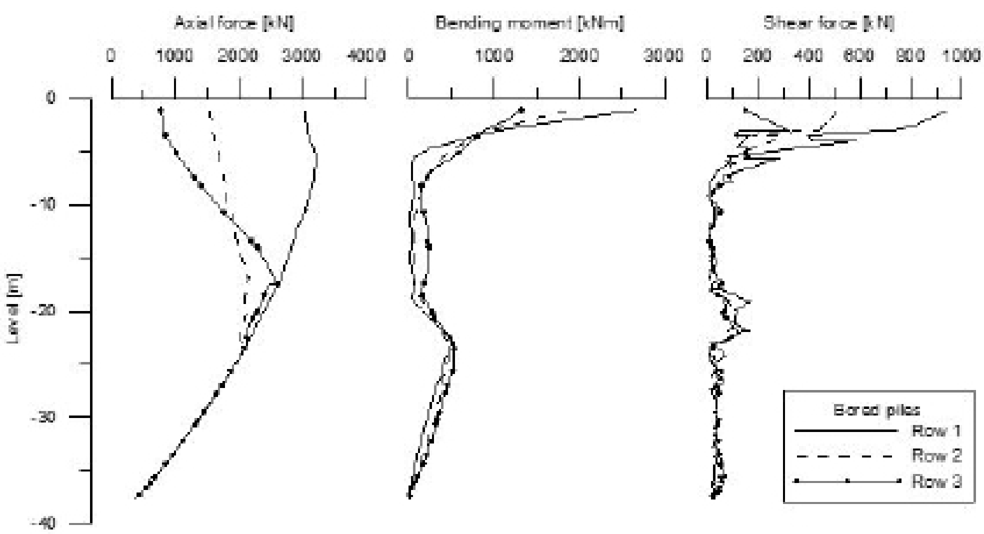

Figure 10 Structural effects for the bored pile solution. The resulting moments and shear forces are shown.

4.3 REINFORCEMENT

The structural effects in the abutment itself have not been analysed, and it has been assessed that the general structural difference due to application of either driven or bored piles is not significant compared to the difference in the pile solution. Below is described an estimate of the pile reinforcement necessary to sustain the observed structural effects:

Applied concrete and reinforcement necessary to sustain the structural effects in the piles are:

› **Precast driven piles**

Concrete:	Characteristic strength of 50 MPa
Reinforcement:	Longitudinal bars: 24 NR. H20
	Ties: H8/200

› **Bored piles**

Concrete:	Characteristic strength of 40 MPa
Reinforcement:	
Front row:	Longitudinal bars: 22 NR. H25
	Ties: Upper 3 m H12/125,
	Lower 33 m H12/250.
Middle row:	Longitudinal bars: 24 NR. H20
	Ties: H12/250
Rear row:	Longitudinal bars: 20 NR. H20
	Ties: H12/400

5. SUMMARY

The objective of the present paper is to demonstrate that driven piles are a good technical alternative to bored piles as a foundation solution for a bridge project. The case study focus on an 8.8 m high abutment, and the comparison of the two foundations solutions are based on structural behaviour, displacements and structural effects.

The foundation solution with the precast driven piles consists of 61 Nr piles with a cross section of 350x350 mm and a length of 18 m. 55 Nr of the 61 Nr driven piles are raked 1:8, the bored pile solution consists of 26 Nr vertical piles with a diameter 1000 mm and a length of 36 m. The ratio of pile cross-section area is 2.73 (bored vs driven).

The relative high embankment results in immediate and consolidation settlements of the embankment fill and the underlying natural deposits. The settlements of the abutment originate, in general, from the consolidation of the soil below the pile toe. The abutment with the piles prevents displacements to some extent and the piles act as stabilising elements (dowels) and they transfer the loads to deeper lying layers. This is most pronounced for the bored piles.

The two foundation solutions behave generally differently. The short, however many, precast driven piles undergo primarily a stiff body rotation. This is due to a combination of the stiff body rotation of the abutment itself, the vertical settlements of the abutment, the axial stiffness of the piles and not least the lateral resistance exhibited by the lower glacial deposit. In contrast, the long, however few, bored piles behave more like flexible piles embedded in the deeper cohesive glacial deposit. The large embedment depth of the bored piles results in a maximum horizontal displacement at the lower two-thirds of the pile, hence the bored piles penetrate the zone where the primary horizontal soil movements occur.

The displacement behaviour is reflected by the structural effects, and comparing the variation of the sectional forces from the driven and the bored piles shows that vertical piles have a tendency of being pushed down by the settlements of the embankment. Extending the piles below approximately level -25 m improves the general behaviour of the embankment and abutment, implying an increased bending of the piles.

Use of raked driven piles implies that the lateral loads are transferred to the ground as axial forces in the piles. The use of the relative small pile dimensions of the driven piles enable a pile length which is significant shorter than the bored piles. However, the bored piles ends up acting as dowels needing reinforcement in depth.

It has been demonstrated from a technical point of view, that both driven precast concrete piles and bored piles are feasible as foundation elements for the abutment. Both foundation solutions behave as intended, and the potential advantages of the two solutions can be exploited. However, for a given project the preferable choice of foundation type depends on many different aspects, such as project economy, construction process etc. The companion paper, Rogers et al (2017), elaborate more on this, and the two papers together demonstrate that a driven pile solution is a feasible alternative to the more traditional bored pile solutions in the UK.

6. INTRODUCTION

THE BENEFITS OF DRIVEN PRECAST CONCRETE PILES FOR LOW CARBON INFRASTRUCTURE

One of the focus areas across the construction industry for a significant number of years has been sustainability and "green" construction. It could be argued that across the building sector, this has proved relatively straightforward to implement, with the addition of sources of renewable energy, energy saving technology within the design of buildings and new products used for construction. The infrastructure sector has lagged somewhat behind, in particular transport. This is in part due to the fact that to build new transport infrastructure, there is typically a lot of muck to be shifted and the primary building materials are concrete and steel.

In recent years, there have been a number of publications and reports regarding driving for lower carbon infrastructure. These include Construction 2025, the Infrastructure Carbon Review and Delivering Low Carbon Infrastructure.

Construction 2025 is the product of collaboration between Government and Industry. The strategy aims to ensure that Britain is at the forefront of construction over the coming years. Part of the Vision for 2025 explains a goal to be "an industry that has become dramatically more sustainable…delivering low carbon assets more quickly and at a lower cost." The figure below illustrates three of the key themes of the document.

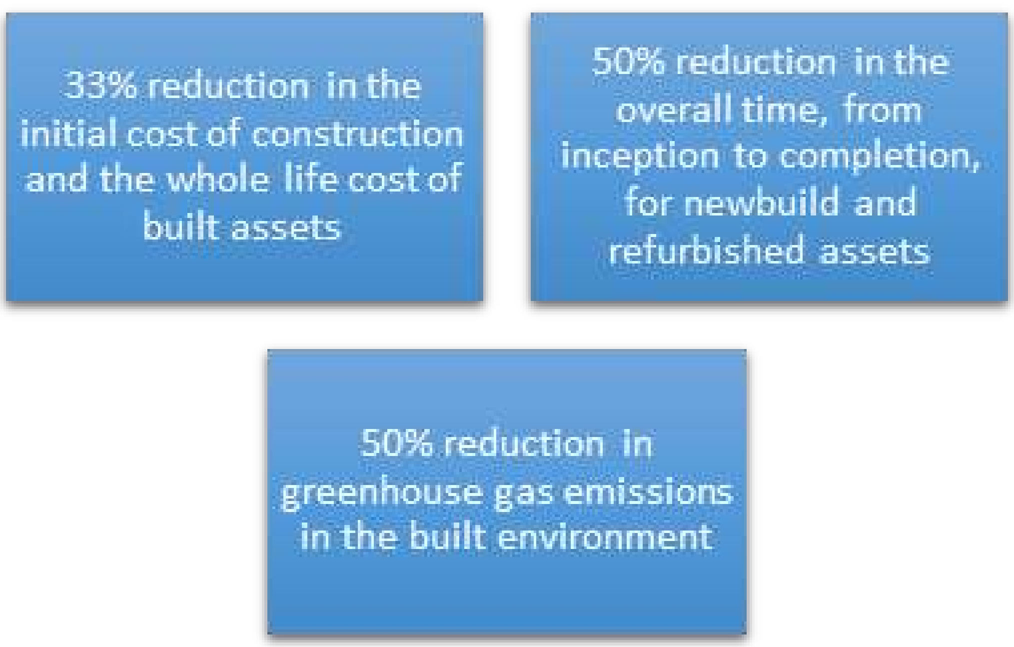

Figure 1: Targets contained within the Construction 2025 Strategy

In November 2013, the Government published the Infrastructure Carbon Review. The report describes the compelling business case for reducing carbon in infrastructure assets and makes a clear link that reducing carbon, reduces costs. The report identified that the infrastructure industry currently has control over 16% of the UK's total carbon emissions, with influence over a further 37%. The report suggests that this total impact figure of 53% is set to grow to 90% by 2050, due to decarbonisation in other sectors. One of the concepts introduced in the report is to tackle carbon early, with greater savings possible the earlier in the asset development clear decisions are made. Figure 2 below illustrates the potential savings that can be realised at different stages of the development process.

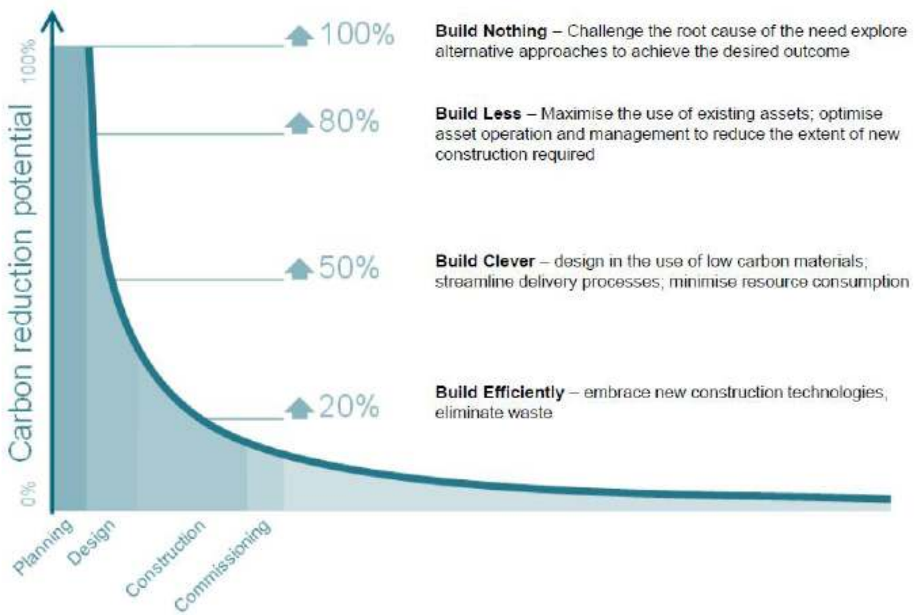

Figure 2: Carbon reduction curve

7. THE DRIVEN PILE PROCESS

A driven pile is a preformed pile which can be manufactured from a variety of materials such as concrete, steel or timber to provide a predetermined, quality assured shape and size which can be examined prior to installation and physically tested before and during the driving process. They are installed by impact hammering, vibrating or pushing into the soil.

Figure 3. Raking precast concrete piles being installed with a hydraulic impact hammer

Driven piles fall into a category of pile often referred to as "displacement" piles. These differ from the other commonly referred to category of "replacement" piles. The key difference between the two categories being that very little or no spoil is generated from a displacement pile.

Installation begins with pitching the preformed pile over the desired position. The pile is then driven into the ground to either a predetermined length or to a predetermined "set" or refusal. Piles can be lengthened by adding additional "segments" to the previously driven pile. Driven piles can be installed as vertical piles or raking piles.

8. DRIVEN PRECAST CONCRETE PILES VS BORED PILES

QUALITY

Driven precast piles are manufactured in a factory environment under strict quality control. The piles are produced to known dimensions using high strength materials and can be inspected prior to installation on site. A bored pile, on the other hand, requires more time and resources in order to provide quality control and assurance. Driven piles maintain their shape during handling and installation and do not bulge in soft soil conditions.

COST EFFECTIVE

A foundation solution utilising a driven precast concrete pile, as opposed to a bored cast in-situ pile, typically utilises fewer resources in terms of plant and labour as well as a reduced quantity of materials (concrete and steel). Hence significant cost savings can be realised. This is further enhanced by the reduction in waste (including spoil generated from the installation process) leading to the associated reduction in disposal costs.

FLEXIBLE

Precast concrete piles can be adjusted to suit site conditions, even during installation. Modern pile manufacturing includes robust connection details, which can also include joints designed to transfer full moment and tension forces. An initial pile length will be derived from the design, using the available ground investigation data. However, using probe piles across the site in the first working shift, any variation in ground conditions can be accommodated and different section lengths delivered as required.

RELIABLE & AVAILABLE

As explained, precast piles are manufactured in a factory environment. The factories are maintained to the highest standards and the process is highly automated. This leads to a reliable source of elements. Reliability and availability of production can also be improved for very large projects by adopting the concept of "flying factories." The critical element for production in this scenario would be the moulds. Concrete can be sourced from an external supplier. For a large enough project, mobile batching plants could be established, further adding to the certainty of supply.

With fewer resources and elements required for a driven precast solution, programme delivery is more certain.

ENVIRONMENTALLY SOUND

As a displacement pile, a driven precast concrete piles produces little or no spoil at the surface. This makes them particularly beneficial in the redevelopment of brownfield sites where contamination is present in the sub-surface soils. In addition to this, the producer of the piles has direct control over the source of the materials and as such can ensure that sustainable procurement practices are applied.

A common perception with precast driven piles is the noise and vibration associated with the installation process. Modern plant and equipment has reduced these impacts, with the addition of shrouding of the hammers and a better understanding of the way the noise is emitted. It is key that during the planning stages, third-party stakeholders are engaged, such that any sensitive receptors can be accommodated and rig orientation and programme of installation can be fine-tuned to meet the necessary requirements.

9. THE CASE STUDY

Driven precast concrete pile groups, incorporating raking piles, were considered as the appropriate foundation solution for abutment and pier foundations for two approach structures. These were namely the Ditton Junction viaduct and Widnes viaduct. Ground investigations identified the ground profile as consisting of Made Ground (various composition) with a thickness of 3m, underlain by 15m of cohesive Glacial Deposit (firm to stiff slightly sandy/gravelly clay) and a 5m thick bed of granular Glacial Deposit (medium dense to very dense slightly clayey/gravelly sand). A mainly cohesive Glacial Deposit with some lamination was encountered below the granular layer at the base of the boreholes (firm to stiff slightly sandy clay). A preliminary design suggested bored piles would extend to a length of approximately 30m. In addition, contamination was identified in the Made Ground. This led the decision to consider alternative options for the foundation solution. The designer engaged with a specialist subcontractor to investigate the possibility of adopting a driven precast concrete pile solution.

The design was progressed and a programme of preliminary test piling was scheduled, along with working test piles to validate the design assumptions. During the design process, a challenge was encountered regarding cover to reinforcement. The presence of high levels of chloride contamination necessitated the need for increased concrete cover to the reinforcement within the piles. However, due to the automated manufacturing process, this was not easily achieved within the precast piles. This was resolved by referring to the standards, Common Rules for precast concrete products (BS EN 13369), which recommends cover values based on environmental conditions, concrete strength and type of reinforcement bar. Further adjustments can then be made if further testing is carried out on the proposed concrete mix, in the form of water absorption tests. This was done in this case and the proposed cover to reinforcement was accepted.

As described previously, for the purposes of the technical review of the use of precast driven concrete piles for bridge foundations forming the previous paper, the ground model and loading situation was simplified. **Table 1 below summarises the output the technical paper in terms of pile layouts and dimensions, while Table 2 summarises the designed reinforcement details.**

Driven Precast Piles					Bored Piles			
Row	No.	Rake	Dimensions	Length (m)	No.	Rake	Dimensions	Length (m)
1	19	1:8	350x250mm	18	11	Vertical	1000mm	36
2	18	1:8	350x350mm	18	10	Vertical	1000mm	36
3	18	1:8	350x350mm	18	5	Vertical	1000mm	36
4	6	Vertical	350x350mm	18		-	-	-
Total	**61**				**26**			

Table 1. Summary of abutment pile details

Driven Precast Piles				Bored Piles					
Row	Main Bar	Length	Shear Links	Main Bar	Length	Shear Links	Main Bar	Length	Shear Links
1	20 B20	18m	B12@200	14 B32	5m	B12@125	7 B25	36m	B12@240
2	20 B20	18m	B12@200	8 B32	5m	B12@240	8 B25	36m	B12@240
3	20 B20	18m	B12@200	6 B32	5m	B12@240	6 B25	36m	B12@240
4	20 B20	18m	B12@200	18	-	-	-	-	-

Table 2. Summary of reinforcement details

9.1 BENEFITS & ADVANTAGES

Based on the design output from the simplified case study, the authors have compared various aspects, including material quantities and carbon footprint, and these are presented in Table 3 below.

	Driven Precast Concrete Piles	Bored Piles	Saving (%)
Concrete Volume (m^3)	135	846	84
Reinforcement (t)	68	56	-20
Spoil (m^3)	0	1,142	100
Programme Duration (inc. set up)	9 shifts	20 shifts	55
Vehicle Movements (Nr.)	26	514	95
Carbon Footprint (tCO_2e)	**160**	**440**	**63**

Table 3. Technique comparison

Table 3 illustrates the potential savings that can be realised if a driven precast concrete pile solution is adopted over a traditional bored cast in-situ solution. As can be seen from the table, the major savings are found in the concrete volume, spoil generation and vehicle movements. These factors have a direct impact on the carbon footprint of the opposing solutions.

The factors affecting the carbon footprint calculations for the two solutions are primarily materials (concrete and steel), waste and freight. The graph in Figure 4 below illustrates the comparison between the carbon footprints for the two solutions. The calculation used the EFFC Carbon Calculator tool.

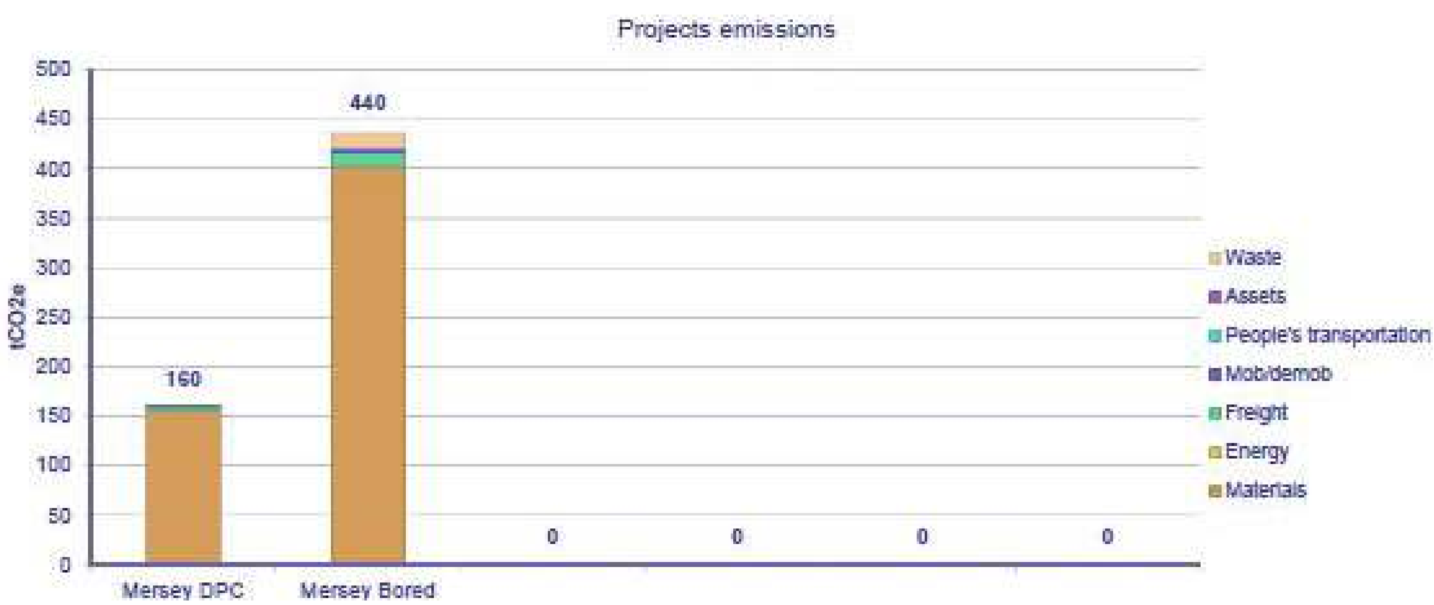

Figure 4. Carbon footprint comparison

These are also the major contributors to the vehicle movements, the key differences between the two solutions being spoil removal and the need to deliver the wet concrete and reinforcement cages as elements as opposed to the precast reinforced elements of the precast piles.

With regards to the vehicle movements, the dramatic reduction with the precast concrete piles has an added, almost unintended consequence. The impact on the geographic areas that the works are being undertaken is vastly reduced. Many of the major infrastructure projects either in progress or in the pipeline are routed through rural areas of the UK. This is due to the very nature of the schemes to improve communications networks across the country. The figures in Table 3 above demonstrate the benefits that a driven precast solution can deliver to the rural communities that these schemes are constructed through. This dramatic reduction in vehicle movements has an impact on the health, safety and wellbeing of the communities around the projects and also serves to reduce congestion. This reduction in congestion can be further linked to a reduction (or certainly a limited net increase) in carbon emissions.

As an individual measure, the carbon footprint demonstrates that the foundation solution for large infrastructure structures can play a key role in the overall reduction of carbon for the project.

10. CONCLUSIONS

This paper by Caspar et al demonstrates that technically, a driven precast pile solution incorporating raking piles is a viable solution for bridge structures, it also identifies a number of other benefits and advantages that can be realised.

There are clear resource benefits, which cannot be ignored with the ongoing skills shortage. Quality control is improved and as a consequence, costs associated with quality or correcting defects is reduced. Overall programme duration is reduced, which delivers cost savings as well as benefit for third-parties living around these schemes during construction. Waste is significantly reduced, saving costs through zero waste to landfill and preventing potentially contaminated spoil from brownfield sites being excavated.

In collaboration with government, industry has committed to playing its part in the drive for reducing carbon emissions. Using a simplified case study, this paper has identified that the potential reduction in carbon associated with the foundations of infrastructure projects can be significant. It adds weight to the Government's call, which is widely echoed by a number of client organisations, to think differently in order to bring about real change. With early engagement across the consultant and contractor community, it is possible to deliver true low carbon assets through existing practice. Innovation in materials e.g. low carbon cements, can only serve to increase the benefits.

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