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Demonstrating environmental benefits of ground improvement

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Many ground improvement methods generate much less environmental impact than other deep foundation methods, for example concrete piling. Creative use of various ground improvement methods has already generated tangible benefits to completed projects, such as the Dartford Park project in the UK. The experience gained in these ground improvement projects highlights where further use of proven and emerging technology can provide still greater opportunity to reduce the environmental impact of deep foundation systems. The present study compared the environmental impact of common methods of ground improvement against more traditional deep foundation methods to show that, using a like-for-like comparison, ground improvement methods can offer sustainability advantages. Case studies illustrate how sustainable principles have been implemented in practical ways on routine projects. Perceived barriers and constraints that may hinder realisation of greater sustainability advances are identified and some suggestions as to how these may be overcome are presented.

1. INTRODUCTION

Construction in the UK accounts for 8% of gross domestic product, employs around 3 million workers, consumes around 25% of all the country's raw materials and produces around 30% of national landfill waste (DBERR, 2008). Worldwide these activities are having a significant impact on the environment and scientific evidence strongly suggests global warming since the mid-twentieth century is largely due to human activity (Defra, 2009). To protect our environment for future generations humankind must find ways of existing in a more sustainable way. With the pressure to become more sustainable, ways of reducing the environmental impact of the construction process to reduce energy demand, generation of greenhouse gasses and production of waste are being vigorously sought.

Within the field of foundation engineering, ground improvement methods can be shown to generate less environmental impact when compared with other foundation solutions, such as concrete or steel piling, for example, as described by Spaulding *et al.* (2008). In the present study the environmental impact of common methods of ground improvement were compared with the more traditional deep foundation methods to show that, using a like-for-like comparison, ground improvement methods can offer sustainability advantages.

2. REDUCE, REUSE AND RECYCLE

The environmental impact of any product or service can be minimised by application of the principles of reduce, reuse and recycle.

2.1. Reduce

Reducing the amount of raw or processed material in a product conserves natural resources, reduces energy demand and hence the release of greenhouse gases. As will be shown below, by improving the ground, the need for piles can be avoided thereby utilising less raw material (stone aggregate) and processing energy (e.g. to make cement and steel). The main thrust of this paper is a discussion on reducing the carbon dioxide footprint (an indicator of embodied energy) of deep foundation solutions by the use of ground improvement as an alternative to piling.

2.2. Reuse

Traditional steel and concrete piling creates artefacts which remain in the ground when the original structure they were supporting is demolished and the site redeveloped. Although the reuse of piles is to be encouraged, as set out by Butcher *et al.* (2006), currently only a relatively few projects have been completed in which this has happened. Fewer and less troublesome obstructions are left in the ground where vibro is used, and none where dynamic compaction is adopted. In this sense ground improvement future-proofs the site for potential reuse. There have been a number of cases in which previously vibroed sites have been redeveloped and the stone columns re-used. In certain cases new stone columns have been installed next to or within the original stone column layout.

2.3. Recycle

Recycling saves on raw materials and saves energy. Stone columns present an ideal opportunity to use recycled aggregate, for example as described by Serridge (2005). However, such material may have different physical properties in comparison with virgin stone, as discussed by Slocombe (2003).

3. THE ENVIRONMENTAL BENEFITS OF GROUND IMPROVEMENT

This paper reports a study that has been undertaken to compare the embodied carbon dioxide (ECD) for a number of projects where both piling and ground improvement solutions were proposed. In most cases the schemes were received by Keller UK as invitations to tender for piling. As a specialist geotechnical contractor Keller UK has the required skill and experience to quickly assess the feasibility, cost–benefit and environmental impact of alternative foundation solutions, such as ground improvement. The sites of the projects reported on below were found to be suitable for ground improvement and alternative proposals were developed by Keller UK. Usually the main drivers for proposing ground improvement alternatives are cost and programme savings. Routinely ground improvement alternatives will yield cost savings of 30–60% compared with the cost of a piling solution. As a result of embedding a carbon footprint calculator within its estimating process, Keller UK has discovered that very significant reductions in ECD (typically of the order of 90%) are achieved when ground improvement alternatives to piling solutions are adopted.

The concept of ECD is useful as it provides an indication of the amount of greenhouse gas (GHG) emitted by a particular activity or production process. This is clearly of the highest importance given the link between GHGs and the onset of climate change (Defra, 2009). The ECD is defined as the carbon dioxide that is emitted by burning fossil fuels during the manufacture and transport of a product as well as the carbon dioxide emitted through chemical processes, such as when manufacturing cement.

The ECD is related to, but not synonymous with, other sustainability metrics, such as embodied energy and production of waste. ECD is principally an environmental metric rather than a more direct measure of sustainability, but as there is the specific UK government target to reduce the UK's carbon dioxide emissions by 80% on 1990 levels by 2050, consideration of the impact on the ECD of different foundation solutions seems most appropriate.

The following methods of ground improvement and piling were considered within this study.

(*a*) Vibro replacement stone columns (see Sonderman and Wehr (2004) for a full description of this method).
(*b*) Deep dynamic compaction. Densification of ground and hence the improvement of bearing capacity and settlement performance is achieved by the systematic dropping of a large weight onto the ground surface. This process is described by Slocombe (2004).
(*c*) Continuous-flight auger (CFA) and driven cast-in-situ piling, as explained at www.keller-ge.co.uk.

4. EMBODIED CARBON DIOXIDE FOR PILING AND GROUND IMPROVEMENT SOLUTIONS

The ECD for piling and ground improvement solutions for a range of different projects was calculated and the results are compared in Table 1. In each case the proposal of the ground improvement was a direct replacement of a 'conforming' piling solution, therefore providing a direct like-for-like comparison. Complete substitution by ground improvement was not possible on project (f) and although substitution by ground improvement was undertaken for some of the piles, some piling remained. Nonetheless, as this was a large project, worthwhile reductions in ECD are demonstrated.

5. METHOD FOR ASSESSING EMBODIED CARBON DIOXIDE

All of the comparisons undertaken here follow the principles of *PAS 2050, Specification for the Assessment of the Life Cycle Greenhouse Gas Emissions of Goods and Services* (BSI, 2008). Certain assumptions are necessary and the specification requires that these are stated to support the carbon dioxide assessment and to ensure transparency in the calculations.

The method adopted here assesses the life cycle GHG emissions on a business-to-business basis. The ECD of materials entering the process from the time they leave the factory gate (batching plant or quarry), plus the carbon dioxide generated during transporting the raw materials, construction on site, mobilisation of plant and workforce to site, and transport of spoil from site (if applicable) are incorporated to give the value of ECD of the foundation solution, as handed over by Keller to the project. It excludes additional construction steps (e.g. breaking down piles to form a pile cap) and potential removal, disposal or recycling during future demolition or redevelopment of the site.

The B2B approach is consistent with the 'cradle-to-gate' approach described in BS EN ISO 14040 (BSI, 2006).

Figure 1 illustrates a process map using the B2B approach for the construction of vibro stone columns. The process map for the construction of concrete or steel piles would be similar, except that the assessment of ECD in the production of steel and particularly concrete is much more complex than for the procurement of stone column aggregate. The ECD for the constituent materials utilised in the calculations will now be outlined. Table 2 summarises the values described in the following subsections.

5.1. Concrete

The ECD in concrete arises from the manufacture and transport of its constituent cement or cement replacement, aggregate and water.

For piling applications the cement content of the concrete will be influenced by the design strength, durability class and workability (e.g. for pumping).

The British Concrete Association (2008) gives a value of ECD for a typical UK concrete of 225 $kgCO_2/m^3$ (300 kg/m^3 cementitious content, characteristic strength C28/35, water/cement (w/c) ratio 0·55). This would increase to 255 $kgCO_2/m^3$ for a concrete with 340 kg/m^3 of cementitious content with a w/c ratio of 0·45 (i.e. required where durability resistance up to a DC-2 mix is required (BRE, 2005)).

5.2. Stone column aggregate

Hammond and Jones (2008) suggest an ECD of 5 $kgCO_2/t$; however, the Environment Agency Carbon Calculator (Environment Agency, 2009) uses a value of 8 $kgCO_2/t$. This

Project	Location	Conforming piling scheme scope	Alternative ground improvement scope	Embodied carbon dioxide: Conforming piling scheme: t CO_2	Embodied carbon dioxide: Alternative ground improvement scheme: t CO_2	Saving in carbon dioxide: %
(a)	Newbury	544 no. 600 mm CFA piles 6 m long	1280 no. Minicat VSC 3·34 m long	275·66	20·70	92·5
(b)	Wigan	263 no. 340 mm DCIS piles 5·8 m long	324 no. Minicat VSC 2·18 m long	44·89	3·43	92·4
(c)	Gateshead	395 no. 350 mm CFA piles 14·2 m long	834 no. Minicat VSC 3·78 m long	256·31	13·79	94·6
(d)	Sudbury	72 no. 400 mm CFA piles 20 m long	300 no. Minicat VSC 3·0 m long	60·08	4·15	93·1
(e)	Norwich	340 no. 340 mm DCIS piles 7 m long	425 no. Minicat VSC 1·2 m long	76·76	2·96	96·1
(f)	Dartford Park*	8301 no. DCIS and VCC piles up to 14·5 m long	5747 no. DCIS up to 14·5 m long + 1356 top feed VSC 4·9 m long + 4940 m^2 DC	5387·58	3427·96	36·4

* Dartford Park was not 100% replacement of piles with ground improvement.
CFA, continuous-flight auger; DCIS, driven cast-in-situ; DC, dynamic compaction; VCC, vibro concrete column; VSC, vibro stone column

Table 1. Summary of ECD

latter, more conservative value, was adopted in the calculations supporting this study. The winning of virgin aggregate produces little carbon dioxide compared with the production of most other construction materials. For recycled aggregate a value of 3·69 $kgCO_2/t$ was adopted.

Due to the relatively low ECD for the raw material, the contribution to the overall ECD from the transport of the stone from the source to the worksite can be significant in percentage terms. For the studies presented here the distance from the quarry gate to the worksite was obtained from each supplier and the transport emissions calculated (assuming 20 t loads carried in a rigid HGV in rural driving conditions with a Euro II engine emitting 4·4 gCO_2/km).

5.3. Reinforcing steel

Steel reinforcement for cast-in-place piles usually comprises steel bar, which in the UK is 100% recycled. For each case study the tonnage of reinforcement required to produce the piling solution was calculated and the transport distance from the supply depot ascertained. The ECD for the recycled steel was taken as 420 $kgCO_2/t$ (Hammond and Jones, 2008). It was assumed the steel was transported in 20 t loads by rigid HGV in rural driving conditions with a Euro II engine emitting 4·4 gCO_2/km.

5.4. Site plant mobilisation

Emitted carbon dioxide due to mobilisation of construction plant to and from site was assessed, based on the number of return vehicle journeys from the headquarters depot to the worksite. In all cases this proved a very small percentage of total ECD and is of little significance.

A similar estimate for workforce transport, based on a weekly commute to site and a daily allowance of 20 km per person per day is also included but shows a similarly insignificant ECD contribution.

5.5. Energy consumed during construction

From records of the fuel consumption of the combinations of plant used to install the different products, it was possible to develop average values of ECD per hour of operation on site for the different plant systems and combinations (e.g. top-feed and bottom-feed vibro, CFA piling). An ECD of 2·63 $kgCO_2/l$ of diesel was applied in these calculations as taken from Defra (www.defra.gov.uk/environment/climatechange/uk/individual/pdf/actonco2-calc-methodology.pdf) and based on the direct emissions from end-use combustion.

6. COMPARISON OF PROJECTS

Six projects were included in the study to assess whether the ECD savings were dependent upon type of project, as well as the soils. The projects (a) to (f) were for the following respective developments

(*a*) three-storey data centre
(*b*) two-storey housing development of semi-detached and terraced units
(*c*) two-storey office development
(*d*) low-rise sports development including gymnasium
(*e*) two-storey care home.
(*f*) large distribution centre.

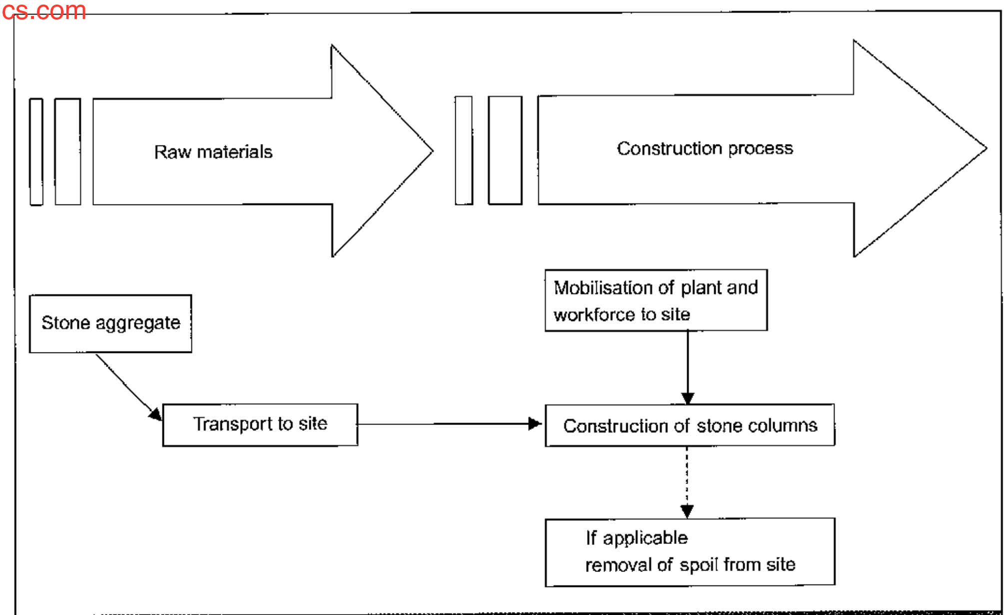

Figure 1. Process map for stone column construction

Materials	Embodied carbon dioxide	Notes
Concrete (cement content 300 kg/m^3)	225 kg/m^3	Based on data for UK average concrete from Concrete Centre
Concrete (cement content 300 kg/m^3)	255 kg/m^3	Based on data for UK average concrete from Concrete Centre
Reinforcing steel	420 kg/t	Based on recycled steel values (Hammond and Jones, 2008)
Quarried stone aggregates	8·00 kg/t	Carbon calculator (Environment Agency, 2009)
Recycled stone aggregates	3·69 kg/t	Carbon calculator (Environment Agency, 2009)
Fuel	2·63 kg/l	www.defra.gov.uk/environment/climatechange/uk/individual/pdf/actonco2-calc-methodology.pdf
ICE – aggregate – virgin	5·0 kg/t	Hammond and Jones (2008)

Table 2. Summary of embodied carbon dioxide for construction materials

Projects (a) to (e) represent a typical range of small- to medium-sized piling projects. The ground conditions for these projects comprised typically about 2·0 to 4·0 m mixed granular and cohesive made ground, in variable states of compaction, underlain by either stiff gravelly clay onto mudstone or gravelly sand onto chalk. Project (b) included up to 1·0 m thickness of soft to firm laminated clay immediately beneath the made ground. Of the 50 house units in project (b), 13 were underlain in a defined area by a greater thickness of peat than permitted for treatment under the NHBC vibro rules. These units had to be piled and the comparison shown in Table 1 compares the piling to vibro solutions for the remaining 37 units.

Project (f) located at Dartford Park next to the M25 Thames Crossing (Sustainable Solutions at Dartford Park, 2008) represents a significant ground engineering project with a value in excess of £1 000 000. The main part of the project was a 42 000 m^2 distribution centre to house computerised high bay racking. The site geology consisted of a mantle of made ground derived from silt and firm clay underlain by a sequence of both cohesive and granular alluvium above Taplow Gravel, which was underlain by the Upper Chalk.

The southern part of the site had been gravel extraction pits, later infilled by the deposition of a significant thickness of spoil (believed to be from the second Dartford bore). The northern part of the site was underlain by alluvial soils over 6 m in thickness and containing impersistent bands of peat up to 2 m thick. However, the central part of the site was underlain by a thin (2 m) mantle of competent granular made ground over a zone where neither gravel extraction had taken place nor alluvium was present. In the conforming piling scheme, precast piles were proposed for the frame and the floor slab founding in the chalk.

In the Keller alternative scheme, driven cast-in-situ (DCIS) piles were used to support the structural frame and the northern and southern ends of the floor slab. In the centre of the building, where the deep fill and/or the alluvium was absent, a combination of deep dynamic compaction to treat the upper granular fill and Taplow Gravel, with a stiffer transition zone comprising vibro replacement stone columns dovetailing into the piled areas, was adopted for the slab.

This alternative combination of DCIS piles and ground improvement generated cost savings of about £1·5 million and a faster construction programme compared to the fully conforming piled scheme. Furthermore assessment of the ECD shows that a saving of 1960 t CO_2 (36%) was achieved.

7. DISCUSSION

The key features of the reduction in ECD where ground improvement alternatives are provided are now discussed. Project (c) is used as a typical example to illustrate the salient points, being typical of an average small- to medium-sized piling scheme.

7.1. Features of typical carbon footprints for the different products

Figures 2 and 3 compare the breakdown of ECD for the piling and vibro stone column solutions for project (c). The proportions of carbon dioxide attributed to the different constituents (concrete, reinforcing steel, fuel consumption of construction plant etc.) were found to remain fairly constant for a given foundation solution across a range of different projects. As would be expected the total ECD varied with the size of the project and the foundation solution adopted. The following features in Figures 2 and 3 are noted.

For the CFA piling option (Figure 2) the total estimated ECD for the conforming piling scheme was 235 t. The concrete contained the most ECD, 67% of the total (158 t from its manufacture but only 0·02 t for transport to site). Reinforcing steel was the next biggest element, 65 t (27%). The fuel consumption of the construction plant involved with on-site construction generated 4·2% (9·8 t) of the total ECD. Spoil disposal, to a tip 10 km from the site, emited around 1·3% of the total carbon dioxide (3·1 t) and was not very significant. Prelims and labour transport together comprised much less than 0·2% and could effectively be ignored.

For the vibro stone column solution (Figure 3) the total estimated ECD for the vibro stone column alternative was 13·8 t (about 6% of that of the piling scheme). The biggest saving was due to concrete and reinforcing steel not being required (saving 223 t of carbon dioxide). In place of concrete and steel primary stone aggregate from a quarry located 50 km from the worksite was proposed, the production and transport of which accounted for 9·3 t of carbon dioxide. It should be noted that the haul distance in this particular case was unusually large, a typical distance being around 10 km. Not withstanding this, the stone aggregate contributed 67% of the ECD for the vibro solution. This was found to be fairly typical for this type of project. The fuel consumption of site plant was the next biggest carbon dioxide contributor (4·3 t or 31% of the total ECD). Because vibro stone columns can be installed faster and with lighter-weight plant than CFA piles, the fuel consumption was found to be around half of that for the piled solution in this case; proportionally site fuel makes a larger contribution to the ECD than for piling schemes. As for the piling option prelims and site labour, transport was a very small CO_2 contributor in absolute terms, and in any case less than 1·5% of the total.

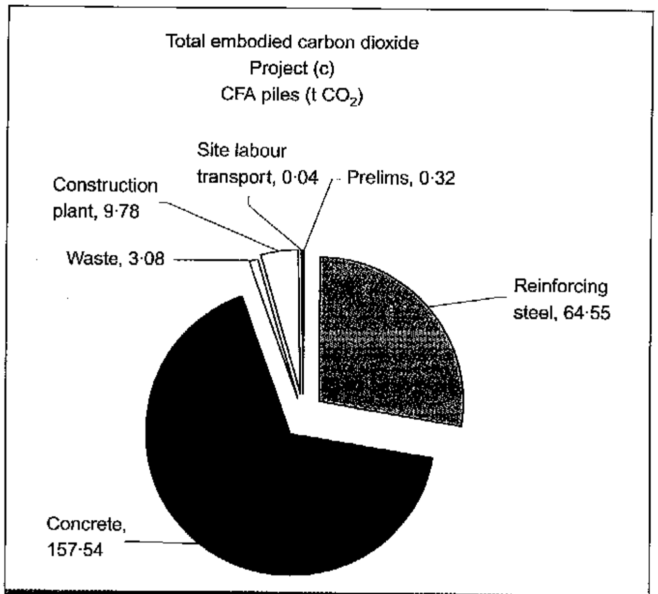

Figure 2. Embodied carbon dioxide for the piling solution for project (c)

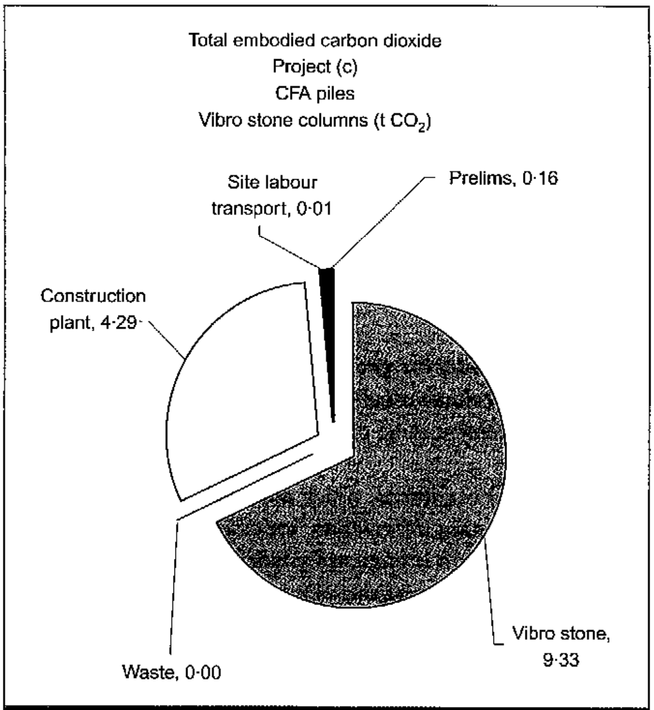

Figure 3. Embodied carbon dioxide for the alternative vibro stone column solution for project (c)

The principal sources of the ECD savings come from avoiding the use of steel and concrete which have high ECD in favour of stone aggregate which, as noted above, has a much lower ECD value. Further savings are possible where recycled or recovered aggregate can be used in the stone columns. Optimising the strength of the ground, particularly near the surface, through greater use of the physics of load transfer from the foundations and the interaction of the ground with the stone columns means that, on a like-for-like basis, stone columns, although more numerous than piles, are usually much shorter. Stone columns are usually installed more quickly and with smaller and more fuel-efficient rigs than is the case for piling.

Usually the cost of a vibro solution is around 30 to 60% of the conforming piling solution. This commercial advantage is usually the reason that ground improvement is adopted on schemes. However, and arguably of more long-term impact in the context of climate change, ground improvement alternatives typically yield a saving of around 90% in ECD.

8. OPPORTUNITIES AND BARRIERS TO THE USE OF VIBRO STONE COLUMN SOLUTIONS

There are many opportunities to use lower carbon ground improvement alternatives as foundation solutions, where the ground conditions are suitable for the proposed loading requirements and serviceability performance expectations. Lower carbon ground improvement solutions will not be suitable for all (or part) of many developments; ground improvement will not, on its own, create a carbon dioxide utopia.

8.1. Requirements for ground improvement solutions

The following features usually need to be present to enable ground improvement to be considered.

Suitable ground conditions, which must be proved by adequate ground investigation information, are essential. (Suitable ground investigation is often sadly lacking in quality and quantity (Egan, 2008) and this often presents an insurmountable barrier.)

Situations of light to moderate loading (typically bearing pressures up to 80 kPa in weak soils to 250 kPa in compact soils are frequently achieved) are most appropriate for ground improvement often accompanied by tolerance of a lower performance expectation in terms of total (and possibly differential) settlement compared with what would usually be expected from a piled solution.

Finally the willingness of the client and his design team to accept an alternative solution is essential and occasionally the design team may adopt an entrenched position in favour of a piled solution to protect their credibility.

8.2. Barriers

Barriers to the implementation of ground improvement, with some possible solutions, include unsuitable ground conditions, poor ground investigation information, high load capacity and the application of unrealistically high settlement specifications.

Unsuitable ground conditions, which if truly the case, can rule out ground improvement entirely. However, poor ground investigation preventing adequate analysis of the ground properties, such that the suitability of a vibro stone column solution can be demonstrated, is a more common problem. Many vibro schemes have been shelved because of the difficulty in demonstrating adequacy due to lack of adequate ground investigation information or because the site investigation report does not refer to or consider the feasibility of ground improvement.

The requirement for high load capacity, if such high loads are truly to be applied, can rule out the use of ground improvement. There may also be a lack of understanding by structural engineers of the mechanisms governing the behaviour of ground improvement which can manifest itself as an entrenched over-conservatism within the wider design team when it comes to specifying the building loads. It is suggested that this is born out of a lack of incentive or understanding for the building designer to engage with the ground improvement designer to supply realistic loads.

Specification of unrealistic settlement performance requirements is often encountered, in particular unwarranted tight total settlement criteria, where differential settlement between different parts of the structure is a more pertinent measure of acceptability. Jarrett *et al.* (1974) report settlement of a number of mainly brick buildings of different sizes in the range 8–237 mm at an ICI facility in Grangemouth. The data were recorded over several decades and there were no indications of distress or serviceability problems associated with the buildings. Lack of knowledge/understanding of the actual settlement tolerance of modern buildings can lead to unnecessarily tight settlement criteria being specified. For piling a total settlement of around 10 mm at working load is common while between 15 and 30 mm is a common, and perfectly adequate, range in vibro stone column specifications.

Finally rate effects may be a key element of ground improvement design. For certain types of scheme, for example road embankments, or other upfilled sites, sufficient time to allow for consolidation settlement (with attendant monitoring) may be required. This demands better planning and earlier consideration of ground improvement for a potential foundation solution.

8.3. The importance of representative foundation loads

In most cases ground improvement designs are governed by serviceability limit state (SLS) requirements, (i.e. total and differential settlement). This is not to say ultimate limit state (ULS) requirements (e.g. bearing capacity) are not important. In commercial ground improvement design SLS conditions are first considered to arrive at a suitable density of ground treatment. The ULS calculations are completed thereafter. There is a self-governing aspect to this approach since it is unlikely (although not impossible) that adequate SLS performance will be achieved when ULS requirements are not, although of course the ULS check should always be performed.

In the context of the SLS calculations, settlement is dependent on the magnitude of the applied load, the thickness of the compressible strata, the size and shape of the area under load, and is also time dependent in soils of low permeability. Efficient ground improvement design therefore requires an understanding of all of these facets of the applied load, but rarely is it possible for the ground improvement designer to obtain this information from the scheme designer.

An example of a typical warehouse will be used to illustrate the point. The loads from the structural frame will have elements of self-weight (dead load), imposed load (e.g. arising from maintenance activities, snow load) and wind loading. The wind loading element can be a very large proportion of the total load, especially over the bays where the frame is braced. However, wind loading will be transient in nature and its settlement-generating potential likely to be much less than the dead load element because of this. If the elements of load are not separated out the designer has no option but to design for the full allowance on all frame bases. This can be highly inefficient, and may even lead to the use of ground improvement being discounted.

When considering floor slabs the situation can be even worse. The practice of specifying conservative loads without accounting for their plan extent is a common source of inefficiency. Typically, an institutional load will be specified (say 50 kPa) acting over the whole plan area of the warehouse (which could easily be of the order of 20 000–40 000 m^2). In reality, areas of the floor under racking may conceivably be loaded to this magnitude (but in most cases even this will be unlikely), but the intervening aisles and handling areas will not be. While it may be correct to take the maximum possible applied load for the design of the structural elements and the floor slab itself, taking this over the whole building footprint for the purpose of settlement estimation is unrealistic. It is common in these situations to take a time-averaged load of, say, 50–70% of the institutional load for the estimation of settlement.

9. OPTIMISING THE USE OF GROUND IMPROVEMENT IN THE FUTURE

To encourage greater opportunity for the reduction of ECD in foundations it is necessary to better publicise the use of ground improvement as a technically acceptable alternative to piling which has significant environmental benefits. Client's technical advisors, who have an influence early in the life of a project, need to be aware of the significant cost and environmental benefits of ground improvement and have the incentive to go about investigating its viability and accepting realistic settlement performance. It is early in the design phase of a scheme that careful specialist design input (before a less environmentally friendly solution becomes a fixed part of the project) can have greatest impact. However, none of this increased focus on ground improvement will yield benefits if the there is inadequate geotechnical ground investigation (the scope of which is often drastically reduced in favour of shallow environmental investigation).

10. CONCLUSION

The contribution of greenhouse gases to climate change appears now to be beyond reasonable doubt. The target to reduce carbon dioxide emissions by 80% on 1990 levels by 2050 has been set by the UK government and in many areas this will be a tough target to reach. It has, however, been repeatedly demonstrated that using ground improvement as a foundation solution in place of more traditional piling can yield savings of the order of 90% in ECD when the two approaches are compared on a like-for-like basis on the same project.

Every effort should be made to educate clients and their technical advisors of the advantages and capability of ground improvement and its ability to deliver significant carbon dioxide benefits along with cost and time-saving advantages.

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