COMMENTS ON COSTS, BENEFITS, CONSTRAINTS AND OPPORTUNITIES IN THE PROVISION OF SUSTAINABLE GROUND IMPROVEMENT FOR URBAN REGENERATION PROJECTS

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This paper compares 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 are used to illustrate how sustainable principles have been implemented in practical ways on routine projects. The topics covered include the use of recycled and recovered aggregate, reduction in waste, future proofing the ground to facilitate later development and technological advances in improving polluted or marginal ground. The paper concludes by highlighting perceived barriers and constraints that may hinder realisation of greater sustainability advances and offer some suggestions as to how these may be overcome.

INTRODUCTION

Construction has been reported to account for about 8% of the UK's Gross Domestic Product with buildings accounting for almost half of the country's carbon emissions, about one third of landfill waste and a quarter of all raw materials used in the economy. Reducing the environmental impact of the construction process to reduce energy demand, generation of greenhouse gasses and production of waste is increasingly important.

Many ground improvement methods are currently used for urban regeneration projects, the most common being Vibro Stone Columns. This technique, besides being normally less expensive, generates much less environment 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. The experience gained in these ground improvement projects highlight where further use of proven and emerging technology can provide still greater opportunity to reduce the environmental impact of deep foundation systems.

REDUCE, REUSE AND RECYCLE

The environment impact of any product or service can be minimised by application of the principles of Reduce, Reuse and Recycle.

Reduce

Reducing both the amount of raw and processed material in a product conserves natural resources, reduces energy demand and hence release of greenhouse gasses (GHGs). As will be shown below, by improving the ground, the need for piles can be avoided while utilising less raw material (stone aggregate) and processing energy (for example to make cement and steel). The main thrust of this paper is a discussion on reducing the CO_2 footprint (and hence an indicator of embodied energy) of deep foundation solutions by the use of ground improvement as an alternative to piling.

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. While re-use of piles is to be encouraged, as set out by Butcher et al (2006), today only a relatively few projects have been completed where 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 re-use. There have been a number of cases where previously vibro'd 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.

Recycle

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

THE ENVIRONMENTAL BENEFITS OF GROUND IMPROVEMENT

This paper reports a study that has been undertaken to compare the embodied CO_2 (ECO_2) 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 piled solutions. However, the sites were suitable for ground improvement and alternative proposals were developed. Usually the drivers for proposing ground improvement alternatives are cost and programme savings. However, as a result of embedding a carbon footprint calculator within its estimating process, Keller have discovered that very significant reductions in ECO_2 (typically of the order on 90%) are routinely achieved when ground improvement alternatives are adopted.

The concept of embodied CO_2 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. The embodied CO_2 is defined as the CO_2 that is emitted by burning fossil fuels during the manufacture and transport of a product as well as the CO_2 emitted through chemical processes, such as when manufacturing cement.

Embodied CO_2 is related to, but not synonymous with, other sustainability metrics, such as embodied energy and production of waste. However, since there is the specific government target (2008) to reduce the UK's CO_2 emissions by 80% on 1990 levels by 2050, consideration of the impact on the ECO_2 of different foundation solutions seems most appropriate.

The following methods of ground improvement and piling are considered within this study:-

- Vibro replacement stone columns (see Sonderman and Wehr (2004) for a full description of this method);
- 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);
- Continuous flight auger (CFA) and driven cast in situ (DCIS) piling.

EMBODIED CO_2 FOR PILING AND GROUND IMPROVEMENT SOLUTIONS

The embodied CO_2 for piling and ground improvement solutions for a range of different projects has been calculated and 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 of ground improvement was not possible on Project F and although substitution of ground improvement was undertaken for some of the piles, some piling remained. Nonetheless, as this was a large project, worthwhile reductions in ECO_2 are demonstrated.

METHODS FOR ASSESSING EMBODIED CO_2

All of the comparisons undertaken here follow the principles of PAS2050 'Specification for the assessment of the life cycle greenhouse gas emissions of goods and services (2008). Certain assumptions are necessary and the specification requires that these are stated to support the CO_2 assessment and to ensure transparency in the calculations.

The method adopted here assesses the life cycle GHG emissions on a Business-to-Business (B2B) basis. The embodied CO_2 of materials entering the process from the time they leave the factory gate (batching plant or quarry), plus the CO_2 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 ECO_2 of the foundation solution, as handed over by Keller to the project. It excludes additional construction steps (for example breaking down piles to form a pile cap) and potential removal, disposal or recycling during future demolition or re-development of the site.

The B2B approach is consistent with the 'cradle-to-gate' approach described in BS EN ISO 14040.

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 embodied CO_2 in production of steel and particularly concrete is much more complex than for the procurement of stone column aggregate. The ECO_2 for the constituent materials utilised in the calculations, as given in Table 2, will now be outlined.

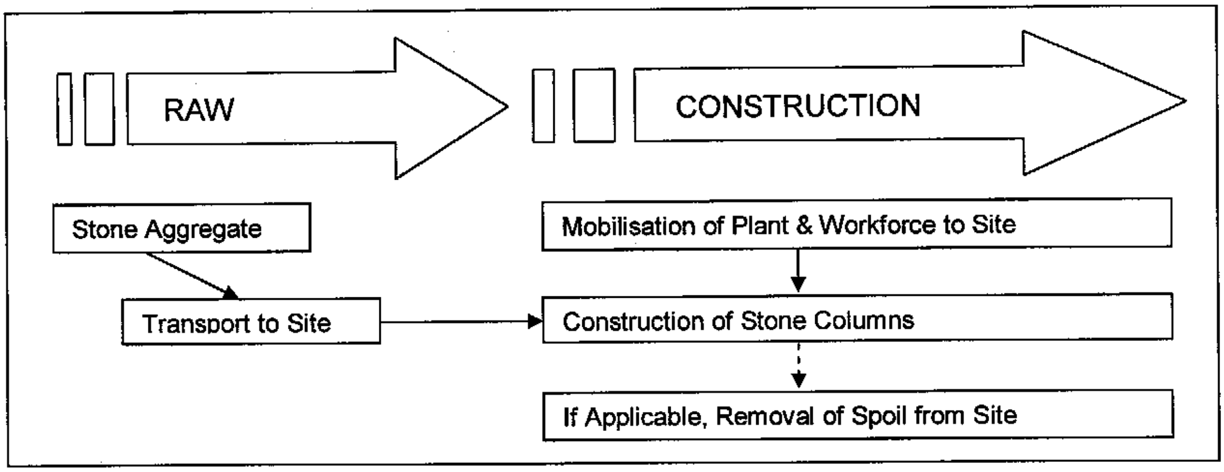

Figure 1 Process map for stone column construction

Concrete
The embodied CO_2 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 (for example for pumping).

The Concrete Centre web site gives a value of embodied CO_2 for a typical UK concrete of 225 $kgCO_2/m^3$ (300 kg/m^3 cementitious content, characteristic strength C28/35, water cement 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 water cement ratio of 0.45 (i.e. required where durability resistance up to a DC-2 mix is required, BRE 2005).

Stone Column Aggregate
Hammond & Jones (2008) suggest an ECO_2 of 5 $kgCO_2/t$. However the Environment Agency Carbon Calculator web site uses a value of 8 $kgCO_2/t$. This latter value has been adopted in the calculations supporting this study. The winning of virgin aggregate produces little CO_2 compared with the production of most other construction materials. For recycled aggregate a value of 3.69 $kgCO_2/t$ is adopted.

Due to the relatively low ECO_2 for the raw material the contribution to the overall ECO_2 from the transport of the stone for the source to the worksite can be significant in percentage terms. For the studies presented here the distance from the quarry gate to the work site was obtained from each supplier and the transport emissions calculated (assuming 20t loads carried in a rigid HGV emitting 4.4 gCO_2/km).

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 ECO_2 for the recycled steel is taken as 420 $kgCO_2/t$. It was assumed the steel was transported in 20t loads by rigid HGV emitting 4.4 gCO_2/km.

Site Plant Mobilisation
Emitted CO_2 due to mobilisation of construction plant to and from site was assessed based on the number of return vehicle journeys from the HQ depot to the work site. In all cases this proved a small percentage of total ECO_2 and is of little significance.

A similar estimate for workforce transport, based on a weekly commute to site and a daily allowance of 20km per person per day is also included but shows a similarly insignificant ECO_2 contribution.

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 ECO_2 per hour of operation on site for the different plant systems and combinations (for example top- feed and bottom-feed Vibro, CFA piling, etc). An ECO_2 of 2.63 $kgCO_2$/litre of diesel was applied in these calculations.

COMPARISON OF PROJECTS

Six projects were included in the study to assess whether the ECO_2 savings were dependent upon type of project, as well as the soils.

The projects A to F were for respective developments of:

- 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.

Projects A to E represent a typical range of small to medium sized piling projects. Project F represents a significant ground engineering project with a value in excess of £1,000,000.

For project B of fifty house units, thirteen were underlain in a defined area by 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 to the remaining thirty seven units.

Project F (located at Dartford Park next to the M25 Thames Crossing, 2008) comprised the main element of a 42,000m^2 distribution centre to house computerised high bay racking. Figure 2 shows a plan on the building. The site geology consists of a mantle of made ground consisting of silts and firm clays underlain by a sequence of both cohesive and granular alluvium above Taplow Gravel, which is underlain by the Upper Chalk.

The southern part of the site had been gravel extraction pits, later infilled by the deposition 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 6m in thickness and containing impersistent bands of peat up to 2.0m thick. However, the central part of the site was underlain by a thin (2m) mantle of competent granular made ground over a zone where neither gravel extraction had taken place and no 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 over the northern and southern sections 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 (Figure 3) to treat the upper granular fill and Taplow Gravel, with a stiffer transition zone comprising vibro replacement stone columns (Figure 4) dovetailing into the piled areas, was adopted for the slab.

This alternative combination of DCIS piles and ground improvement was designed to generate cost savings of about £1.5 million and faster construction programme compared to the fully conforming piled scheme. Furthermore assessment of the embodied CO_2 shows a saving of 1,960 tCO_2 (36%) was achieved.

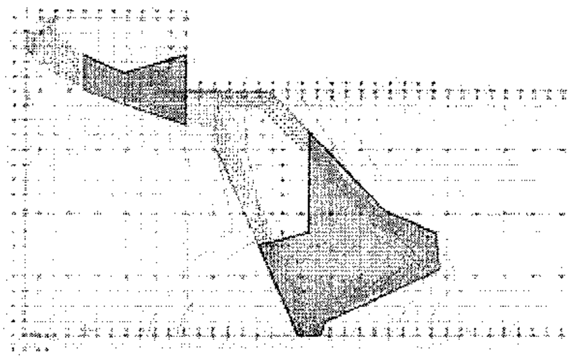

Figure 2 Plan on building showing extent of ground improvement for floor slab support

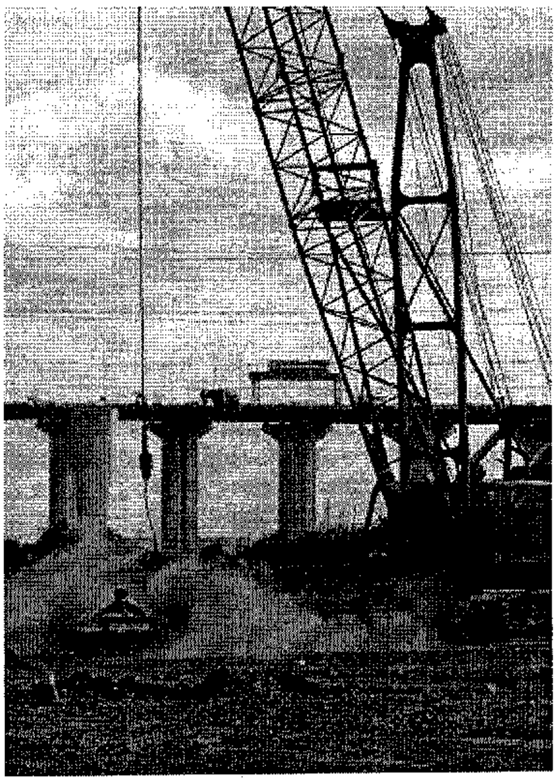

Figure 3 Dynamic Compaction at Dartford Park

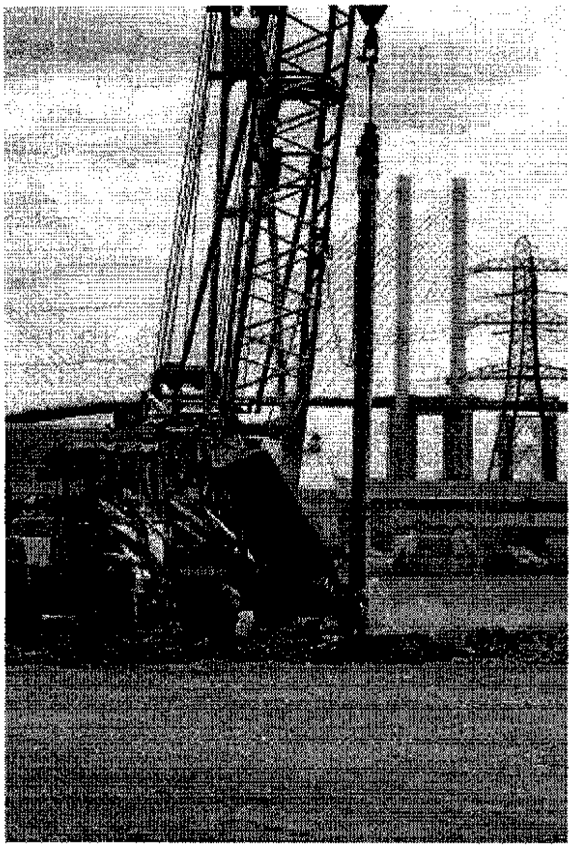

Figure 4 Vibro stone columns at Dartford Park

DISCUSSION

The key features of the reduction in ECO_2 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.

FEATURES OF TYPICAL CARBON FOOTPRINTS FOR THE DIFFERENT PRODUCTS

Figures 5 and 6 compare the breakdown of embodied CO_2 for the piling and vibro stone column solutions for Project C. The proportions of CO_2 attributed to the different constituents (concrete, reinforcing steel, fuel consumption of construction plant etc) are found to remain fairly constant for a given foundation solution across a range of different projects. As would be expected the total embodied CO_2 varies with the size of the project and the foundation solution adopted. The following features in Figures 5 and 6 are noted.

For the CFA piling option (Figure 5):-

- The total estimated embodied CO_2 for the conforming piling scheme is 235t;
- The concrete contains the most embodied CO_2, 67% of the total, (158 t from its manufacture but only 0.02t for transport to site);
- Reinforcing steel is the next biggest element, 65t (27%);
- The fuel consumption of the construction plant involved with on site construction generates 4.2% (9.8t) of the total embodied CO_2;
- Spoil disposal, to a tip 10km from the site, emits around 1.3% of the total CO_2 (3.1t) and is not very significant;
- Prelims and labour transport together comprise much less than 0.2% and can effectively be ignored.

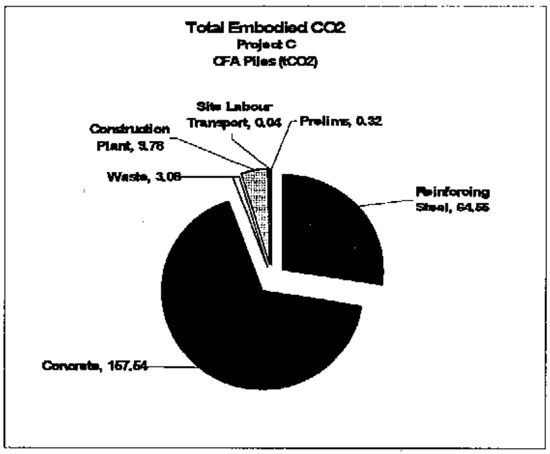

Figure 5 Embodied CO_2 for piling solution to Project C

For the vibro stone column solution (Figure 6):-

- The total estimated embodied CO_2 for the vibro stone column alternative is 13.8t (about 6% of that of the piling scheme);
- The biggest saving is due to concrete and reinforcing steel not being required (saving 223t of CO_2). In place of concrete and steel primary stone aggregate from a quarry located 50km from the work site was proposed, the production and transport of which accounts for 9.3t of CO_2. It should be noted that the haul distance in this particular case was unusually large, a typical distance being around 10km. Not withstanding this,

the stone aggregate contributes 67% of the embodied CO_2 for the vibro solution. This is found to be fairly typical for this type of project;

- The fuel consumption of site plant is the next biggest CO_2 contributor (4.3t or 31% of the total embodied CO_2). Because vibro stone columns can be installed faster and with lighter weight plant than CFA piles the fuel consumption is found to be around half of that for the piled solution in this case; proportionally site fuel makes a larger contribution to the ECO_2 than for piling schemes.
- As for the piling option prelims and site labour transport is a very small CO_2 contributor in absolute terms, and in any case less than 1.5% of the total.

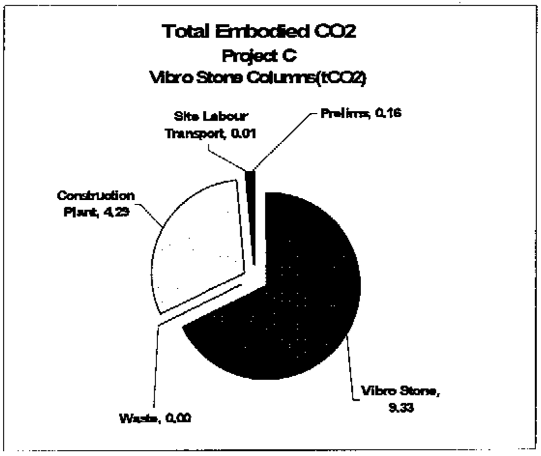

Figure 6 Embodied CO_2 for alternative VSC solution to Project C

The principle sources of the savings come from:-

- Avoiding the use of steel and concrete which have high ECO_2 in favour of stone aggregate which, as noted above, has a much lower ECO_2 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. This usually means that, on a like for like basis, stone columns, while more numerous than piles, are usually much shorter. Careful design and good quality control are prerequisites for successful implementation of such ground improvement solutions.
- Stone columns are usually installed more quickly and with smaller, 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 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 ECO_2.

OPPORTUNITIES AND BARRIERS TO THE USE OF VIBRO STONE COLUMN SOLUTIONS

There arise many opportunities to use lower carbon ground improvement alternatives as foundation solution, 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 CO_2 utopia.

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, (although this is often sadly lacking in quality and quantity, Egan, 2008);
- Light to moderate loading (typically bearing pressures up to 80 kPa in weak soils to 250kPa in compact soils are frequently achieved);
- Tolerance of a lower performance expectation in terms of total (and possibly differential) settlement compared to what would usually be expected from a piled solution;
- The willingness of the client and his design team to accept an alternative solution. Occasionally the design team may adopt an entrenched position in favour of a piled solution to protect their credibility.

Barriers

Barriers to the implementation of ground improvement, with some possible solutions, include:-

- Unsuitable ground conditions, which if truly the case can rule out ground improvement;
- Poor ground investigation preventing adequate analysis of the ground properties,

such that the suitability of a vibro stone column solution cannot be demonstrated. Many vibro schemes have been shelved because of the difficulty in demonstrating adequacy due to lack of 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 high loads are truly to be applied then ground improvement may have to be ruled out. More frequently there is a lack of understanding by structural engineers of the mechanisms governing behaviour of ground improvement. Frequently there is an entrenched over conservatism within the wider design team when it comes to specifying the building loads. It is suggested 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. This is considered in detail below.
- Specification of unrealistic settlement performance requirements. 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 report settlement of a number of mainly brick buildings of different sizes in the range of 8mm to 237mm at an ICI facility in Grangemenouth. The data were recorded over several decades and there were no indications of distress or servicability problems associated with the buildings. Lack of knowledge or 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 10mm at working load is common while between 15mm and 30mm is a common, and perfectly adequate, range in vibro stone column specifications;
- Certain institutions, particularly those who provide insurance in addition to the warranties provided by the specialist ground improvement contractor, appear to have developed a view that sites with foundation problems require piled support.
- 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 may require better planning and earlier consideration of ground improvement for a potential foundation solution;

<u>The Importance of Representative Foundation Loads</u>

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 cohesive soils. 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 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 etc) 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 50kPa) acting over the whole plan area of the warehouse (which could easily be of the order of 20,000m^2 to 40,000m^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 is unrealistic. It is common in these situations to take a time averaged load of say between 50% and 70% of the institutional load for the estimation of settlement.

OPTIMISING THE USE OF GROUND IMPROVEMENT IN THE FUTURE

To encourage greater opportunity for the reduction of embodied CO_2 in foundations it is suggested that the following issues need promoting:-

- Publicise the use of ground improvement as a technically acceptable alternative to piling which has significant environmental benefits;
- Emphasise the need for careful specialist design input early in the design process (before a less environmentally friendly solution becomes a fixed part of the project);
- Educate client technical advisors who have an influence early in the life of a project about the benefits of ground improvement and how to go about investigating its viability by specifying realistic loads and settlement performance;
- Continue to emphasise the crucial importance of adequate geotechnical ground investigation (the scope of which is often drastically reduced in favour of shallow environmental investigation).

CONCLUSIONS

The contribution of green house gasses to climate change appears now to be beyond reasonable doubt. The target to reduce CO_2 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 embodied CO_2 when the two approaches are compared on a like for like basis on the same project.

Not all projects will be suitable for the implementation of ground improvement due to reasons such as:-

- Unsuitable ground conditions;
- High foundation loads;
- Unusually stringent settlement tolerances.

However of the many sites that are suitable for the use of ground improvement its use is often inhibited. Some barriers to the wider use of ground improvement and particularly vibro stone columns include:-

- Poor ground investigation preventing demonstration of suitability for ground improvement;
- Institutional requirements for unrealistically high loading requirements and tight settlement criteria;
- Overly cautious restrictions put on the use of vibro stone columns by the providers of insurance backed warranties;
- Insufficient understanding at an early stage in a project of the advantages that ground improvement may provide.

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 CO_2 benefits along with cost and time saving advantages.

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			Embodied CO_2		
Project	**Conforming Piling Scheme Scope**	**Alternative Ground Improvement Scope**	**Conforming Piling Scheme** (tCO_2)	**Alternative Ground Improvement Scheme** (tCO_2)	**Percentage Saving in CO_2**
A	544No. 600mm CFA piles 6m long	1280No. Minicat VSC 3.34m long	275.66	20.7	**92.5%**
B	263No. 340mm DCIS piles 5.8m long	324No. Minicat VSC 2.18m long	44.89	3.43	**92.4%**
C	395No. 350mm CFA piles14.2m long	834No. Minicat VSC 3.78m long	235.31	13.79	**94.1%**
D	72No. 400mm CFA piles 20m long	300No. Minicat VSC 3.0m long	60.08	4.15	**93.1%**
E	340No. 340mm DCIS piles 7m long	425No. Minicat VSC 1.2m long	76.76	2.96	**96.1%**
F[(a)]	8,301No. DCIS & VCC piles up to 14.5m long	5,747No. DCIS piles up to 14.5m long + 1,356 Top feed VSC 4.9m long + 4,940m^2 DC	5,387.58	3,427.96	**36.4%**

Table 1 Summary of embodied CO_2

Note (a) Project F at Dartford Park was not 100% replacement of piles with ground improvement.

Material	**Embodied CO_2**	**Notes**
Concrete (cement content 300kg/m^3) Concrete (cement content 340kg/m^3)	225 kg/m^3 255 kg/m^3	Based on data for UK average concrete from The Concrete Centre
Reinforcing Steel	420 kg/t	Based on recycled steel values
Quarried stone aggregate	8.00 kg/t	EA Carbon Calculator
Recycled stone aggregate	3.69 kg/t	
Fuel	2.63 kg/l	
ICE – Aggregate – Virgin	5.0 kg/t	Hammond & Jones

Table 2 Summary of embodied CO_2 for construction material