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Ground Improvement Technologies for a Sustainable World

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ABSTRACT: In an effort to assess the carbon footprint for a range of geotechnical construction methods, several case studies were selected where a conventional deep foundation technique was compared to a ground improvement alternative. The case studies are: improvement of an uncontrolled fill using Dynamic Compaction versus excavation, replacement and compaction in-place; installation of a driven pile foundation under a structural slab compared to the use of Controlled Modulus Columns under a slab-on-grade for a residential townhouse development; and the installation of a cement bentonite cut-off wall compared to a Soil-Bentonite wall.

Each technology's carbon footprint was analyzed using recognized carbon emissions calculation tools and values both for direct and indirect emissions. The authors have found that, in all cases, ground improvement technologies were not only more cost effective but also did significantly reduce the carbon footprint during the project construction phase; in two applications the reduction of carbon footprint was the result of the use of more 'carbon-efficient' construction materials, such as slag/flyash mixes or even recycled materials from site; in the remaining case, engineering the exisiting fill by Dynamic Compaction simply proved to be a much better use of resources.

INTRODUCTION

Evaluation of the carbon footprint of a given work activity is one of the first steps towards the reduction of greenhouse gas (GHG) emissions. Within the construction industry, one of the primary GHG contributors is the cement manufacturing sector, which alone accounts for about 3-4% of global man-made CO2 emissions through calcining of limestone. The transportation of material to and from borrow pits, fabrication plants and storage facilities, as well as the fuel consumption of the on-site equipment, are other causes of large GHG emissions by the construction sector.

General strategies are starting to be developed at government levels through tax breaks and rewards for energy-efficient processes. Other private / public initiatives, such as the development of Life Cycle Assessment tools designed to measure the environmental performance of buildings, contribute to promote the use of construction technologies with reduced carbon footprint including through the utilization of more ‘carbon’ efficient materials (slag/flyash mixes instead of concrete for example).

This paper will compare the carbon footprints of three ground improvement technologies with traditional foundation methods in the light of recent case histories.

CASE HISTORY #1: Industrial / Office Building in Pittsburgh, PA

This project was developed on a fill site located in the northern part of Pittsburgh, PA along Interstate 279. A two-story building and satellite dish farm totaling about 4,000 m^2 were proposed to be built. The building is constructed with a brick and masonry façade supported by interior and exterior columns. The southern half of the building is constructed with a mezzanine. Maximum column loads range from about 200 to 900 kN. The building is constructed using a slab-on-grade and spread footings approach.

The proposed building site is covered with a man-made fill material that varies in thickness from zero at the western side to a maximum of about 15 m at the eastern side. The fill material is very heterogeneous both in composition and in-situ densities. It ranges from fine-grained silts with boulders and rock fragments to coarse-grained sands and gravels in a matrix of silty sands. Based on the standard penetration resistance values (SPT-N), the fill exhibits medium dense to dense characteristics. However, it has been recognized that some of the higher blow counts may be attributed to the sampler hitting boulder size obstructions and not being representative of the soil matrix compactness. Accordingly, the fill has the potential for experiencing large differential settlements with time and was deemed not suitable as a foundation material for a slab-on-grade and footings structure. The initial design proposed to excavate 3 m of existing fill material across the building footprint and replace it with engineered fill placed and compacted in lifts with a roller. An alternate was proposed using Dynamic Compaction (DC) across the building footprint using a 15 t weight dropped from 25 m height. This solution, more economical than the initial design, was selected by the general contractor and approved by the Engineer.

The basic principle behind DC is that high-energy shockwaves are transmitted to the soil in order to improve its characteristics. Essentially, the soil is densified by the repetition of impacts of a pounder (10 to 40 t) dropped from heavy lifting cranes (10 to 40 m) in a pre-designed grid pattern. The impact of a falling weight results in immediate densification of granular soils through the generation of high energy waves. This energy is transmitted to the soil by applying several blows for each impact location and with several phases of a variable impact grid. DC can be applied on granular soils (sand, rock, mountain fill, etc…) but is also efficient for the rehabilitation of landfills, for road construction, industrial complexes or recreational landscaping.

For the calculation of the carbon footprint of the initial solution, it was assumed that a total of 12,000 m^3, corresponding to 4,000 m^2 of 3 m high fill material, would need to be excavated and replaced by granular material and compacted in place using a roller. A swell factor of 1.2 was calculated to evaluate the volume of material that will be hauled away and brought on site. Based on discussions with the general contractor, it was assumed that 100% of the fill material would have to be transported to a disposal location situated 35 km from the jobsite. The borrow pit location was assumed to be 22 km from the jobsite. All emissions related to the following activities were calculated using values published in ADEME (2007), as well as fuel consumption data from a leading equipment manufacturer found in Caterpillar (2007):

- excavation and loading of the 10 t dump trucks using 2 - 35 tons excavators
- disposal by dump trucks of all the fill material
- spreading of fill material at disposal facility
- processing and loading of granular material at borrow pit
- transport of granular material by dump trucks to the jobsite
- unloading and placement of granular fill by D6 type bulldozers
- re-compaction of granular fill using several passes of vibratory roller.

In summary, for the initial design, the above calculations showed that a total of 218,000 l of diesel fuel would have been necessary to perform the work, with a total duration of roughly 30 days.

The carbon footprint of the alternative ground improvement solution using DC was calculated based on actual production data, as the jobsite is now completed. A 15 t weight dropped from 25 m was used for the production passes and a 15 t ironing weight dropped from 17 m for the ironing pass; the compactive effort resulted in 0.85 drops/m^2 for a total 3,468 drops. The job was performed in 8 days with an average of 425 drops per day. The on-site equipment included a crawler crane type Bucyrus Erie BE71 and a D6-type bulldozer to backfill the craters after each pass of Dynamic Compaction.

As a result of the fill densification process by DC, an overall volumetric reduction of the fill material occurs (0.3 m on this site). The fuel usage corresponding to the quarrying, transport and compaction of the quantity of import fill needed to restore the working platform to its initial level was also included.

In total 15,000 l of diesel fuel were used for the DC alternative, translating into a total savings of approximately 200,000 l of diesel fuel compared to the initial design. Overall, the foundation works helped reduce the overall carbon footprint of the building by 160 t eq. C, representing the offset for emission of carbon of 28 persons for a year based on a per capita carbon emission of 5.6 t eq. C as given in Blasing et al. (2004) and World Bank (2004)

CASE HISTORY #2: Luxury Townhouse / Condominiums in Weehawken, NJ

The second case study to be presented considers a luxury townhouse and condominium subdivision along the banks of the Hudson River in Weehawken, New Jersey. The project called for the construction of 68 individual 3-story units located on a reclaimed railroad yard overlooking the financial district of Manhattan. The as-built foundation system featured Controlled Modulus Columns (CMC) as the sole foundation and slab support means.

This technology is a proprietary ground improvement system in which CMCs are used as an alternative to traditional deep foundations. CMCs are semi-rigid inclusions that are made of a specially designed cementitious grout mix, installed using a displacement tool that generates only a minimal amount of spoil. The CMCs reinforce the soil rather than function as distinct structural elements or piles, resulting in an improved soil matrix having increased stiffness with improved settlement and bearing characteristics. As a result, the entire foundation design plan can be optimized for a substantial reduction of concrete and steel since large pile caps, grade beams, and heavy steel reinforcement are no longer needed to support the building loads. Consequently, the emissions reductions associated with CMC technology (from both direct material costs and production-related operational costs) have an immediate impact on the total carbon output of the foundation system and, in turn, of the project.

For the current investigation, site soil conditions included a stiff upper layer of urban fill underlain by up to 23 m of highly compressible organic silts and clays. A suitable bearing stratum of dense sand and glacial till was found at an average depth of 23 m, with sandstone bedrock appearing between 13 and 39 m below grade.

Due to the thickness of the compressible organics, deep driven piles were recommended as the most feasible foundation support method, with an average target depth of 33 m. The alternate proposal relied on CMCs installed to an average depth of 23 m, which would bridge the compressible soils and terminate in the sand and till strata. The sustainability analysis was based on the comparative carbon emissions of the recommended deep foundation scheme of driven H-piles with a structural slab versus the as-built ground improvement system consisting of CMCs supporting a slab-on-grade.

A detailed quantity takeoff was done using the bid package, where it was determined that a total of 164 t of rebar, 6725 t of HP14x73 piles and 4358 m^3 of concrete would have been required for the original foundation plan. These values included concrete from slabs, pile caps and grade beams; steel quantities were derived from the piling and any required concrete reinforcement. Then, the direct carbon emissions associated with the deep foundation method were calculated using accepted constants and conversion factors for these building materials. This resulted in a total output of 3697 t eq. C for the driven H-pile support system.

Using the same procedure, the CMC-supported slab was analyzed, considering the grout from the CMCs and the concrete for the slab as the CO2 sources (steel was not required with this design). It was found that 7908 m^3 of grout and 4925 m^3 of concrete were required. With CMCs, it was found that the ground improvement system had a total emission of 1857 t eq. C, half of that of the deep foundations.

In order to put this number into perspective, it was assumed that the completed townhouses would have a total operating capacity of 136 residents. Adopting the same per capita carbon emission as previously, the total annual carbon footprint of the community was calculated to be 731 t eq. C. Using these results it was found that the carbon savings directly attributable to CMC technology was able to offset the environmental impact of all 136 residents for two and a half years.

Table 1. Comparative Emissions in t eq. C

	STEEL[1]	CONCRETE[2]	GROUT[2]	TOTAL
H-Pile System	3256.0	440.6	0.0	3696.6
CMC System	0.0	498.0	1358.9	1856.9
CMC Savings				**1839.7**

[1] – Rawlins et al. (2007).
[2] – Wilson (1993).

CASE HISTORY #3: Soil-Bentonite Slurry Cut Off Wall in Australia

The strategy selected by the Regional Land Management Corporation (representing the New South Wales government) for the remediation of a former steelworks facility, located at Mayfield in NSW, was to confine the contaminated area using an up-gradient groundwater barrier associated with a low permeability clay cap on a 37 hectare site; the cut-off wall, 800 mm wide, represented 50,000 m^2 and impacted the riverfront over a length of 900 m.

One advantage of that scheme was that no collection system was needed; instead, the hydrogeological model showed that the rapid exhaustion of the aquifer gradient between the contaminated area reservoir and the Hunter River would significantly reduce the migration of contaminants and bring them to acceptable levels within a short period. A more detailed description of the project is given in Jones et al. (2007).

The two alternative methods selected at tender time were Cement Bentonite (CB) and Soil Bentonite (SB) barriers. The SB option was finally selected on the basis of a range of parameters, which did not include carbon emission. An analysis of the equivalent carbon emissions for each scheme however, as summarized in Tables 1 and 2, shows that the difference in carbon footprint for each method is quite significant.

For the SB wall, the level of emissions of greenhouse gases related to the consumption of energy by the machinery was taken directly from the actual site fuel consumptions. The incorporated raw materials consisted of natural dry bentonite imported from India as well as a quantity of local ‘Virgin Excavated Natural Material’ clay used to increase the fines content in the SB mix; native materials dug from the trench were predominantly re-used in the wall backfill (approximately to a rate of 75%) ; the remainder of the excavated material, including material with some level of contamination, was permanently stockpiled on site in a series of buried containment areas.

For the CB option, the use of cement was the main carbon contributing factor, resulting in a significantly higher level of carbon emissions compared to SB.

Table 2. Carbon Emissions for a SB Wall (in t eq. C)

Soil Bentonite		Carbon print		Quantity	Unit	teqC
Energy	diesel during construction	4.2	kg eq C/m^2	50,000	m^2	209
Material	bentonite extraction & transport	8.0	kg eq C/t	2,500	tons	20
	clay extraction & transport	1.5	kg eq C/t	29,000	tons	45
Labour	staff and labour (21)	6	t eq C/year	12.25	pers.yr	74
Total Carbon Emissions in t eq. C						**348**

Table 3. Carbon Emissions for a CB Wall (in t eq. C)

Cement Bentonite		Carbon print		Quantity	Unit	teqC
Energy	diesel during construction	2.9	kg eq C/m^2	50,000	m^2	147
Material	Cement	235	kg eq C/t	8,350	tons	1,962
	Bentonite extraction & transport	8.0	kg eq C/t	2,500	tons	20
Labour	staff and labour (21)	6	t eq C/yr	12.25	pers.yr	74
Total Carbon Emissions in t eq. C						**2,203**

CONCLUSIONS

Through the comparative study of three case studies, this paper has shown that various acceptable geotechnical solutions for improving subsoil conditions can directly mitigate unfavorable environmental impacts. As shown in Table 4, estimates of carbon emissions resulting from selected site construction activities could vary in a ratio of over 10 to 1 depending on which option was selected. An example was given by comparing the fuel consumed during the construction of engineered foundation soils, in one case using the excavation and backfill approach (45 kg eq. C / m^2) and in the other relying on a ground improvement alternative using dynamic compaction (5 kg eq. C / m^2).

Table 4. Comparison of Carbon Emissions for Three Case Histories (in t eq. C)

Case History	Reduction Using Ground Improvement Alternative	Ratio of Carbon Emissions Traditional Technology / Ground Improvement
Industrial / Office Building – PA	160 t eq. C	1,450 %
Townhouses / Condominium – NJ	1840 t eq. C	200%
Soil Bentonite Slurry Cut-off Wall - NSW	1,855 t eq. C	630%

In addition, the materials used for the foundations can be one of the most important factors in determining the carbon footprint of a foundation system. In the last example, it was estimated that replacing the soil bentonite wall with a cement bentonite wall would have multiplied the carbon emissions by a factor of 7. The second case history, which compared a suspended slab supported on piles to a slab-on-grade built on Controlled Modulus Columns (using a flyash based mix), showed that the use of steel piles and a thicker concrete slab would have resulted in twice the carbon emissions as the selected method.

Overall, as demand for new construction continues to increase worldwide, so does the need for developing sustainable means and methods through which projects can be delivered while keeping adverse environmental impacts to a minimum. This creates a somewhat paradoxical situation when one considers that many of the current material production and construction implementation practices are inherently very energy intensive, releasing significant quantities of greenhouse gases into the atmosphere each year. As discussions on rising emissions levels have recently come to the forefront in political, social, and economic arenas, so too has the push towards a more environmentally conscious construction industry. To this end, it follows that any advance in technology or technique that promotes the reduction of GHG emissions would be at once both interesting and beneficial to the construction community at large, as more engineers, designers, and contractors re-evaluate their approach to sustainable building practices. The preceding analyses presented three such cases whereby the selection of an alternate ground improvement system resulted in significant emissions reductions for the project; this should serve as an indication that with the proper consideration and construction technique selection, progress towards a long-term sustainability goal can be achieved without compromising schedule, budget, or quality.

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