EFFECTIVE WAYS TO REDUCE CARBON FOOTPRINT IN A DEEP SOIL MIXING SOLUTION – A CASE STUDY FROM A HIGH-RISE PROJECT FOUNDATION IN SINGAPORE

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ABSTRACT

Construction projects directly impact economies' social, economic and environmental progress. The carbon footprint of construction projects could be reduced in their various phases – conceptual, design and construction. This paper talks about ways to reduce the carbon footprint of projects during the construction phase using the case study of the development of an 11-storey high-rise building with two basements. The earth retaining and stabilizing structure (ERSS) used diaphragm walls as a retention system with a top-down construction method to facilitate basement construction. A soil improvement block, using two techniques, deep soil mixing (DSM) and Jet Grouting (JG), is constructed below the final excavation level to provide lateral support and stiffness to the retention system. The original design uses CEM I Ordinary Portland Cement (OPC) to produce cement grout in DSM and JG works. To lower the carbon footprint of the solution, the project team followed the carbon hierarchy. A low-carbon replacement for cement, namely ground granulated blast furnace slag (GGBS), is adopted as an alternative. An alternative cement CEM III/A, with 60-65% of OPC replaced with GGBS, is used while complying with the original engineering requirement - unconfined compressive strength (UCS) and stiffness modulus (E) of the DSM columns. In addition, a larger diameter DSM mixing tool is deployed, reducing the resources needed compared with the original smaller diameter. As a result, overall project carbon emissions are reduced by 7% compared to budget carbon emissions. This paper discusses the details of carbon emissions savings and operation aspects that helped achieve carbon reduction.

Keywords: deep soil mixing, jet grouting, excavation, carbon emissions, cement-replacement, carbon reduction.

BACKGROUND

Under the Land Use Plan 2030, the Singapore Ministry of National Development has allocated and safeguarded Singapore's surface land space for several uses – industrial, infrastructure and utilities. To meet the growing needs of the urban environment, some of these uses could be moved below ground (Urban Redevelopment Authority 2018). Hence, to preserve the precious land space in Singapore, vertical development (above and below ground) consisting of high-rise buildings with multi-level basements is often adopted. With the global construction industry being the leading contributor of carbon emissions, such high-rise developments with a complex construction sequence may involve a significant carbon footprint. The 2022 Global Status Report for Buildings and Construction, UNEP highlights that the carbon emissions from the global building operations and construction sector hit an all-time high of 10 $GtCO_2e$, which is a 5% increase from 2020 and 2% from 2019 levels. The building and construction sector accounts for 40% of annual carbon emissions (International Energy Agency, 2022). Studies have shown that a variety of factors slow down the move towards a carbon neutral construction industry. A study conducted in Singapore and Hong Kong found that lack of awareness, education, incentives and high initial costs are the obstacles to such a move (Chan et al. 2009). There are several studies focused on carbon emission reductions at various phases in the construction project (Sizirici et al., 2021). This paper describes the carbon reduction measures successfully implemented during the construction phase for the foundation of an 11-storey high-rise building in Singapore.

PROJECT SOIL CONDITIONS

The project site for this development is in the eastern part of Singapore. An 11-storey commercial building is being constructed with two levels of basement. The soil condition at this site consists of a 3m thick fill layer, underlain by a 10m thick very-soft marine clay layer with SPT N ≤ 2. This is further underlain by residual soils consisting of 6m thick loose – medium dense silty sands of Old Alluvium with SPT N = 5 – 13. This is further underlain by very dense to dense silty sands of Old Alluvium with SPT N = 37 – 82 with thickness of 8m. The marine clay layer, which belongs to the Kallang Formation with low SPT N values and undrained shear strength less than 25 kPa, is the main soil layer of concern if not treated prior to underground construction works. Hence, the adopted geotechnical solution must satisfy the overall stability of the earth retaining and stabilising structure (ERSS).

GEOTECHNICAL SOLUTION

In this project, the ERSS system used diaphragm walls as a retaining system and adopted top-down construction. The soil condition and structural scheme of the basement system is shown in Fig.1. Based on the design, the final excavation level is in the very-soft marine clay layer as shown in Fig.1.

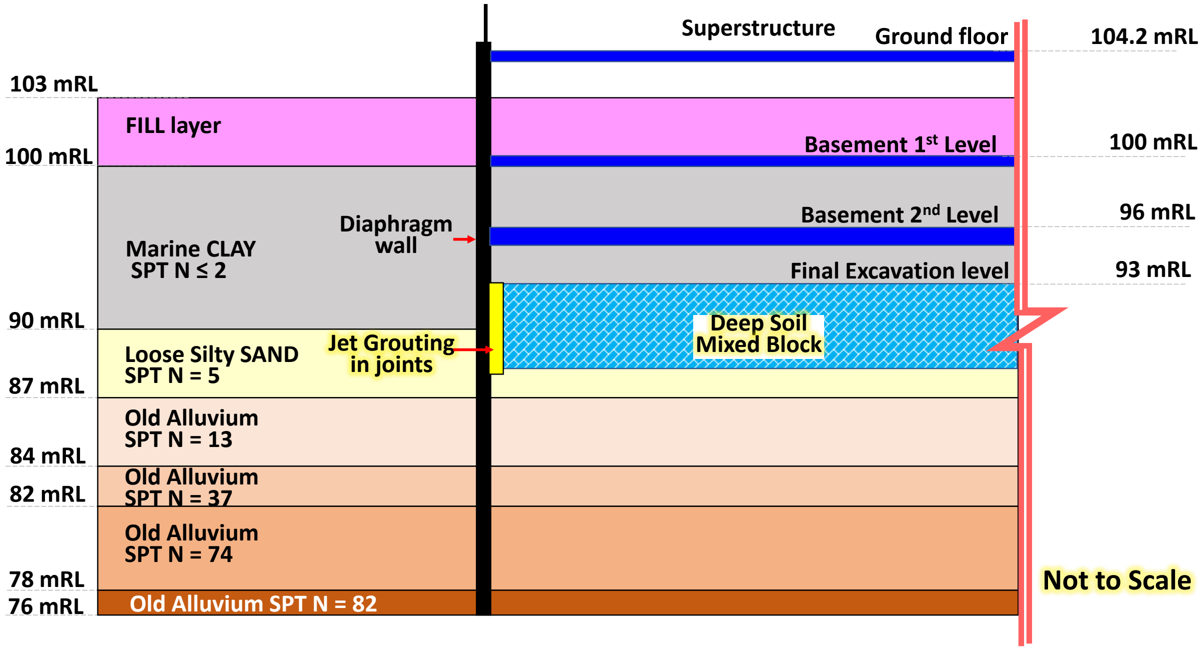

Fig. 1. Soil conditions, structural system, and soil improvement block (DSM + JG)

The top-down construction sequence of the basements is shown in Fig. 2. At first, the diaphragm walls are installed by others to form the boundary of the ERSS system. As lateral support to the ERSS system, a soil improvement block of 5.5m thick is required at the final excavation level. To construct this soil improvement block, DSM columns are installed within the boundary of the diaphragm walls, followed by jet grouting (JG) at the corners to seal the gaps between diaphragm walls and DSM columns. The upcoming sections of the paper give details on the soil improvement works focusing on the construction and control of carbon emissions.

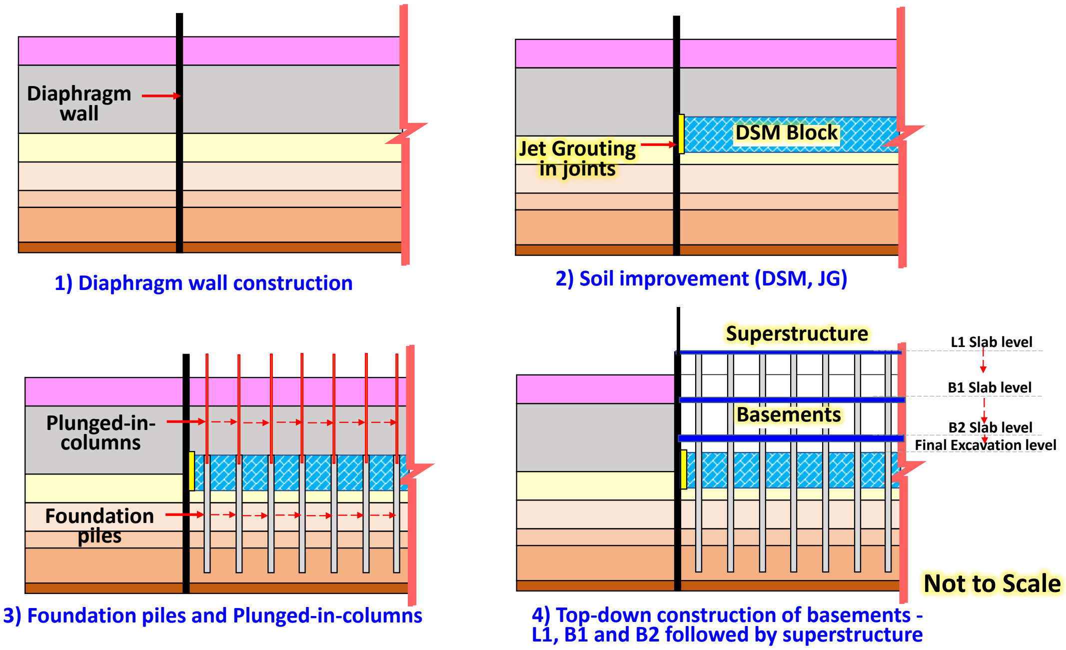

Fig. 2. Schematic of construction sequence

SOIL IMPROVEMENT BY DEEP SOIL MIXING AND JET GROUTING

The soil improvement block is formed by installing the DSM columns first followed by JG works to seal the gap between the DSM columns and diaphragm walls. DSM columns are installed using multi-purpose rotary drilling rig with 330 kN of pull / push crowd force and equipped with 273 kNm torque rotary drive. Such high-capacity rigs can install DSM columns as large as 2.2m in diameter. As part of the data acquisition system, a real time monitoring device is installed in operator's cabin to allow for real time control of DSM installation. A photo of the DSM rig and schematic of DSM process is shown in Fig. 3. First, drilling is carried out using water, assisted by air for preconditioning of the soil into a mixable state. This is followed by mixing of grout uniformly in the soil using mixing blades. In JG works, after drilling to the design depth, soil is preconditioned using high pressure water injection, followed by high pressure grout jetting to create uniform mixing of grout and soil within the treatment zone. A photo of the JG rig and a description of the process is shown in Fig. 4. Upon completion of DSM and JG works, installation records are transmitted to an online database via wireless network for easy access. Upon completion of DSM and JG works, coring is carried out after 28 days to obtain samples for verification of engineering requirements such as compressive strength and stiffness modulus. A photo of a typical cored sample is shown in Fig. 5.

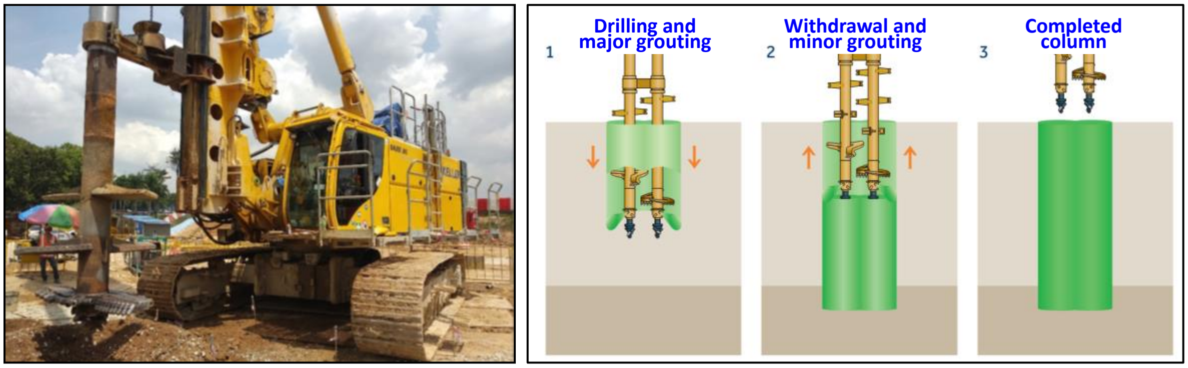

Fig. 3. Deep Soil Mixing rig photo (left); Process Description (right)

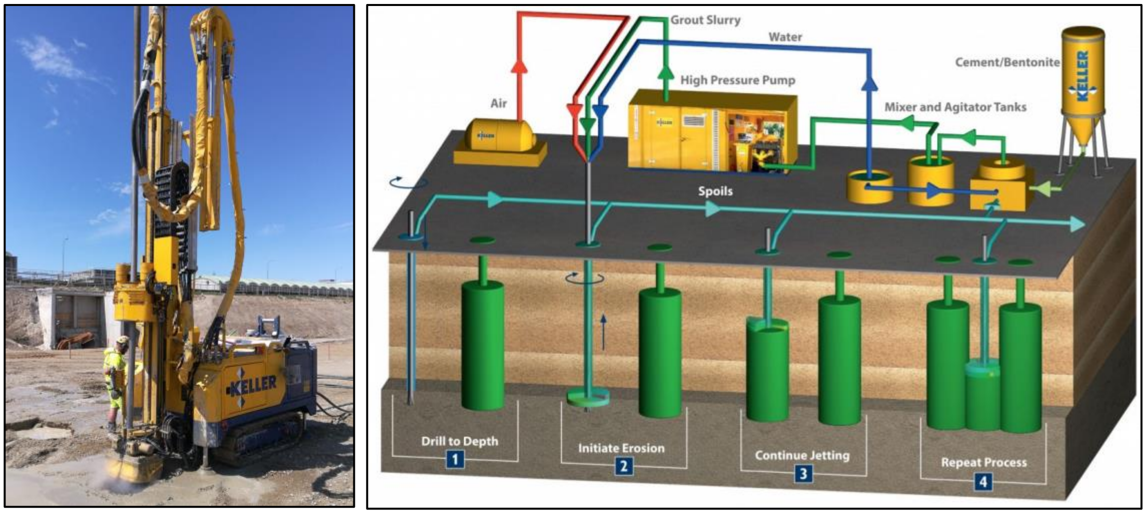

Fig. 4. Jet Grouting rig photo (left); Process Description (right)

Fig. 5. Cored sample photo

In this project, instead of the initially proposed 1.8m diameter columns for DSM works, a 2.2m diameter DSM mixing tool is adopted. To identify the optimal cement content, trial DSM columns are installed with cement contents ranging from 185 to 230 kg/m^3. Based on the Unconfined Compressive Strength (UCS) test results from trial columns, a cement content of 200kg/m^3 is found to be optimum. The project required foundation bored piles to be installed by others after DSM works. In addition, due to the nature of the drilling process, the ground is disturbed during the drilling process of DSM installation which necessitates additional treatment of the ground surface to create a safe and stable working platform for the follow-on activities. Upon completion of DSM works, the drilling tool is retrieved near to the ground surface and a 2m thick working platform is formed by DSM with an optimized cement content of 100kg/m^3 determined by field trial. On similar lines, trials are carried out for JG works with various combinations of cement content to determine the optimum dosage.

As both DSM and JG works involve drilling the soil with water and mixing with grout, there is spoil generation caused by backflow of materials during the installation. The management of spoil (transport out of site and its management thereon) involves carbon emissions. To minimise spoil generation, soil properties are examined, and field trials are carried out to determine the optimum installation parameters. To identify opportunities for minimising spoil generation, the parameters are reviewed whenever the drilling rig moved to a new location or when variation in ground condition is observed.

QUANTIFYING CARBON EMISSIONS

A holistic carbon footprint calculation for a project, often called the “cradle-to-gate” approach, calculates carbon emissions from the materials and from extracting, transporting, consuming and disposing them to recycling plants. To estimate the carbon emissions of this lifecycle, the concept of embodied CO_2 is helpful as it indicates the amount of Green House Gases (GHG) emitted by not just the materials used but also the activities associated with the project (Slocombe and Egan 2010). Carbon dioxide equivalent, represented as CO_2e, is a standard unit for measuring the overall carbon footprint. The European Federation of Foundation Contractors (EFFC) and Deep Foundations Institute (DFI) proposed a sector-specific carbon accounting methodology. They rolled out a “carbon calculator” for foundations and geotechnical works intended to be an internationally adopted tool for ground engineering works. In 2011, a working group comprising geotechnical contractors, funded by EFFC and DFI, tailored a methodology with a Microsoft® Excel-based carbon calculator to help engineers and planners calculate the carbon footprint of a construction project. The detailed procedure to calculate the CO_2e is described in the EFFC-DFI Carbon Calculator Methodological & User Guide version 2.2.

Carbon hierarchy and its implementation in the project

The EFFC Sustainability Working Group (SWG) compiled good practices for geotechnical companies to plan their carbon reduction journey. The hierarchy is summarised in Fig. 6. Broadly, it is based on guidelines from the Institute for Environmental Management & Assessment (IEMA, 2020).

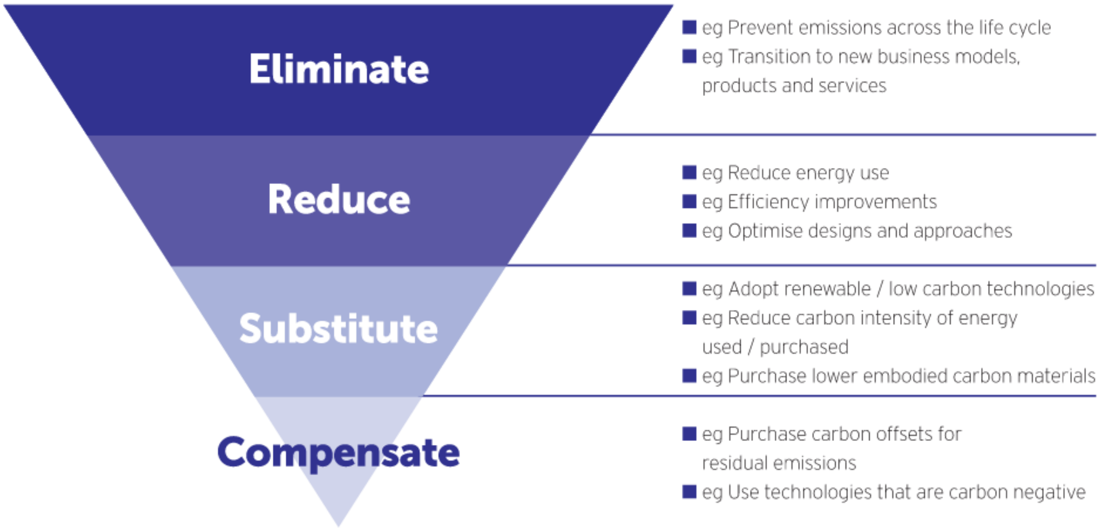

Fig. 6. Carbon reduction hierarchy (IEMA, 2020) extracted from EFFC Sustainability Guide for Foundation Contractors: Guide No. 1 Carbon reduction (First Edition 2022)

Different stages in the project, such as execution and maintenance, provide opportunities to implement the carbon hierarchy steps such as ***"Reduce"*** and ***"Substitute"*** to minimise carbon emissions. For instance, in this project, the type of cement used in DSM and JG works is a major contributor to carbon emissions. Eco-friendly types of cement, such as those with suitable constituents that can partly or in a majority proportion replace conventional cement while ensuring the same engineering performance, will be a good example of ***"Substitute."*** In addition, during the execution of soil improvement works, any process improvements such as adopting efficient construction methods to reduce time and increase productivity, reducing fuel usage, and reducing people's transportation can classify as ***"Reduce."*** The various ways that helped achieve carbon reduction in the project are elaborated on in the subsequent sections.

CARBON MANAGEMENT FOR THE PROJECT

Carbon management is about taking steps to measure and manage greenhouse gas (GHG) emissions within the organisation and extend the reduction of emissions across the supply chain (Paia Consulting Singapore 2020). In this project, this concept is applied uniquely. A typical project management process involves monitoring safety, quality, costs and progress. In addition to these four facets of project management, a fifth facet, namely carbon emissions, is added to the project lifecycle management.

Typically, a Project Manager prepares a budget cost calculation at the start and strives to complete the project within the budget cost. This project applies the same concept for carbon emissions monitoring to measure, monitor and manage carbon emissions. Before mobilising to the project site, a carbon budget is prepared using the EFFC-DFI carbon calculator v5.0. Then during the execution, monthly information—such as the resources used, quantities of DSM and JG installed—are collected. Using the data thus collected, a monthly carbon emissions calculation is prepared and compared with the budget as the project progresses. The target is to finish the project with a carbon emission within or less than the budget. This way, the carbon emissions are treated as important as the other essential aspects of project management.

At the start of the project, the potential carbon emissions estimated using the EFFC-DFI calculator is about 10,500 tCO_2e, as shown in Fig. 7. The top sources of carbon emissions are cement, energy (diesel for the rigs and other equipment), and transport of wastes from site to other places numbered as 1, 2 and 3 in the Fig. 7 legend. The carbon emissions from cement consumption are about 9,350 tCO_2e which is 89% of the total carbon emissions in this budget calculation. The initial plan for the project consisted of using Ordinary Portland Cement (OPC), also called CEM I. The carbon emissions from cement could be reduced by exploring several types of cement that use low-carbon alternatives. For example, a kind of cement known as CEM III/A imparts emissions of 363 $kgCO_2e$ per tonne. This is 60% less carbon-emitting than CEM I, with 913 $kgCO_2e$ per tonne of cement. This CEM III/A has typically 36-65% of cement content replaced with by-products from blast furnaces such as ground granulated blast furnace slag (GGBS). Using the CEM III/A with 50% cement replaced by GGBS, total carbon emissions are about 6,800 tCO_2e resulting in 35% fewer carbon emissions than the potential emissions with CEM I, as summarised in Fig. 7. The budget carbon emissions for this project are 6,800 tCO_2e.

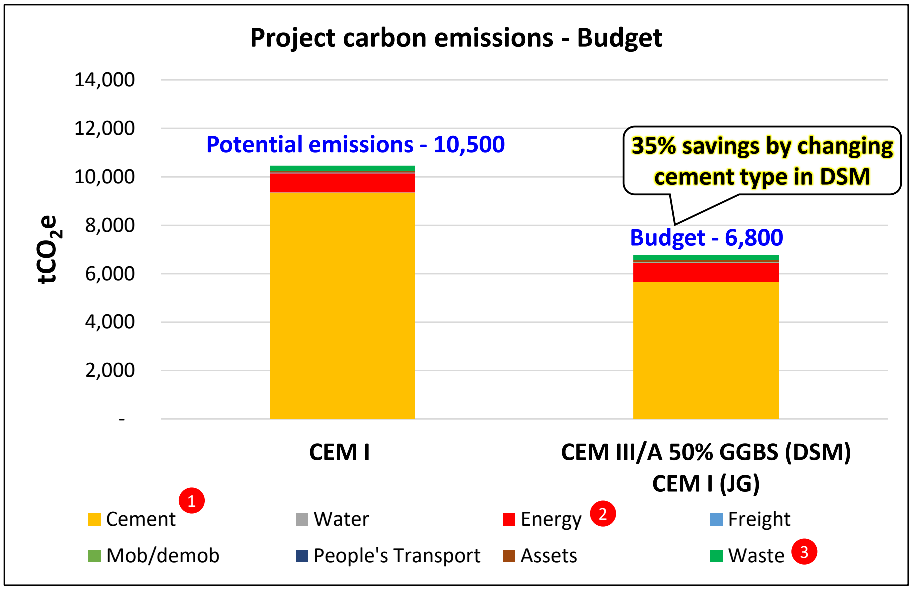

Fig. 7. Carbon emissions budget for the project

CARBON REDUCTION IN THE CONSTRUCTION PHASE

Additional opportunities are explored during the construction phase to reduce carbon emissions further. The first method is increasing the replacement ratio of GGBS in cement from 50% to 65%. The second method is deploying a larger diameter DSM column to form the soil improvement block while maintaining the design area replacement ratio. Both these methods are applied successfully and explained in the following paragraphs.

Replacement of 65% of cement with GGBS

According to the engineering requirement, the DSM columns shall achieve a minimum compressive strength of 600 kPa and a stiffness modulus of 150,000 kPa. These parameters are to be verified from the Unconfined Compressive Strength (UCS) Tests carried out on cored samples. Additionally, DSM columns are to be installed close to each other with overlap so that the area replacement ratio is 100%. Any value engineering proposed, such as cement type change, larger diameter DSM columns, etc., is expected to comply with this engineering requirement. Further to the discussion with the engineer, trials are conducted by installing several trial columns to verify if the 65% cement replacement with GGBS complies with the engineering requirement. The compressive strength test results at 28 days, summarised in Table 1, proved that the DSM works with CEM III/A with 65% replacement of cement are successful in achieving the required compressive strength and stiffness modulus and accepted by the engineer. In addition, CEM III/A with 65% cement replacement is also applied to JG works successfully. Hence, using CEM III/A with a 65% replacement of GGBS is effective in providing a low-carbon alternative material for DSM and JG works.

Table 1. Summary of UCS test results of trial DSM columns with 65% cement replaced with GGBS

Sample	Date	Depth (m)	Mass (g)	Size of grout (mm) (dia)	(height)	Density (g/cc)	Unconfined Comp. strength (UCS), (kPa)	Stiffness Modulus, E, (kPa)
A	4/12/2021	9.0 – 10.5	608.1	63	126	1.55	1,889	220,000
B	4/12/2021	10.5 – 12.0	631.9	63	126	1.61	1,214	173,000
C	4/12/2021	13.5 – 15.0	596.0	63	109	1.75	1,447	164,000

Use of larger diameter DSM columns

The original design diameter of the DSM columns is specified as 1.8m. To maximise the resources and increase productivity, larger diameter 2.2m DSM columns are implemented at the site. Compared to the 1.8m diameter, the 2.2m diameter DSM columns resulted in fewer DSM columns as coverage area in the plan per column is more than that at 1.8m diameter. With fewer DSM columns, overall resources required are also reduced. The productivity increased by 13% with the larger diameter, which resulted in about 52 tCO_2e carbon savings from diesel usage (energy). In addition, deployment of the second DSM rig resulted in an 18% shorter project duration and 190 tCO_2e carbon savings. As JG works are carried out after DSM works, a shorter DSM duration also resulted in carbon savings from JG works. Hence adoption of larger diameter DSM columns resulted in overall carbon emissions reduction in the project.

With the improvements mentioned above, the final carbon emissions of the project are calculated to be 6,300 tCO_2e, which is a 7% reduction from the budget emissions of 6,800 tCO_2e. The actual carbon emissions of the project are 40% lower than the potential emissions, as shown in Fig. 8. Hence these process improvements contributed to effective carbon emissions reduction in the project. The concept of budgeting carbon emissions and its periodic comparison with final carbon emissions helped the carbon emissions monitoring be more effective in reducing the project's overall carbon footprint.

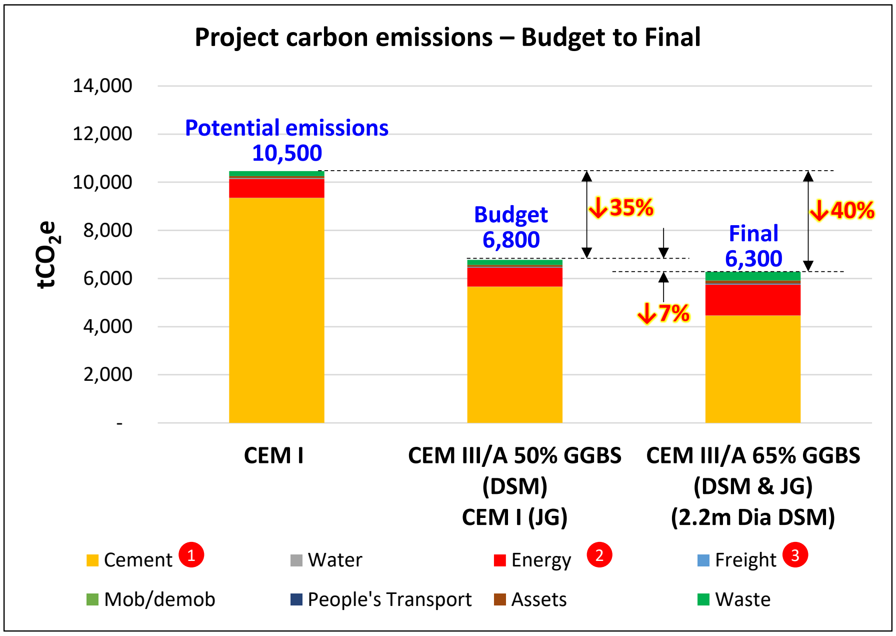

Fig. 8. Carbon emissions budget for the project

The carbon emissions reduction journey from budget to the final stage is summarised in Fig. 9. As explained in previous sections, the change of cement type from CEM I to CEM III/A 50% GGBS contributed to a 35% reduction in carbon emissions from 10,500 to 6,800 tCO_2e. A further 18% reduction is achieved by increasing the GGBS content from 50% to 65%. Overall, there are additional carbon emission of about 1,441 tCO_2e due to various factors such as engineering requirements (increase in cement content), increase in diesel consumption and increase in waste generation. The significant reduction in carbon emissions of 5,641 tCO2e due to cement type change to CEM III/A resulted in the final carbon emissions for this project being about 4,200 tCO_2e lower than the potential emissions estimated at the start.

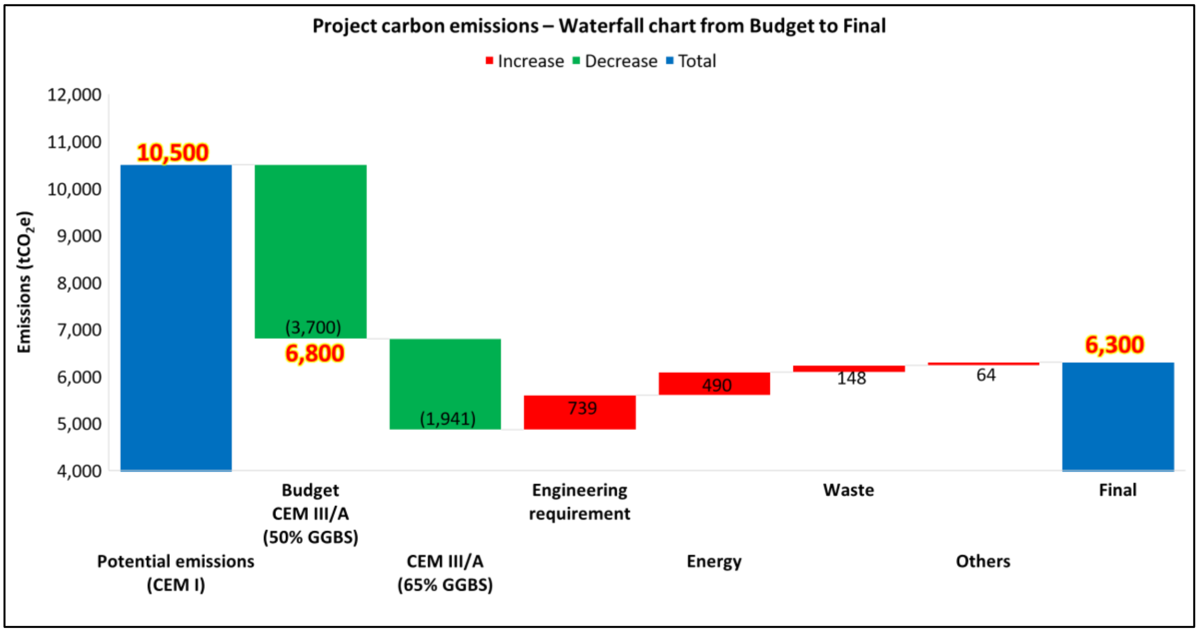

Fig. 9. Carbon emissions waterfall chart from budget to final

Summary

This project's total carbon emissions savings between the potential emissions and the final emissions is about **4,200 tCO2e.** As summarised in Fig. 10, this amount of carbon emissions savings is equivalent to the energy needed to drive an average passenger car around the earth's equator 380 times. It also is identical to the energy required to charge the smartphones of all Singapore residents for about 90 days. And to purify the air from these carbon emissions, one would need a forest of 4,509 acres working one full year. The soil improvement solution, along with the efficient carbon reduction methods applied in this project, positively impact the environment.

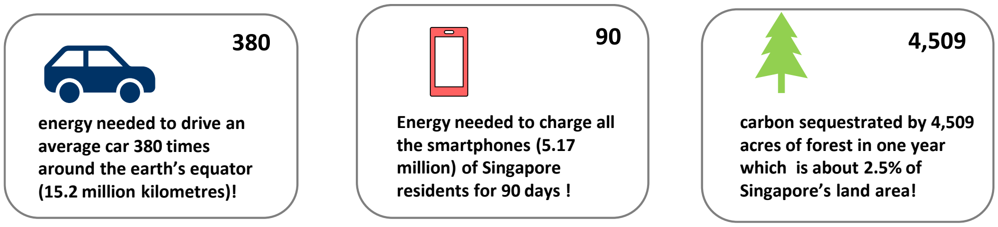

Fig. 10. Positive impact on environment

FUTURE OPPORTUNITIES

The authors came across various other ways to reduce carbon emissions during this project. Many of these methods are under study or in early implementation stages worldwide. With more trials and further data, these methods could be implemented in future projects but eventually will be subject to technical feasibility, cost, material availability and local regulations. There are several avenues to focus on to achieve carbon reductions in a project. With the significant carbon emissions contributors being – cement and diesel – a few methods are described below to reduce carbon emissions from these two primary sources.

CEM III/C cement (upto 95% GGBS replacement)

CEM III/C is a commercially available cement that typically replaces 81 – 95% of the cement content with GGBS. With higher GGBS content, CEM III/C cement has the lowest carbon emissions at about 152 $kgCO_2e$ per ton of cement compared to 363 $kgCO_2e$ for CEM III/A cement and 913 $kgCO_2e$ for CEM I (OPC) cement. The carbon emissions per ton of three main types of cement are summarised in Fig. 11. Project owners could envisage various kinds of cement, which reduce the overall carbon footprint. Factors like the availability of these types of cement, cost, technical compliance and local regulations must be investigated by stakeholders before actual application.

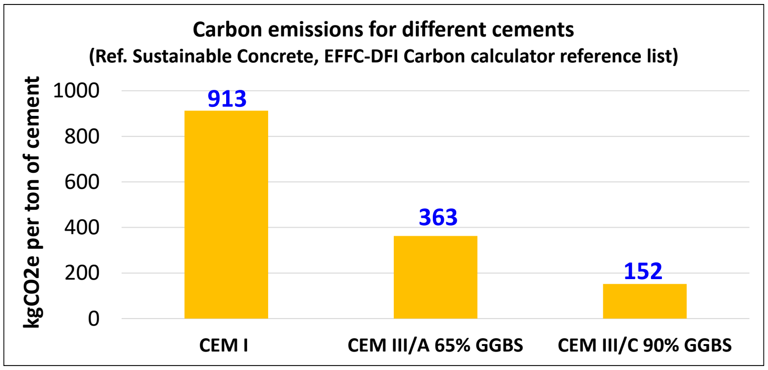

Fig. 11. Carbon emissions per ton of several types of cement

Sustainable biofuel to replace fossil fuels

One of the fuels that can replace fossil diesel is hydrogenated vegetable oil (HVO). The carbon emissions from HVO over the fuel's life cycle are roughly 75-95% less than fossil diesel (Neste 2019). In this project, the total diesel consumption equals 397,490 litres with associated carbon emissions of 1,280 tCO_2e, which is 20% of the overall emissions (6,300 tCO_2e). Based on the unit carbon emissions for HVO, the estimated carbon emissions by replacing diesel with HVO will be about 128 tCO_2e, giving a 90% emissions reduction. HVO presents an excellent opportunity in future projects, subject to availability, cost, machine manufacturer requirements and local regulations.

Spoil reduction

The overall spoil generated in this project is about 72% (volume of spoil generated/ volume of improved soil). This contributes to a considerable amount of carbon emissions. Including additives in the grout mix preparation could minimise water usage, resulting in less spoil generation and lower carbon emissions. This approach, however, needs to be studied in detail in future projects and is subject to outcome of field trials.

CONCLUSION

This paper described the application of soil improvement techniques to support the top-down construction of a two-level basement for an 11-storey structure in Singapore. The final carbon emissions for this project are 6,300 tCO_2e, 40% lower than the potential emissions with CEM I. Future opportunities summarised in the paper showed potential to reduce carbon emissions by adopting low carbon alternative materials and efficient construction methods. Hence, applying soil improvement techniques with the carbon reduction methodologies proved to be a technically robust and less carbon-intensive solution that helped construct this high-rise building development.

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