WHERE AND HOW TO EXECUTE SUSTAINABLE SOIL IMPROVEMENT UTILIZING VIBRO REPLACEMENT (STONE COLUMNS) IN THE NORDICS

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KEYWORDS

Alternative Soil Improvement, stone Columns, vibro replacement, environment, sustainable Solution, local material and knowledge

ABSTRACT

In parallel to the increase of population in Nordic region, which is projected to be more than 10% toward 2030, urbanization shows a rising trend especially around the capital cities of Denmark, Sweden and Norway. As the statistics show that building and construction industry globally accounts for 37% of energy and process-related CO2 emissions, significant efforts are required to transform these activities into a green industry by providing circular and sustainable solutions to achieve UN Sustainable Development Goals.

Based on the above it is expected from geotechnical engineers to look into to check constantly where and how the CO2-footprint can be reduced by keeping the projects practical and safe. Therefore, it is obvious that commonly used ground improvement methods in Scandinavia, which are based on cement and lime material, need to be – at least partially - replaced with alternative techniques or alternative binders.

This leads to the investigation on application of more sustainable ground improvement methods like vibro replacement / stone columns. In this case no binder is needed at all and even the re-use of construction materials such as excavated/blasted rock is possible. This leads to a CO2-reduction of 80 – 90% compared to the traditional methods. This paper aims to present the research done for the investigation of how and where vibro replacement can be used considering the typical local soil conditions. Some examples will be shown to underline the practicality of the approach considering typical KPIs based on time, costs and CO2-impact.

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1. INTRODUCTION

In Sweden and Norway, geotechnical considerations play a crucial role in construction and infrastructure development due to the varied nature of soils across the regions. Both countries feature diverse soil types, ranging from soft clay soils, loose sands and gravels to strong bedrock, often influenced by glacial deposits and mountainous terrains. In urban areas, where development is dense, the composition and stability of soils become paramount factors in engineering projects. Soil improvement techniques are frequently employed to enhance the load-bearing capacity and stability of foundations, particularly in areas prone to settlement or landslides.

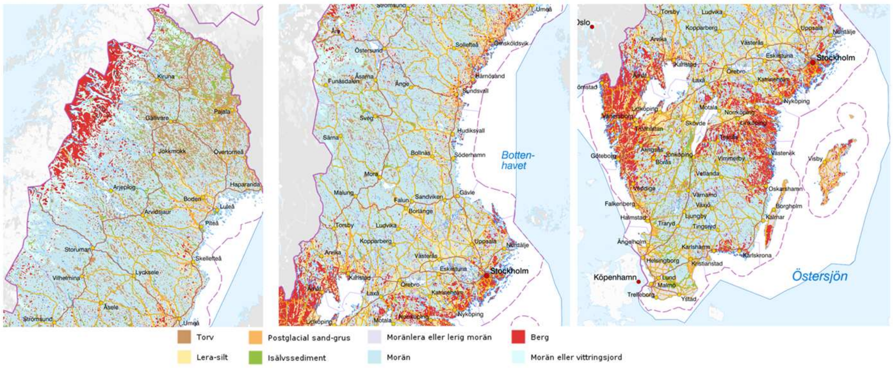


Figure 1 Soil types in Sweden (north, middle, south respectively-Source: SGU Website).

Ground improvement techniques in the Nordic countries contains a range of methods utilized to address the challenges posed by soft clays, peat, permafrost, and other adverse soil conditions. These methods include mainly dry deep soil mixing to increase load-bearing capacity, preloading with surcharges and prefabricated vertical drains to accelerate consolidation of compressible soils as well as soil replacement with engineered (light) fill materials. These techniques are essential for ensuring the stability and serviceability of infrastructure projects in the Nordic region, where challenging soil conditions are prevalent.

2. VIBRO REPLACEMENT AS A GROUND IMPROVEMENT METHOD

Vibro replacement is a globally used soil improvement technique. It involves using a bottom feed vibrator to penetrate fine soils like clay and/or silt, enlarging the voids created with crushed rock or gravel and densifying the installed material with the vibrator to create stone columns including a certain soil replacement of the soil during the construction process. These stone columns enhance soil behavior by increasing strength, stiffness, and permeability. While successful applications of vibro replacement have been documented in various countries, limited documentation exists in Nordics, where challenging ground conditions like partially extremely soft and sensitive clays pose obstacles.

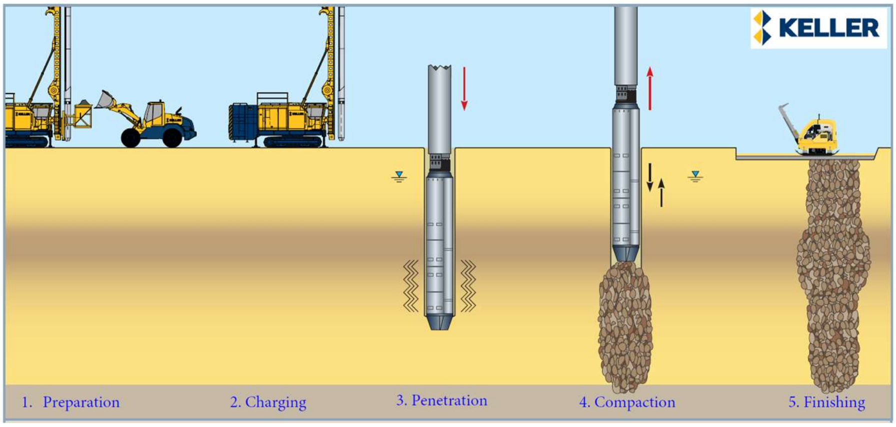


Figure 2 Process of vibro replacement-stone columns.

Stone columns offer a variety of benefits as reducing foundation settlement, increasing bearing capacity, allowing quick drainage of excess porewater, mitigating liquefaction potential, providing slope stabilization etc. In addition to stone columns, vibro concrete and vibro mortar columns are ground improvement techniques that also involve the use of vibration to improve soil. In these methods, a vibrating probe is inserted into the ground as in stone column process, which are then filled with concrete or mortar instead of gravel.

When working with sensitive and very soft soils, the application of vibro-stone columns encounters certain natural limitations. Specifically, for a first evaluation of a project, the remolded undrained cohesion of the soil shall exceed 3-5 kPa with a sensitivity value of 8-10 maximum. While pure stone columns may not be suitable for peat soils, special concrete can replace gravel within peat layers. Utilizing a bottom feed system with an adjustable frequency of the depth vibrator becomes essential in such scenarios. Moreover, the application in extremely soft soils is constrained by the absence of lateral confinement, further complicating the process. In this case geotextile or geogrid encased columns can be a solution to overcome the bulging in the lack of lateral confinement.

Electronic devices are used with all vibro techniques to ensure and automatically record consistent high-quality work. They track various parameters like time, depth, speed, force, and current during penetration and compaction. This information can be shown graphically and printed out for each column, making it easy to monitor and document the process (see Figure 3).

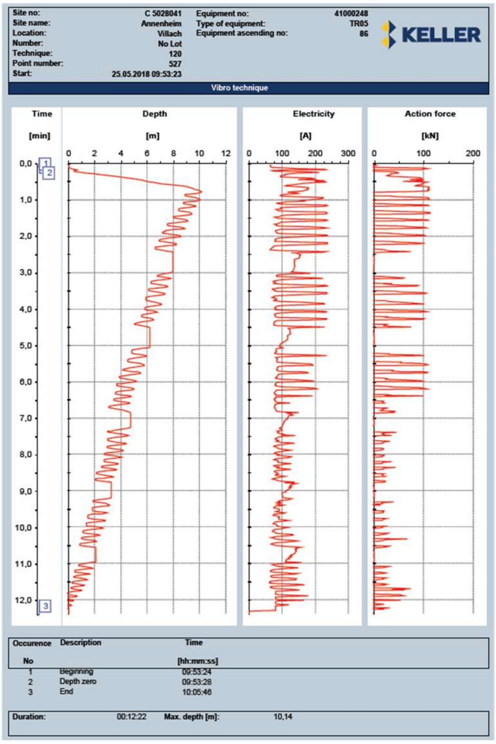


Figure 3 Typical quality control graph .

3. APPLICATION OF STONE COLUMNS IN VERY SOFT SOILS

The above stated constrains were confirmed by Keller's worldwide experience with vibro columns as being crucial for the safe and effective application of this solution. These projects have provided valuable insights into the soil conditions necessary to ensure the successful implementation of vibro techniques. Some of them have been provided and summarized on the table below.

Table 1. Examples of previous vibro projects with low soil shear strength parameters.

Location	**Purpose**	**Type**	**Undrained shear strength**
Sweden [1]	Road emb. stab.	Grouted stone column	8-14 kPa
Sweden [1]	Road emb. stab.	Vibro stone column	15-25 kPa
Austria	Bearing capacity	Vibro stone column	5-10 kPa
Germany	Road emb. stab.	Vibro concrete column	4-8 kPa
UK	Sewage works	Vibro stone column	7-10 kPa
Malaysia [2]	Road emb. stab.	Vibro stone column	5-15 kPa
Poland	Highway emb.	Vibro stone column	5 kPa

In addition to the summarized projects, it's noteworthy that Keller has further advanced its efforts by initiating a real execution trial with a research project for stone columns in Norway, supported by RFF (Regionale Forksningsfond)

Oslo. The VIBE project [3] is investigating sustainable ground improvement solutions for Oslo, with a particular focus on vibratory techniques and the incorporation of recycled raw materials. By conducting large-scale field tests at the Onsøy test field, the project aims to quantify the technical feasibility and environmental impacts of utilizing recycled materials in soil stabilization, especially in Norwegian clays. Initial results and partial findings offer a glimpse into the project's progress and its potential to revolutionize construction practices while promoting environmental sustainability.

The test field served as a platform to explore the impacts of vibrations, coupled with soil displacement, on soil parameters and pore water pressures in such challenging soil conditions. Further research is planned to investigate similar phenomena in typical fine-grained soils with slightly higher residual shear strength, aiming to broaden the understanding of these techniques in diverse soil compositions.

4. SUSTAINABLE SOIL IMRPOVEMENT

Dry soil mixing is widely employed as the predominant method for improving ground conditions in the soft and sensitive clays of the Nordic region. This technique primarily relies on cement and lime as binding agents, which significantly adds to the emission of CO_2. Global increase in CO_2 emission due to cement production over the last 100 years [4] has increased 1500 times . While numerous studies have explored sustainable binders to reduce CO_2 emissions, vibro replacement offers a promising alternative solution to the same geotechnical challenge, presenting a more sustainable option that has already been proven effective.

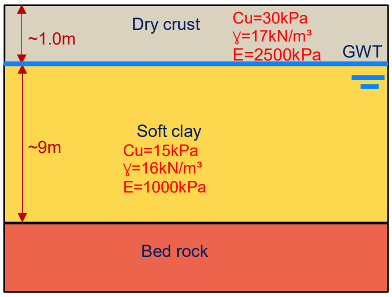
The demand for natural aggregates in stone column construction raises concerns about environmental impacts, including transportation pollution and waste management. Utilizing recycled materials addresses these concerns by promoting waste reuse and recycling. Additionally, substituting primary aggregates with alternative materials like crushed or recycled rock from tunnel excavations or blasting offers sustainability benefits by reducing environmental impact and promoting waste diversion. However, materials like crushed concrete and crushed brick, though popular alternatives, face limitations due to their fine content and suitability for specific soil types. Challenges such as high sulphate content or organic and acidic environments restrict their applicability in certain contexts [5].

5. HOW TO MEASURE THE SUSTAINABILITY WITH EXAMPLES

The EFFC calculator [6] serves as a pivotal tool for evaluating the CO_2 emissions associated with different methods and materials, replacing numerous company-specific calculators and ensuring standardized measurement of carbon output throughout the sector. Covering emissions from raw material extraction to foundation installation, this calculator facilitates the comparison of embodied carbon across various geotechnical solutions. Embraced widely by European geotechnical firms, some companies utilize it to compare projected and actual emissions, with the aim of minimizing their overall carbon footprint. For the examples shown on that paper, this tool has been utilized. Below are two examples demonstrating the quantification of equivalent CO2 emissions for different soil improvement techniques using the EFFC calculator, providing a clearer visualization of their impact:

1st example:
A typical infrastructure project was chosen (see Fig. 4) to compare dry deep soil mixing, stone columns & vertical drains with respect to function, economy and CO2-emission.

- Design of a 100m of road,15m wide, 1m of dry crust + 9m of clay
- 35kPa load from embankment
- Settlements criterion according to Swedish Transport Administration: 35cm in 40years (Ref. speed 40-80km/h)



Comparison sheet

VD: Vertical drain

	DDSM	Stone columns	VD	VD + surcharge	
Materials	110	6	4	15	tCO2e
Energy	9	9	6	5	tCO2e
Freight	1	2	3	18	tCO2e
Mob/demob	1	1	0	0	tCO2e
People's transportation	0	1	0	0	tCO2e
Assets	2	1	0	0	tCO2e
Waste	0	0	0	0	tCO2e
Total	**120**	**18**	**14**	**38**	tCO2e
Working days	5	10	4	5	days
Project value	64,000	90,000	68,500	60,000	€
Total meter	5,680	1,950	16,500	10,745	m

Figure 4. Soil profile and comparison table for all the methods analyzed.

As it can be seen from the comparison charts below (see Fig. 5), emission factor of DDSM is found 85% - 90% higher than stone column and vertical drains.

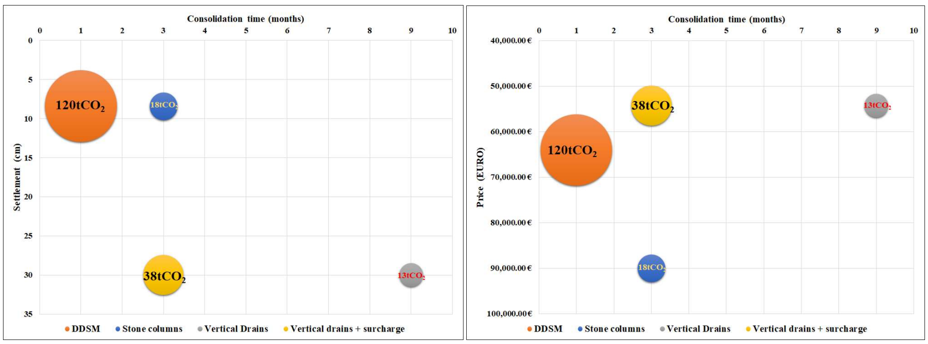


Figure 5. Comparison of all included methods with respect to settlement, price vs consolidation time and equivalent CO_2 emission.

2nd example:
An industrial project that consists of 2m-10m of sulphide bearing clay soil where 5-10m of embankment is going to be placed. The original solution was with DDSM with a coverage ratio of 100%. Area of improvement is 85,000m². Alternative solution was to execute stone columns with a surcharge load to eliminate the settlements. In Fig. 6 is the typical soil profile and a cross section showing the calculation of settlements without and with stone columns resulting in an improvement factor of ≈3.

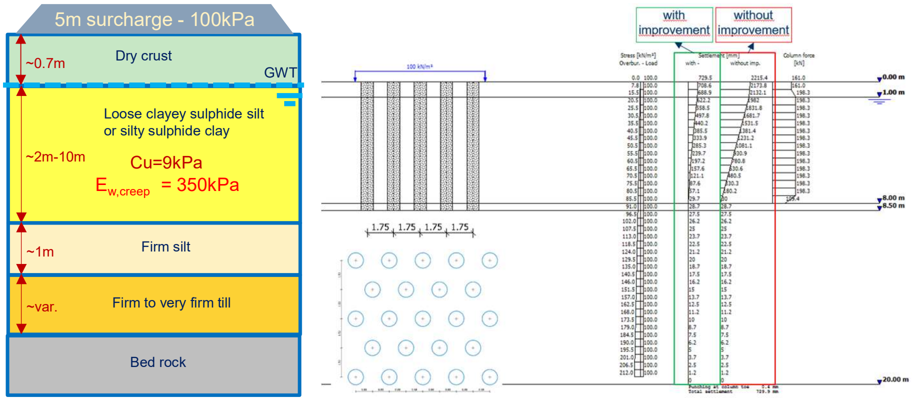


Figure 6. Typical soil profile and calculation of settlement.

EqCO_2 emission calculations for both DDSM solution and stone column solution are performed by using EFFC DFI Carbon Calculator Tool v4.0 and the results are shown below. As it can be seen clearly, with stone column solution the carbon footprint can be reduced ca. 90%.

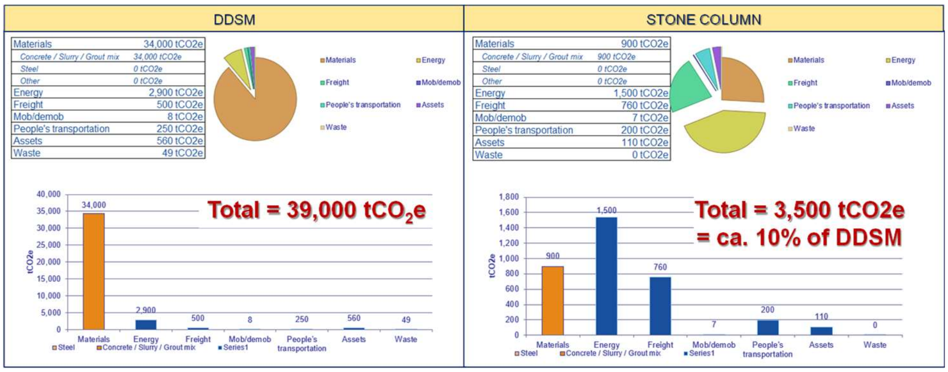


Figure 7. EqCO_2 calculation comparison for the same improvement area with DDSM and Stone columns. .

6. CONCLUSIONS

In conclusion, the Nordic countries of Sweden and Norway are basically aware of the need to get more sustainable solutions into the geotechnical projects. Soil improvement techniques play a vital role in addressing these challenges, ensuring the stability and longevity of infrastructure projects in urban areas and beyond. While methods like stone columns offer effective solutions, their application encounters limitations in certain soil conditions, necessitating ongoing research and innovation. Initiatives such as the VIBE project in Norway exemplify efforts to pioneer sustainable ground improvement solutions, incorporating recycled materials and advanced techniques to mitigate environmental impacts. Moreover, the adoption of tools like the EFFC calculator facilitates the evaluation and comparison of the environmental footprint of different soil improvement methods, guiding decision-making towards more sustainable practices.

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