Proceedings of the XVIII ECSMGE 2024
GEOTECHNICAL ENGINEERING CHALLENGES
TO MEET CURRENT AND EMERGING NEEDS OF SOCIETY

ISBN 978-1-032-54816-6
DOI 10.1201/9781003431749-88

Multidisciplinary design optimisation of vibro stone columns and dynamic replacement

Optimisation multidisciplinaire des colonnes ballastées et substitution dynamique

B. Knabe*, C. Tinat
Menard GmbH, Seevetal, Germany

M. Rosenberg
TU Braunschweig, Institut für Geomechanik und Geotechnik, Braunschweig, Germany

**bknabe@menard.gmbh*

ABSTRACT: The evaluation of construction processes regarding environmental aspects is becoming more important and is of particular interest for the construction business. An evaluation method for stone columns using vibro replacement technique (VRSC) and dynamic compaction with execution of large stone pillars, called dynamic replacement (DR), is presented. The analysis includes both technical and environmental criteria. Life cycle assessment (LCA) is used to evaluate the environmental criteria. The global warming potential (GWP) is considered as relevant indicator because of its informative value regarding climate change. The result of the two analysed ground improvement methods considered here are columns consisting of granular material. With DR an additional improvement can be obtained in the underlying layers through the transmission of the energy of the weight at depth. The results of a logistic centre case study show advantages of DR in terms of environmental impact. With the defined maximum settlement of 1.5 cm, the DR pillars can save approx. 60 % of the GWP compared to the VRSC technique. If larger settlements are allowed, the environmental impacts of both methods can be further reduced. In the future, this decision will have to be made by the investors. In the present example of a so-called “positive footprint building”, the multiobjective optimisation for the ground improvement is carried out with the criteria of minimising the settlement as well as the GWP to reach both targets.

RÉSUMÉ: L'évaluation de l’impact environnemental dans les processus de construction devient de plus en plus important et présente un intérêt majeur pour le secteur de la construction. Cet article présente une méthodologie pour évaluer sur un plan environnemental et technique les colonnes ballastées avec une aiguille vibrante (VRSC), et du compactage dynamique avec installation de colonnes de gros diamètre de matériaux granulaires compactés, appelée substitution dynamique (DR). L’analyse du cycle de vie (LCA) s'avère être la méthode la plus appropriée pour l'évaluation des aspects environnementaux. Le potentiel de réchauffement planétaire (PRP) semble être une mesure pertinente pour ces aspects, ayant l’avantage d’englober plusieurs phénomènes impactant le climat. Les deux méthodes d'amélioration des sols examinées ici produisent des colonnes granulaires. La substitution dynamique génère une amélioration significative des propriétés du sol au-dela la base de la colonne du fait de l’énergie dissipée par la masse lors de l’impact. Avec l'étude de cas d'un centre logistique, les résultats de l'analyse montrent les avantages de la substitution dynamique en terme d'impact environnemental. Avec un tassement admissible de 1,5 cm maximal spécifié, la substitution dynamique permette d'économiser environ 60 % du PRP par rapport aux colonnes ballastées. Si des tassements plus importants sont acceptés, les impacts environnementaux des deux méthodes peuvent être encore réduits. À l'avenir, cette décision devra être prise par les investisseurs. Dans le présent exemple d'un bâtiment à empreinte positive, l'optimisation multiparamétrique est réalisée avec pour objectif de minimiser le tassement ainsi que le PRP pour être conforme aux spécifications.

Keywords: Ground imrovement; life cycle assessment; multiobjective optimisation; dynamic replacement.

1 INTRODUCTION

Climate change and the global warming is one of the biggest challenges of our time and of the future generations. Industrial societies in particular bear a significant responsibility to achieve global climate targets and the necessary mitigation of impacts.

In geotechnical designs of ground improvement works or typical piling, the emissions of the appropriate methods and the construction process itself have not yet been given high priority when selecting the method and awarding contracts. However, a variant investigation with a qualified analysis of the environmental impact based on a life cycle assessment could already be carried out in the early planning stage and thus be included in the decision process of investors. For this purpose CO_2 balancing will play a decisive role in the evaluation of geotechnical concepts.

Ground improvement allows a wide range of technically equivalent methods with different materials and equipment. Technically equivalent solutions lead to different environmental impacts which have only been marginally evaluated so far.

Under uniformly loaded structures such as embankments and slabs-on-grade, stone columns are installed on a regular grid to improve the soil parameters on a defined area. There is not only one geotechnical solution to reach the settlement criteria, but rather a variety of possibilities by varying the grid, diameter or column length. Furthermore, there are different methods in terms of machinery and type of pushing the material into the ground to form the column.

A multidisciplinary evaluation method is presented for two methods of stone column installation. This includes the disciplines of geotechnical engineering and environmental management. Geotechnical engineering considers technical aspects such as bearing capacity and settlement behaviour after treatment. Environmental management identifies the reduction potential regarding environmental impacts by means of a life cycle assessment. The combined method enables the evaluation of individual solutions and optimisation.

2 METHODOLOGY

2.1 Life cycle assessment

The life cycle assessment is a method for the ecological balancing of a product system. The LCA considers the relative environmental impacts of a product system over its entire life cycle. The principles and framework conditions of a life cycle assessment are specified in EN ISO 14040. The EN ISO 14044 provides detailed instructions for drawing up a life cycle assessment. The environmental impacts are quantified using various impact indicators that describe the different environmental impacts.

LCA has become established in the construction industry for quantifying and evaluating environmental impacts (Röder and Finkbeiner, 2021) which can thus lead to optimisation respecting environmental impacts. The LCA includes in addition to the used materials, for example, the handling of construction vehicles during the construction stage (Ays and Geimer 2017). For processes without the use of concrete, the use of fuels and transport accounts for a significant part of the CO_2 consumption, see Figure 1 (Bunieski et al., 2023). Therefore, not only the material consumed can be compared.

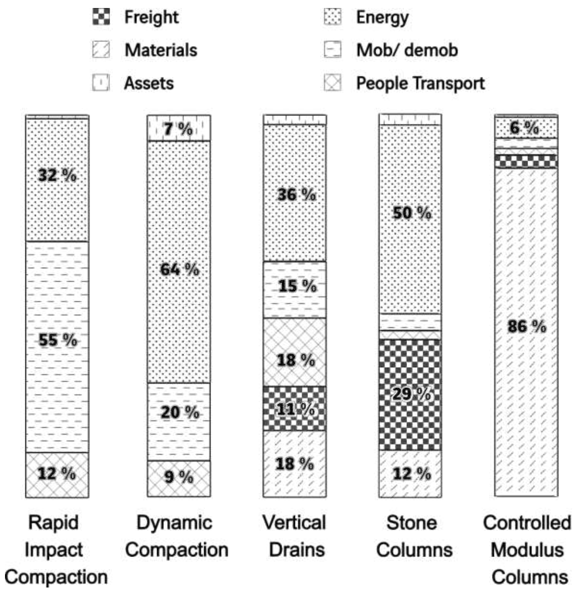

Figure 1. Embodied Carbon Breakdown per Ground Improvement Technique (Bunieski et al., 2023).

So far, no specific regulations exist for the preparation of life cycle assessments of construction processes. For this reason, the presented study is also based on EN ISO 14040 and EN ISO 14044 for the preparation of the LCA. These standards were designed for balancing product systems. From the authors' point of view the basic assumptions can be used and transferred for the preparation of a life cycle assessment for special civil engineering measures.

In general, several impact indicators could be considered in a life cycle assessment (LCA). In this study the CO_2 emissions were analysed. In an LCA, the CO_2 emissions are described by the global warming potential (GWP) indicator. The GWP is calculated by multiplying the quantity by the emission factor. The value is given in tonnes of CO_2 equivalent (tCO_2eq). For example, the calculation of the GWP of the gravel volume:

$$\mathrm{GWP_{gravel}}[\mathrm{tCO_2eq}] = \mathrm{gravel}\ [\mathrm{m^3}] \cdot \mathrm{emissionfactor}\ [\frac{\mathrm{tCO_2eq}}{\mathrm{m^3}}]$$

The emission factor is taken from a database such as the German ÖKOBAUTDAT. It is also possible to use a product-specific emission factor like an environmental product declaration (EPD). The GWP in this study is calculated for the materials used, the fuel for transport, the site facilities and the fuel for the equipment.

2.2 Multiobjective optimisation

Multiobjective optimisation can be used in the planning of a structure by automatically checking a big amount of different parameter combinations and therefore supporting the decision process. Multiobjective optimisation is particularly suitable for complex systems that are influenced by several variables and that are strongly impacted by only one variable.

In geotechnical engineering only random variants with few selected parameter combinations are calculated and compared currently (Seitz and Grabe, 2018).

Multiobjective optimisation considers two or more objective functions to be optimised, which can also compete. Objective functions in civil engineering can refer to the minimisation of financial costs, materials, construction time, energy used and thus also to the minimisation of resources. Restrictive conditions can be stability verifications, settlement criteria or other limitations. (Seitz and Grabe, 2018)

The solution of a multiobjective optimisation usually has no absolute minimum or maximum. There is no solution that fulfils all objective functions, but a solution set. This solution set is called pareto set and consists of solutions that dominate other solutions but are not dominated. A dominating solution in this case means that a solution is better in at least one objective and yet not worse in any other objective. A solution is not dominated if one solution is better than another in one objective, but the other solution is better in another objective and the two solutions are therefore not comparable. Accordingly, the pareto set describes all optimal solutions that cannot be improved in one objective without simultaneously degrade another objective. The pareto set is represented graphically by the pareto front in Figure 2. The grey dots represent all solutions from the parameter combinations, the pareto-optimal solutions are highlighted with red circles. (Knowles, 2008)

The presented multidisciplinary optimisation approach can be understood as a special form of multiobjective optimisation. It includes the disciplines of geotechnical engineering and environmental management. The discipline of geotechnics can be considered, for example, through the criteria of stability or serviceability of the structure. Environmental management deals with the environmental impacts caused by the execution of ground improvement works within the framework of a life cycle assessment.

The considered geotechnical criterion is settlement, which must not exceed a limit value or should be minimised. The LCA sets its criteria through various impact indicators which should also be minimised.

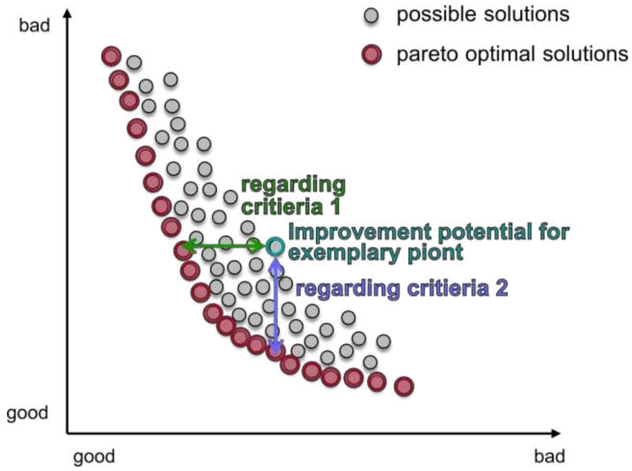

Figure 2. Example for possible pareto-front.

2.3 Technical and environmental aspects of the ground improvement methods

The ground improvement methods considered in this case study are stone columns using vibro replacement technique (VRSC) and dynamic replacement (DR). Both methods are briefly explained below as the basis for the following life cycle assessments.

Classical stone columns are formed by inserting a vibratory probe to incorporate granular material into the ground and create vertical inclusions with small diameters of approx. 0.5 - 0.8 m.

Stone columns are formed by inserting a hydraulic or electric vibroflot equipped with a pressure chamber equipment using air as a jetting fluid. The execution of stone columns requires a rig, as well as a feeding unit for filling the material. Various equipment combinations are available, depending on the diameter and depth of the columns.

Dynamic replacement (DR) is an extension of dynamic compaction to highly compressible and weak soils. In this application, the tamping energy drives granular material down into the compressible soils to form large diameter soil reinforcement columns (with diameter around 2 to 3.5 m). Additional improvement can be obtained in the underlying layers by transferring the energy of the weight at depth. This method combines advantages from both dynamic consolidation and stone pillars by creating large-sized dynamic replacement inclusions with high internal shear resistance. Dynamic replacement columns are formed by dropping a 10 to 35 tons pounder from heights ranging from 10 to 30 m. With this technique replacement ratios of up to 20 to 25 % can be achieved.

In the case of weakly permeable soils the columns are made in several phases so that excess pore water pressure can dissipate. For this technique a crawler crane is used and the filling for the craters is done by a crawler, see Figure 3. Recycled crushed concrete material can be used as fill material which is an advantage over the deep vibrator of the VRSC technique.

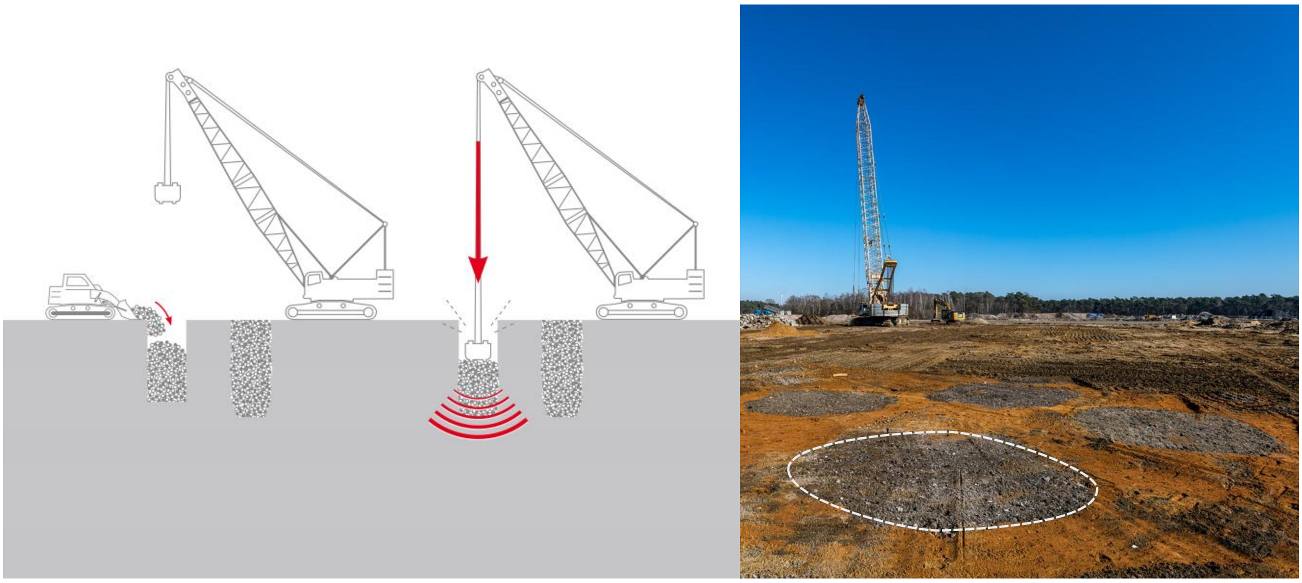

Figure 3. left: principle of DR with crane and compaction below; right: surface of DR pillars in the Dorsten project.

3 APPLICATION EXAMPLE LOGISTICS CENTRE

The developed method was used for the foundation of a logistics centre which requires piling or ground improvement. A high-bay warehouse for Levi Strauss & Co. is being built on a former coal mine area in Dorsten-Wulfen in Germany. The Positive Footprint Wearhouse® is a representative example of sustainable construction. Materials and processes that save resources as much as possible are used and the core of the building is realised according to the Cradle-to-Cradle (C2C) principle.

Figure 4. Levi Strauss & Co Positive Footprint Wearhouse®.

The existing soil was too soft to reach the settlement requirements of the structure. Therefore, piling and different ground improvement methods were considered for the stabilisation of the slab and the single foundations. Finally, the VRSC and DR technique were analysed to achieve the required stiffness of the ground in the high-bay part of the warehouse.

The design method according to (Priebe, 1995) is a frequently used method to estimate the behavior of the reinforced soil. The DR can also be designed as granular columns according to the basic assumptions of Priebe. However, plastic deformations and bulking of the pillars can be neglected because of the geometry (large diameter and shorter length).

4 MULTIDISCIPLINARY ASSESSMENT METHOD

The multiobjective optimisation considers the settlement and the environmentally impact. Accordingly, two objective functions are used: minimising the settlement and the GWP.

The variable design parameters are the column diameter, the column spacing and the column length. The optimisation problem is solved by a self-developed algorithm using the software package Matlab. This calculates every possible parameter combination of the three variable parameters. For each possible parameter combination, the settlement and the GWP are calculated. The settlements are calculated with an implemented function for an infinite spread load. In the calculation the improved stiffness of the soil after treatment are applied according to the Priebe approach (Priebe, 1995). The paretoQS function is used to determine the pareto-optimal solutions (Tom R, 2022).

The parameters are varied in different limits. In the script of the stone columns about 3,900 and of the DR about 5,300 parameter sets are calculated.

To decide on a solution, it has to be weighed up which settlements are acceptable in order to reduce the GWP (definition of settlement criterion). A larger grid spacing and a smaller column diameter can reduce the column volume and the construction time whereby the GWP is reduced. Varying the grid, the column diameter or the column length show the optimisation potential and the multitude of optimal solutions. Based on the selection of a priority, a solution can be chosen from a set of optimal solutions.

The result of this multiobjective optimisation for stone columns, with the objective functions of GWP and settlement, is shown in Figure 5. Each marker represents a parameter set for the VRSC design.

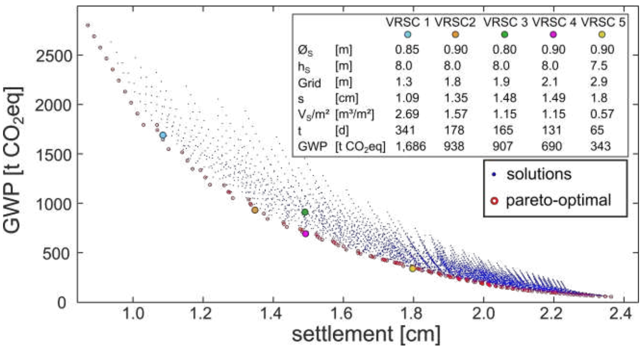

Figure 5. Multiobjective optimisation vibro replacement stone columns (GWP vs. settlement).

A reference design and an optimised design are selected to compare the results indicated by the green and pink circles respectively. The reference design (VRSC 3) has been chosen prior to optimisation as possible VRSC layout in order to demonstrate the optimisation possibilities of the algorithm. The reference solution is a non pareto-optimal solution. More than 200 t CO_2 equivalent can be saved with the VRSC 4 solution with almost the same settlement. The construction time of the VRSC is calculated based on the installation performance which depends on the column length. The diameter of the columns is not included in the calculation of the construction time. However, the diameter is considered by the volume of fill material.

Figure 6 shows the results of the multiobjective optimisation for the DR pillars with the objective functions of the GWP and the settlement.

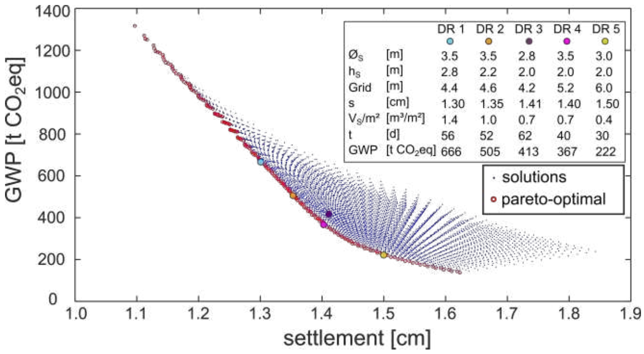

Figure 6. Multiobjective optimisation DR-pillars (GWP vs. settlement).

The reference solution DR 3 is a non pareto-optimal solution, there are solutions with the same settlement, but with a smaller GWP. By choosing the solution DR 4, about 50 t CO2 equivalent can be saved compared to DR 3.

The lengths of the pillars of the pareto-optimal solutions are shorter compared to the VRSC. The underlaying soil layers are compacted by the pounder and represent an additional improvement of the deeper ground. The construction time is calculated via the specified installation performance. The installation performance of the DR pillars is significantly dependent on the grid spacing and soil conditions. Consequently, a larger grid spacing, in addition to a low material requirement, contributes significantly to minimising the GWP.

The pareto-optimal solutions of both methods are shown in Figure 7. The DR pillars shows the best solutions possible to the optimisation problem for minimising settlement and GWP. With a settlement criterion of 1.5 cm applied for this study, the DR columns can save about 60 % of the GWP compared to the VRSC.

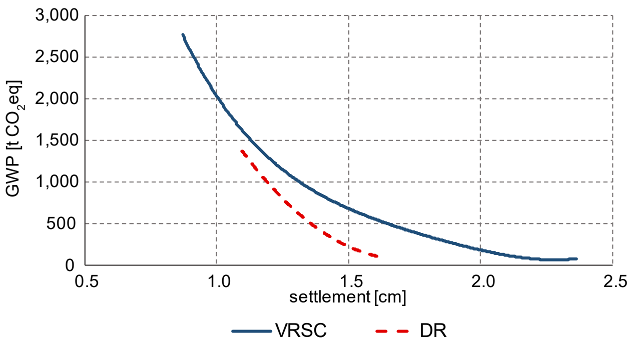

Figure 7. Comparison of the global warming potential of the pareto-optimal solutions (criteria: GWP – settlement).

Considering the entire building the ground improvement has only a small share of the GWP of the overall balance - with piling it would be much more. This kind of building has a GWP of around 15,000 to

20,000 t CO_2 equivalent only from the materials used in the shell, without including the construction process. The GWP of the ground improvement with DR pillars of 285 t CO_2 equivalent has a share of 1 to 2 % of the GWP of the material used in the building shell. The environmental impact and thus the savings potential in the structural engineering part is significantly higher. The optimisation of ground improvements in terms of environmental impact is nevertheless important. Due to the many variation possibilities savings in GWP are possible without increasing settlement or decreasing the bearing capacity. Further, saving GWP means also saving costs. Therefore, a contribution to saving resources and emissions can also be made in foundation engineering.

5 CONCLUSIONS

Overall, the developed evaluation method is a good way to find optimal solutions for the considered ground improvement methods. An increase of the maximum allowable settlements by a few millimetres can reduce the environmental impact to a minimum. The multiobjective optimisation can be performed with the criteria of settlement and global warming potential for VRSC and DR. The evaluation method can be applied to other projects, as only the input parameters of the optimisation code (like soil parameters and layers). The determination of the construction time is sufficiently accurate. A determination of the construction time by means of a construction process model would include all influencing aspects on the construction time and thus lead to an even more accurate result. The presented evaluation method represents an easy-to-use and practical application to optimise the design of ground improvement methods about settlement and environmental impacts. The extension to other techniques is given.

REFERENCES

Ays, I. and Geimer, M. (2017). CO2e Quantifizierung von mobilen Arbeitsmaschineneinsätzen im Erdbau, Steinbruch, Straßen- und Hochbau, CO2e quantification of mobile machine operations in earthworks, quarries, road construction and building construction (in: german), In: *Hybride und energieeffiziente Antriebe für mobile Arbeitsmaschinen: 6. Fachtagung, 15. Februar 2017,* Wissenschaftlicher Verein für Mobile Arbeitsmaschinen, KIT Scientific Publishing, Karlsruhe, Germany, pp. 145–161.

Bunieski, S.; Boyd, G. and Isenegger, N. (2023). Methodology to calculate and compare Embodied Carbon associated with Ground Improvement techniques. *Geo Saskatoon 2023*, Saskatoon, Canada.

Röder, A. and Finkbeiner, M. (2021). Was jeder im Bauwesen über Ökobilanzen wissen sollte, What everyone in the construction sector should know about life cycle assessments (in: german), In: *Nachhaltigkeit, Ressourceneffizienz und Klimaschutz: Konstruktive Lösungen für das Planen und Bauen: aktueller Stand der Technik*, Wilhelm Ernst & Sohn, Berlin, Germany, pp. 137–145.

Knowles, J.; Corne, D. and Deb, K. (2008). Introduction: Problem Solving, EC and EMO, In: Knowles, J. et al. [Ed.] *Multiobjective Problem Solving from Nature*. Berlin, Heidelberg: Springer Berlin Heidelberg, Germany, pp. 1–28. https://doi.org/10.1007/978-3-540-72964-8_1.

Priebe, H. J. (1995) Die Bemessung von Rüttelstopfverdichtungen, The design of vibro compaction (in: german), *Bautechnik 72. 1995, Nr. 3*, pp. 183–191.

Seitz, K.-F. and Grabe, J. (2018). Einsatzmöglichkeiten der multikriteriellen Optimierung im digitalen Bauen, Possible applications of multiobjective optimisation in digital construction (in: german), In: *Digitale Infrastruktur und Geotechnik 2018, Jg. 42 von Veröffentlichungen des Instituts für Geotechnik und Baubetrieb der Technischen Universität Hamburg*, Hamburg, Germany, pp. 169-181.

Tom, R. (2022). *Find multi-objective Pareto front using modified quicksort.* [software]. https://www.mathworks.com/matlabcentral/fileexchange/73089-find-multi-objective-pareto-front-using-modified-quicksort, MATLAB Central File Exchange. [acess on: 09.07.2022].