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Numerical optimisation of geotechnical constructions

Optimisation numérique des constructions géotechniques

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ABSTRACT

Geotechnical constructions are sophisticated buildings due to the complex behaviour of soil and its interaction with the structure. Passed design processes are commonly confined as difficult and, depending on possibilities and skills of the processor, more or less innovative, creative and heuristic search for defined objectives under given constraints. Wholistic approaches using numerical optimisation to support the constructive engineer in this task do not exist until now. Therefore, potential cost effectiveness, construction time, load capacity and/or serviceability are often not fully exploited.

In this paper systematic approaches for comprehensive optimisation of selected geotechnical constructions are presented. Different optimisation paradigms are introduced and demonstrated using evolutionary algorithms. The methods presented here conveniently allow the achievement of effective designs concerning various intentions, as is shown exemplarily.

RÉSUMÉ

Les constructions géotechniques sont des édifices exigeants à cause du comportement complexe du sol et de l'interaction entre le sol et la structure. Le procès du design dépend des possibilités et des connaissances de l'ingénieur et se montre comme une recherche peu ou prou créative et heuristique d'un objectif défini en regardant les limites attribuées. Jusqu'a ce jour, des approches globales qui utilisent l'optimisation numérique pour aider l'ingénieur constructif n'existent pas. À travers, les potentiels concernant les coûts, la durée de la construction, la résistance et/ou l'aptitude au service ne sont pas épuisés.

Dans cet article, des approches systématiques d'une optimisation globale sont présentées. Elles sont appliquées à quelques constructions géotechniques. Des différents paradigmes de l'optimisation sont décrits et appliqués en utilisant des algorithmes évolutifs. La simplicité de cette méthode pour obtenir un résultat plus effectif est présentée par quelques exemples.

Keywords: Optimal design, Evolutionary Algorithm, Multi-Objective Optimisation, quay wall, combined pile-raft foundation

1 INTRODUCTION

Design processes in engineering represent an innovative, creative and heuristic search to achieve a defined objective within given constraints. System-related problems particularly in geotechnical concepts can be ascribed to the complex soil-structure interaction as well as the non-linear behaviour of the soil.

The quantitative impact of modifying design parameters to certain target values is a priori unknown. Therefore, the design engineer rarely succeeds in meeting all requirements to the same degree (Schmit, 1963).

Wholistic approaches involving different aspects of geotechnical concepts in a unified view do not currently exist. Design concepts and related numerical models are either not at all or just marginally evaluated by sensitivity analyses of free construction parameters. Usual objective values for constructions are often inherently static. Until now, processes concerning the construction or cost effectiveness only have inferior influence into the design process.

Modern methods of mathematical optimisation already gained access to other fields as in mechanical engineering. There, methods of numerical optimisation are successfully employed offering solutions to complex problems. Comparable approaches in geotechnical engineering have only played a minor role to date (Ciegis et al., 2006).

This article will illustrate the advantages in the application of optimisation methods supporting the design of geotechnical structural systems. The potential of these methods for design engineers are elucidated exemplarily.

Approaches and strategies for wholistic mono- and multi-criteria optimisation are represented for chosen geotechnical constructions and first results are presented.

Comparative analyses of the obtained results can be used for better understanding of dependencies and to develop construction rules for future design of similar structural systems.

2 ANALYSIS AND POTENTIALS OF THE GEOTECHNICAL CONSTRUCTION PROCESS

The design concept is subject to versatile requirements (Pohlheim, 1999). Predominant construction principle in geotechnical engineering is the safety of the structures to be designed. Possible hazards are to be avoided under any circumstances. Further aspects that could be considered are construction and maintenance costs, time of construction, construction method, geometry etc.

The practical design commonly underlies static considerations. Any further requirements as for example cost efficiency or rapidity of a construction method are frequently subordinated.

For this reason, ideal construction designs are frequently not discovered in the course of classical calculations. In geotechnical engineering it is customarily that statically specifications are met by the design concept. An iteration concerning the choice of system only takes place for obviously uneconomical or inappropriate systems. Complications arise

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due to the cause and effect principle due to the difficulties in estimating complex mechanical correlations a priori.

To obtain concept designs that best meet several criteria equally, the application of numerical optimisation methods are inevitable. Target-orientated application guaranties an efficient dimensioning and therefore high quality concepts.

3 CONCEPTS OF OPIMIZATION

Distinction is made between mono- and multi-objective optimisation concepts. While mono criteria optimisation tasks involve the minimisation of one single objective function, multi-objective optimisations deals with several objective functions simultaneous. Mono-criteria optimisations possess a global solution, whereas the solution to multi-objective optimisations consists of a set of ideal solutions.

The mathematical descriptions of mono- and multi-objective problems as well as their solutions are specified below.

3.1 *Mono-criteria optimisation*

The mono-criteria optimisation problem consists of the minimisation of one objective function $f(x)$, where applicable with the constraints for equations $g_i(x)$ and inequalities $h_i(x)$:

$$\min\{f(\vec{x}) \mid \vec{x} \in M \mid g_i(\vec{x}) = 0; h_j(\vec{x}) \leq 0\} \ . \tag{1}$$

A valid point $x^S \in M$ with

$$f(x^S) = \min\{f(x) \mid x \in M\} \tag{2}$$

is called global minimum of the defined problem (1).

3.2 *Multi-objective optimisation*

The constrained multi-objective optimisation problem is analogous to equation (1) defined as

$$\min\{\vec{f}(\vec{x}) \mid \vec{x} \in M \mid g_i(\vec{x}) = 0; h_j(\vec{x}) \leq 0,\} \ . \tag{3}$$

In contrast to equation (1) there is rather a set of objective functions considered. The optimality definition of the mono-criteria problem is replaced by the concept of dominance. A solution $\vec{x}_1$ dominates a solution $\vec{x}_2$ if $f_k(\vec{x}_1)$ for all $k = 1,\dots,l$ in no objective is worse but in at least one objective is strictly better than $f_k(\vec{x}_2)$. The mathematical notation is

$$\vec{x}_1 \prec \vec{x}_2 \ . \tag{4}$$

To apply the concept of dominance to the optimisation task a mapping from decision space into objective space is required. The set of non-dominated solutions is defined as Pareto-optimal set.

4 NUMERICAL OPTIMIZATION

For the solution of optimisation problems numerical methods are used. Analytical solutions exist only in special cases. The history of numerical optimisations goes back to Leibnitz and Newton. Conventional procedures are used to determine the extreme values of real-valued functions with one or more variables with or without constraints based on gradient information. There are a large number of optimisation algorithms that solve special optimisation tasks efficiently.

Complicated tasks of practical application require capable and robust procedures. Especially objective functions with a high number of local extreme values as well as complicated problems with non-real parameters or discontinuities in the objective function are non-satisfying solvable with the classical methods. In this case stochastic methods could be successfully applied.

Characteristic for those methods is the combination of specific search and randomness to obviate premature convergence. The structure is relative simple and often inspired by natural adaption processes. The essential advantage is the independence from the structure of objective functions and constraints. Harmful is the high calculation effort caused by a large number of evaluating the objective function.

By using Evolutionary Algorithms for the design optimisation a stochastic optimisation method is adopted. Evolutionary Algorithms are able to solve so called *black-box* problems, their application for solving such problems is shown in a large number of studies (Zilinskas, 2002).

4.1 *Evolutionary Algorithms*

Evolutionary Algorithms are originated from the biological evolution. An Evolutionary Algorithm is a population-based iteration scheme, which examines in each iteration step parallel multiple parameter sets. A benchmark principle is adopted on the sets in the sense of one or more objective functions to reach by truncation of the algorithm an optimal solution (Goldberg, 1989).

After an initial phase at the beginning of the optimisation a specific search over multiple generations is enforced. In every generation the objective function is evaluated for all sets, the highest fitness is assigned to the best solutions. Executing the evolutionary operators like recombination and selection leads to new parameter sets for the next generation. This process ideally leads to even better solutions. Figure 1 shows the basic scheme of an Evolutionary Algorithm.

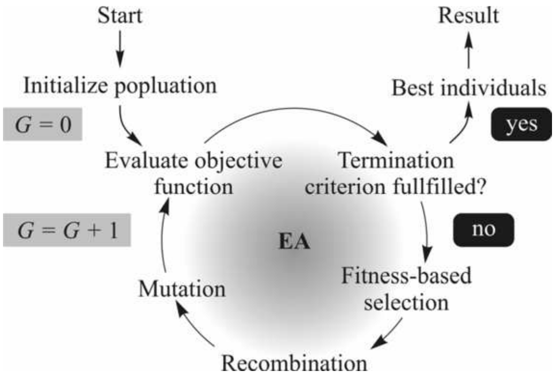

Figure 1. Schematised flow chart of an Evolutionary Algorithm

In contrast to classical deterministic optimisation schemes Evolutionary Algorithms are able to carry out parallel searches, gradient information are not required and the solution of a problem is independent from the representation of the parameter sets. Thus also highly non-linear objective functions as well as discontinuities in objective functions or constraints can be optimised sufficiently (Deb, 2001). Due to parallel search also multi-objective problems could be solved in a single optimisation run.

5 APPLICATION ON GEOTECHNICAL STRUCTURES

5.1 *Optimisation of a quay wall structure*

The requirements of quay wall structures raised in the past 30 years. Realisation of large water depths, substantial load rising of the gantry cranes as well as changes in calculation rules result in new constructions.

The high number of fulfilling requirements precludes a cost-effective solution in the course of a classical static calculation. Although linear constructions like quay walls are well situated for optimisation because the effort for optimisation is overlaid by its use with increasing length of the calculation profile. Below this effect is shown by the exemplary optimisation of a quay wall in consideration of the building costs. In addition the dependencies of costs on specific parameters are explicit shown.

The optimisation of a quay wall structure is carried out based on an economic performance calculation under statically constraints. The structure consists of a combined sheet pile wall behind a row of friction type piles. The concrete superstructure is founded on three vertical piles; the inclined pile carries horizontal loads. The section of the construction is shown in figure 2. Water depth, soil profile and dimensions of the structure are typical for a container terminal at port of Hamburg.

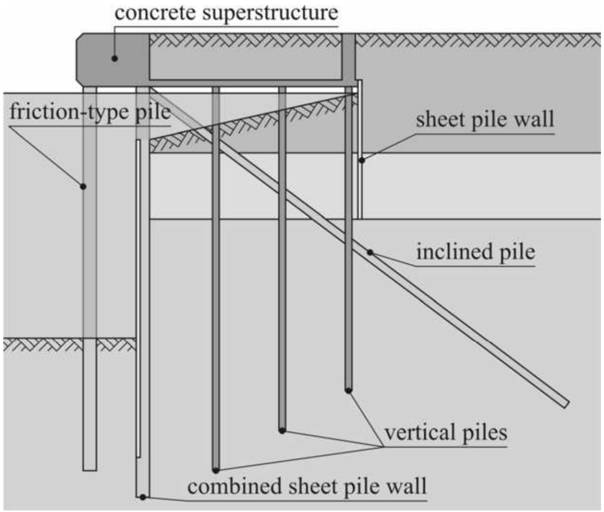

Figure 2. Examined quay wall section

To show the dependencies of construction costs on the geometry and the position of selected components parameterised variations are calculated. In the following two examples are presented. In figure 3 the cost-dependencies for the free construction parameters of the friction-type pile are shown, figure 4 shows the influence on the costs of the inclination and the distance of the inclined pile.

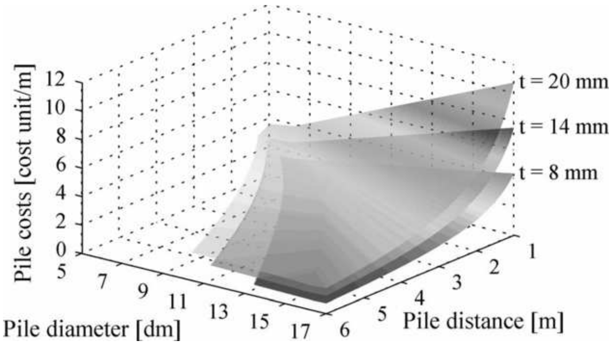

Figure 3. Costs of friction-type pile depending on pile diameter and pile distance for three different wall thickness

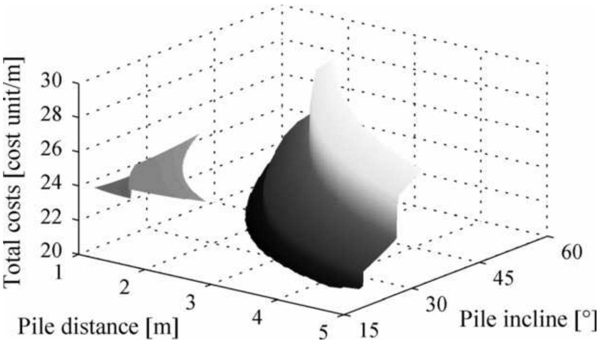

Figure 4. Totals cost of the quay wall structure just depending on anchor pile distance and anchor pile inclination

Regarding the shown plots of the objective functions the character of the objective functions could be estimated. The cost-function of the friction-type pile is obviously a non-linear function on a restricted domain. The cost-function of the inclined pile is discontinuous. The realized parameter study demands a high calculation effort; the estimation of graphical contexts is limited to three dimensions.

Using Evolutionary algorithms to optimise the total costs of the shown quay wall structure the minimum can be found efficiently. For the section shown in figure 2 a cost saving about $11\,\%$ based on the estimated partial cost could be realized compared to the average construction costs.

5.2 *Multi-objective optimisation of a combined pile-raft foundation*

Combined pile-raft foundations are efficient foundation concepts that ensure reduction of settlements and the best load capacity of all foundation elements. The load bearing behaviour of combined pile-raft foundations depends on the complex mechanical interaction of raft and piles coupled structural and interacting via the soil (Kinzler et al., 2007).

An exact prediction of the load bearing and deformation behaviour of a combined pile-raft foundation is difficult. The optimal number and positions of piles as well as the dimension of piles and raft is difficult to determine by assaying. The dependencies of the system answer on these parameters is unknown and only in specific cases predictable (Kim et al., 2000).

Based on an analytic calculation model that represents the raft as Kirchhoff plate and the piles as beam elements the multi-objective optimisation of a combined pile-raft foundation is performed. The soil beneath the plate is modelled with boundary elements and allows the interaction between raft and piles in both directions underlying the solutions of Mindlin and Boussinesq (König, 2008). The results are validated by the recalculations of the measurements of Messeturm, Frankfurt and the high-rise building Westendstrasse 1, Frankfurt.

Below the optimisation of an exemplary chosen combined pile-raft foundation is accomplished. The load of $200\,\mathrm{MN}$ is to found on an area of about $25 \times 25\,\mathrm{m}$ by a combined pile-raft foundation with 9 piles. The optimisation parameters are the raft thickness d_R, the pile positions p_i and the pile lengths l_i.

By using symmetry the piles are grouped into three categories. The optimisations parameters are composed in equation (5):

$$\vec{x} = \begin{pmatrix} d_R & p_1 & p_2 & l_1 & l_2 & l_3 \end{pmatrix}^T \ . \tag{5}$$

The geometric interpretation of the parameters shows figure 5.

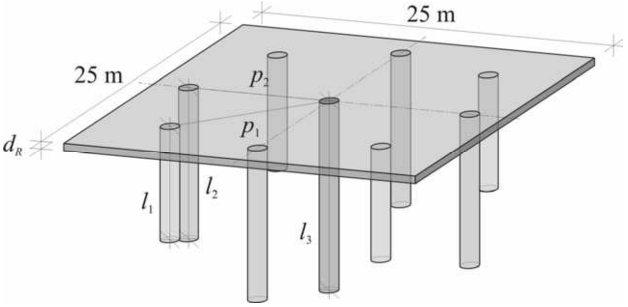

Figure 5. Graphical representation of the optimisation parameters

The domain of the parameters is restricted to reasonable ranges. The plate thickness is limited between 1 and 4 m , the pile lengths between 0 and 40 m and the pile distances from the edge of the raft rather the adjacent pile are minimum the pile diameter. Fulfilling these constraints the foundation is to dimension in that way that the maximum settlement $s_{\max}$ under minimal foundation costs C_{cum} is found.

The maximum settlement $s_{\max}$ is the result of the mechanical calculation. In addition to that an ideal cost function is defined. The cumulative costs of the foundation result in the sum of the costs of raft and piles. The raft costs are consistent to the multiple raft volume; the pile costs are also calculated via their volume respect to a depth-depending exponent. The constant factors suggest the differences in the cost calculation of the constructive elements. The objective functions are presented in equation 6.

$$\begin{aligned} f_1(\vec{x}) &= s \\ f_2(\vec{x}) &= C_{raft} + C_{pile} = \alpha \cdot l^2 \cdot d + \left(l^{\beta} \cdot \pi \cdot \tfrac{d^2}{4}\right) \end{aligned} \tag{6}$$

with $\alpha = 30$ and

$$\begin{aligned} \beta &= 1{,}5 && \text{für} \quad 0 \le l \le 10\,\text{m} \\ \beta &= 1{,}9 && \text{für} \quad 10 \le l \le 20\,\text{m} \\ \beta &= 2{,}2 && \text{für} \quad 20 \le l \le 30\,\text{m} \\ \beta &= 2{,}3 && \text{für} \quad 30 \le l \le 40\,\text{m} \end{aligned} \tag{7}$$

The optimisation is carried out for three different pile diameters d_p by an evolutionary algorithm with 50 individuals and a maximum of 100 generations. The results are shown graphically in figure 6. The coloured gradation represents the pile-raft coefficient α_{KPP} . It is defined as the ratio of load capacity via piles to the load capacity via the raft.

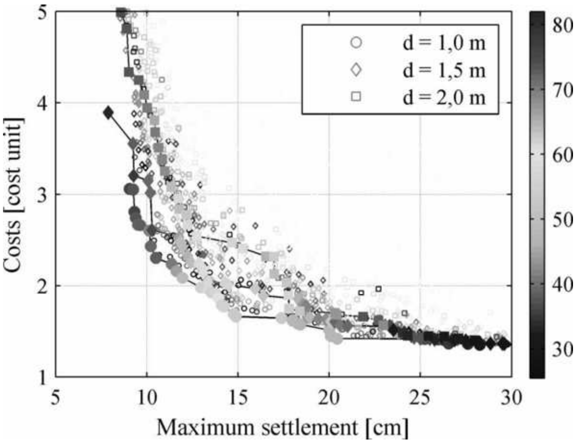

Figure 6. Results of the optimisation of a combined pile raft foundation

The algorithm shows a well-situated convergence the Pareto-optimal set is clearly revealed. Repeated calculations lead to comparable results that can be interpreted as the retrieving of the solution using a stochastic approach. The convergence of the algorithms becomes apparent by having a look on all considered parameter sets in figure 6. The intensity of grey colour shows the iteration step, the dark colour represents the advanced iteration. The darker points are compacted close to the Pareto-optimal set. The coloured points show the individuals in the last iteration step that identify the optima.

The shown results demonstrate clearly the use of optimisation. The dependency of the exemplary chosen costs and the maximum settlement of the free construction parameters get obvious only through the enforced optimisation. The avoidance of inappropriate solutions (grey points in figure 6) is achieved by the optimisation. The parameter space form the beginning of the calculation is limited to the Pareto-optimal sets. Thereby the decision maker is able to choose a solution that is an optimum in either case. Coeval the relation of the design objectives is correlated. The reduce of settlement from 20 to 15 cm for 1.5 m thick piles for example is coherent with additional costs about approximately 40 % .

6 CONCLUSIONS

Numerical optimisation provides methods to support the geotechnical design process. After investment of higher effort in the parameterised problem formulation efficient algorithms are able to deliver highly effective solutions.

The results can be used for realizing different constructions in the stability limit, for visualize the sensitivity regarding the construction parameters or simply for procuring a better market position.

Comparative analyses of the outcomes can also be used to map out construction rules for the prospective design of similar constructions.

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