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Numerical models of the reinforced soil

Les modèles numériques de sous-sol renforcé

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ABSTRACT
The paper considers the issue of ground-medium reinforcement. Based on generally accepted principles the author presents numerical modelling patterns of subsoil reinforced by gravel-columns. The compares the outcome of the numerical simulations with the measured load capacity of gravel columns located along the motorway bypass of Cracow, Poland. The paper constitutes an attempt to summarise and generalise earlier research which involved FEM numeric procedures and the Z_Soil package, and utilised an elastic-plastic model of a ground medium.

RÉSUMÉ
L'article présente les résultats d'une étude sur sol renforcé. Sur une base de donnees générales, sont presentes des schémas de procédure de modélisation numerique du sous sol renforcé par un procede de colonnes balastees. Les méthodes décrites sont accompagnées de donnees numeriques issues de calculs. Les résultats obtenus par les calculs ont été comparés avec des mesures réelles de portance de colonnes balastees exécutées sur l'autoroute péripherique de Cracovie (Pologne). L'etude numerique a été menee à l'aide de la methode des MEF (methode d'éléments finis) ainsi que le logiciel Z_Soil sur la base d'un sol élastique et plastique.

1 INTRODUCTION

Computational science is a relatively new domain of study whose exact definition is still to be agreed upon. In the broad sense of the term computational science involves the use of computers in the scientific investigation by combining and supplementing the area of theoretical and experimental aspects of the conventional research approach.

In the light of the title of the paper the first question to be dealt with should be what is to be understood by *model* and *modelling*. Indeed, *a model* is an artificial form that reflects and reproduces important characteristics, relationships and functions of a real-life object or phenomenon, while *modelling* comprises all of the activities involved in building of a model. The real-life object and its model must share certain features and functions.

A model, by virtue of being a simplification of the reality, is easier to apply than its real-life original. Thus, a model could be described as an abstraction of the reality obtained by reducing the original object to its simpler form. However, models often have features which do not match those in the original objects and there normally may be more than one model of a given real-life phenomenon or object. In practice one could speak of an infinite number of partial models matching an analysis and description of the real-life object to a varying degree.

Now when people need more and more land for building new investments they frequently have to reinforce the weak bearing subsoil. The concept of reinforcing soils with gravel columns is not new, because reinforced soil come into use in the early 1970's but now people reinforced soil using different techniques so new applicable mathematical and numerical models should be adopted for general use.

"(...) *Nothing happens against nature, but only against our limited knowledge"* is the motto of this project. It's objective is to use the available knowledge to build optimal numerical models specifically for certain ground reinforcement techniques, and to make those models both as simple as possible and as close as possible to the real behaviour of a complex ground medium and its reinforcing components.

2 MATHEMATICAL AND NUMERICAL MODELS

An 'actual configuration' is understood as a space containing a continuous medium and technical objects located within it. In this case this is ground-foundation with its reinforcement. Any theoretical investigation aiming to understand the behaviour of such ground medium under internal and external influences demands a mind-model complete with a set of formulae describing its properties, assumptions and simplifications, all of which together would constitute a mathematical or computational model.

2.1 *Mathematical models*

A mathematical model should be understood as a set of mathematical relationships describing the investigated physical phenomenon with certain accuracy. Mathematical modelling is the formulation of the mathematical process description. Various mathematical models can be built for each investigated object depending on the adopted simplifications that make the object description easier, but also affect the accuracy of the solution. While a far-reaching simplification may lead to the omission of important features of the actual object, a overly complex mathematical model could lead to errors in the solution because of the overly complicated computational process.

While there is no single method of building mathematical models there is a widely used set of technical simplifications that typically include, first of all, the assumption of a simple shape of the considered space, linear characteristics of certain physical and mechanical properties of the ground medium, its uniformity and a constant nature of physical properties in time. For the type of models pursued under this project, however, such assumptions are unsatisfactory. Indeed, the physical and mechanical parameters of the ground medium change in time during the construction of the reinforcement components and as a result of the consolidation process, all of which is an intended outcome of the gravel column application. Therefore, the models adopted in this project are far from simple. They assume that the subsoil parameters change in time, and take into account the variability of physical and mechanical parameters in the vicinity of the columns, as an outcome of the technology used in erecting the ground reinforcement components. On the other hand, however, the models are two-dimensional rather than three-dimensional. The assumption of an axis symmetry in the investigation of the configuration makes it difficult to analyse the functioning of arrays of components (gravel columns) reinforcing the subsoil.

2.2 *Numerical models*

Normally, mathematical modelling employs partial differential equations. Digitisation of a continuous mathematical model involving the application of a numerical method leading to a system of algebraic equations (full digitisation), or ordinary differential equations, typically with time derivatives (partial digitisation). Digital modelling of a discrete system involves a selection of a numeric algorithm to solve the equations of the discrete model, while numerical solving of the discrete equations of the model follows the adopted model-testing plan.

When utilising FEM mechanics to solve the task, one has to develop a discrete (computational) model equivalent to a mathematical model of a continuous medium. The process of building the model involves a number of steps, beginning with dividing the studied area V into sub-areas V_e – components; and adoption of nodal points so as to be able to approximate the function sought within the V_e area using approximation functions and independent nodal parameters. The following steps involve the determination of matrix structures describing the properties of a given model at each nodal point and working out matrixes for the entire system. Next comes the determination of boundary conditions and loading of the body followed by the solving of the basic system of equations and computation of functions derived using the determined nodal parameters. Mathematical issues arising during model development and application often require a determination of state parameters. By setting restrictions to such mathematical issues they are transformed into numerical issues: computer models can be applied to determining their set points, as long as the mathematical relationships, equations, inequalities and numerical data are known. Numerical mathematics and numerical data processing cover designing, analysis and application of computer-aided numerical problem solving. A combination of a mathematical issue (of a constructive nature), and objectives pertaining to outcome accuracy are referred to as a numerical problem.

3 PROBLEM SPECIFICATION AND ASSUMPTIONS

Any model development begins with defining the problem by adopting a research objective, problem scope and the expected accuracy. This project aimed to develop numeric models of a reinforced ground-foundation reflecting specific gravel column technologies applied.

The ground-foundation in question included two weak layers: a 1.8 m thick layer at 0.9 m below the surface and another one 0.9 m thick at 3.6-4.5 m. On the surface, a 0.6 m road embankment was erected using geogrid on a geosynthetic mattress (Fig. 1).

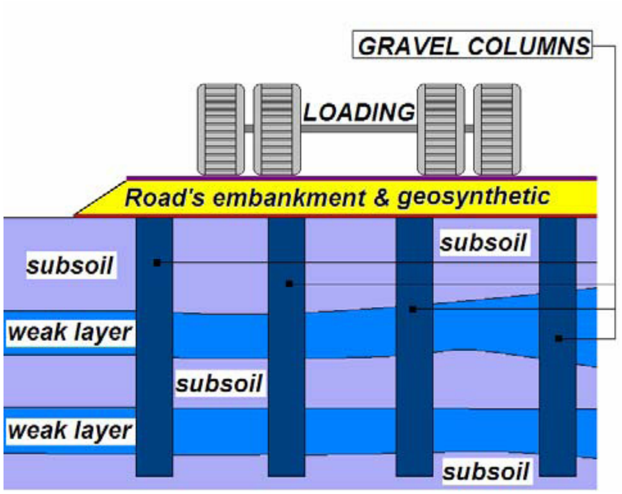


Figure 1. A representative cross-section of the reinforced ground medium.

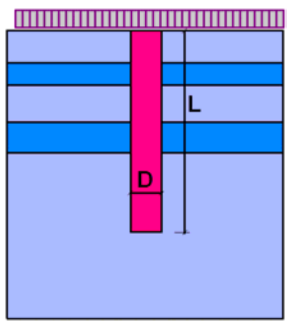
A number of computational models of gravel column-reinforced ground were proposed for this representative cross-section. A two- dimensional model was adopted and the operation of the reinforcement components was first considered as a single row of columns and then as a grid. Additionally, an axis-symmetric system was analysed consisting of a gravel column working together with the ground medium. The following numeric simulations assumed the ground and the reinforcing gravel columns as an elastic-plastic model applying the Drucker-Prager and Coulomb – Mohr criteria, as characterised by the same parameters (E – Young modulus, ν – Poisson ratio, Φ – friction angle, c - cohesion, γ – weight, and so on).

4 NUMERICAL MODEL - VERIFICATION ALGORITHM

Before a model can be adopted for general use it has to be verified using techniques known as verification and falsification. During the development phase a computational model is often modified and reformulated with higher accuracy. With each model component having a considerable influence on the outcome of testing, the development process was broken down into a number of stages.

During the first stage of testing the computational model consisted of a single column, with a known diameter D and length L, placed in the ground. (Tab. 1).

Table 1. Stages in numerical modelling of gravel-column reinforced the subsoil – stage 1.

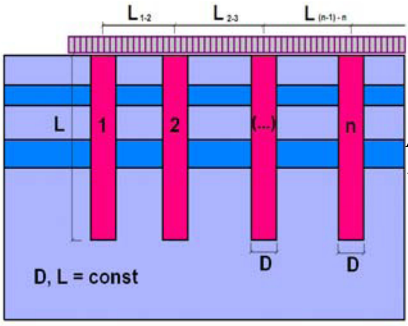
STAGE 1 MODEL OF SINGLE REINFORCEMENT COMPONENT	
MODEL	ANALYSIS
	Analysis of the shape and size of deformation, and determination of overall load capacity.

For such case the shape of deformation, size of warping and load capacity were determined. Nonetheless, this solution begged a number of questions, including: What does the defined load capacity pertain to and what does it characterise? How would a larger area of the ground behave?

Stage two sought to answer these questions with a modified model now involving a set of gravel columns working together, with the same diameter and length. Numeric testing assessed the impact of column spacing ($L_{1\text{-}2}$, $L_{2\text{-}3}$, $L_{3\text{-}4}$, ... , $L_{(n\text{-}1)\text{-}n}$, whereby ‘n’ was the number of columns in cross-section), on the load capacity of the entire configuration (Tab. 2).

Table 2. Stages in numerical modelling of gravel-column reinforced the subsoil – stage 2.

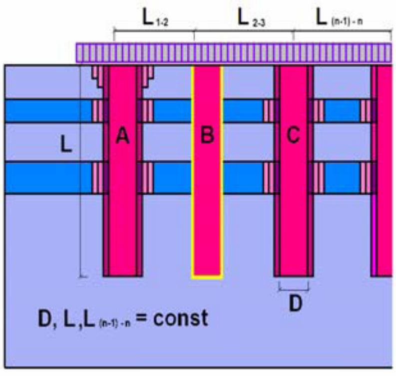
STAGE 2
MODEL OF SEVERAL REINFORCEMENT COMPONENTS WORKING IN CONJUNCTION

MODEL	ANALYSIS
	Analysis of impact of column spacing on deformation, its size and load capacity. Analysis of impact of ground consolidation and column role as drainage on increased overall load capacity.

The next step, involving a pattern of the best-spaced columns, was to test the impact of the compaction process on the scale of displacement and improvement of the overall load capacity. The results of simulation confirmed a considerable role played by the gravel columns as drainage in accelerating the compaction process. However, this conclusion triggered further questions, such as: How to features on the simulation outcome was necessary to determine the actual displacement and load capacity of the reinforced ground-foundation (Tab. 3).

Table 3. Stages in numerical modelling of gravel-column reinforced the subsoil – stage 3.

STAGE 3
MODELLING OF TRANSITION ZONE AT REINFORCEMENT COMPONENT

MODEL	ANALYSIS
	Analysis of impact of construction technology on ground deformation, its size and overall load capacity. Analysis of extent of transition zone and its impact on end result of computation.

The modelling process, therefore, progressed into a following stage generating three new computational models which took into consideration the column shape depending on the construction technology; gravel columns in geosynthetic sleeves, gravel columns made by percussive consolidation, or by vibroreplacement (Fig. 2).

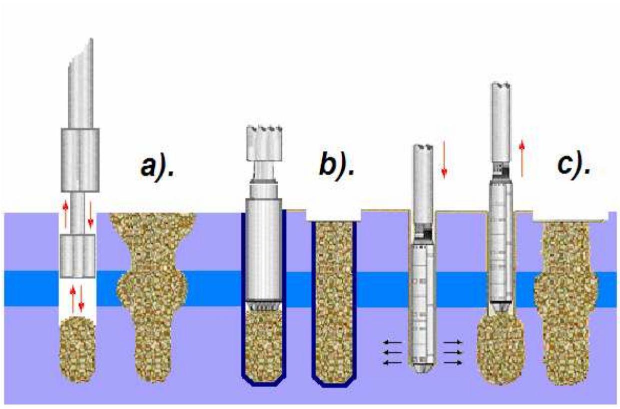


Figure 2. The subsoil reinforced by: a). gravel columns made by percussive consolidation b). gravel columns in geosynthetic sleeves, c). gravel columns made by vibroreplacement.

The computation shows that the column construction technology is an important factor in the development of a numerical model. It has a considerable impact on the end results of numerical testing to determine the ground load capacity and deformation process analysis.

The numerical test results will be compare to the actual load capacity of a reinforced ground-foundation which is measuring under the Cracow motorway ring road, at the Wielcki Junction. The assumed flat models represent in fact a three-dimensional issue and therefore are subject to standard homogenisation procedures and so any future work will aim to arrive at the best possible modelling of the spatial nature of the task and developing of a 3D model. The proposed axis-symmetrical model of a gravel column yields results that can be related to the ground load capacity as measured by proof loading.

In the analysis of the extent of the transition zones evolved during the construction of the reinforcing component using certain technology it remains an open question what are the stiffness modulus values in the ‘compacted zones’ and their size, and then how to take such data into consideration in a numerical model. The most important question to be answered in each case is whether adding more components to the model is bringing a true solution closer or perhaps it is just making the task overly complicated and causes the computational procedures and numerical approximations generate errors distorting the final outcome.

5 CONCLUSION

Theoretical instigation, simulation and empirical experiment are closely related and none of these cognitive methods should be applied separately. A simulation, i.e. analytical or numerical solving of model equations, can generate full and credible results only if it is theoretically and empirically verified. In order to arrive at the best possible model of the actual system further testing is necessary to determine the impact of the various assumptions and simplifications adopted on the end result of the investigation, which should be followed by a selection of a computational model that is both as simple as possible and provides results that are the nearest to real-life.

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