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GEO-ENGINEERING COMPUTER SIMULATION SEEMS ATTRACTIVE BUT IS IT THE REAL WORLD?

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Abstract: Correct formulation of the differential equation system for equilibrium conditions of subsoil, especially in terms of controlled numerical calculation, is discussed. The problem of solution stability is also considered. The solution of problems, which are ill-posed, have no practical value in the majority of cases and in this way the engineering prognosis can lead to a real disaster. The object of this paper is quite relevant if its application is taken into account. Numerical calculations of boundary value problems must often be performed as true predictions. Unfortunately, the ability to submit a reliable prediction seems to be lacking in geotechnical engineering. Several reasons, which may be responsible for this disappointing state, are described.

1. INTRODUCTION

Routine usage of numerical tools such as finite element, finite difference in computational soil dynamics or statics analysis software in geoengineering design has increased in recent years. Advances in software and hardware technology mean more nonlinear and therefore complex three-dimensional analyses are being performed. However, these powerful software, which are in most cases "black box", in nature, may potentially lead to "computer-aided-disaster" in the hands of analysts who may have the "computing" skills but, on the other hand, they are not necessarily experienced in extensive engineering and in computational mechanics. A strict implementation of quality assurance procedures may not necessarily ensure an appropriate numerical model or analysis technique (BACKMAN [1]).

The key to validating the computed results is an independent calculation that does not involve the use of numerical software tools. In some cases, these solutions are available. But in other cases, it can only resort to laboratory or field observations and measurements.

There have always been errors – arithmetical errors, errors in assumptions, errors in mathematical models, errors in interpretation of codes, errors in the use of formulas, tables, charts and nomograms, and many others. There were errors when calculations were done by hand, and not only did those errors persist but there were additional errors when calculations were done with the help of slide rules, mechanical calculators and electronic calculators.

If we are of the opinion that a certain amount of errors under the initial or boundary conditions is unavoidable, then these errors will manifest themselves in the solution, too. This problem is not trivial because not always the error in the solution also proves small. Such boundary value problems are called *well-posed*. One should mention that the solutions of problems, which are ill-posed, have no practical value in the majority of cases, and in this way the engineering prognosis can lead to a real disaster. This is of great importance if the solution application is taken into account (SIKORA [8], CHAMBON et al. [2]).

Now we are dealing with computer-related errors resulting from defects in the computer hardware, bugs in the software, inexperienced users and other computer-related shortcomings. Errors can really lead to various types of engineering failures – poor solutions to problems in civil engineering, poor performance of facilities, or even catastrophic failures of civil engineering facilities.

While the change from hand calculations to slide rules, calculators, and currently computers speeded up the calculation process and increased the degree of automation, each change resulted in additional types of errors. However, because of no available data it is not possible to show whether or not the number of failures, with each change, increased, was the same, or decreased.

Currently, civil engineering facilities are designed using a combination of hand calculations (performed with the aid of electronic calculators, formulas, tables, charts, and nomograms) and computers.

The design of geotechnical structures is mainly based on a numerical calculation of boundary value problems. Contrary to standards, which usually cover only the most simple cases or give vague recommendations, numerical simulations seem to produce impressive pictures of the overall behaviour with a detailed distribution of the values for all important design variables and physical quantities.

In spite of the effective marketing of software producers and audacious projects of engineering companies, there are still many weak points in our knowledge and we still do not master numerical simulations as we would wish to do.

2. EXAMPLES OF KNOWN PREDICTION

The main task in civil engineering is making predictions. Predictions are needed for design, for the evaluation of serviceability or for the estimation of risk. They simulate unknown state-parameters in planned and existing structures or the impact of natural phenomena. Although predictions can be made intuitively or rather empirically, nowadays it is expected to perform numerical predictions using mathematical models (HERLE [3]).

The sole way of evaluating the quality of numerical predictions is to compare them with measurements and observations, and if it is possible in situ.

Let “MIT trial embankment” be the example of the construction built on a normally consolidated soft clay layer (figure 1). Prior to its construction the laboratory experiments with the subsoil were done and the first construction stage up to 12.2 m in height was monitored by field measurements (LAMBE [5]). These data allowed the prediction of deformations, pore pressure and maximum additional height of the embankment at subsequent rapid filling leading to failure.

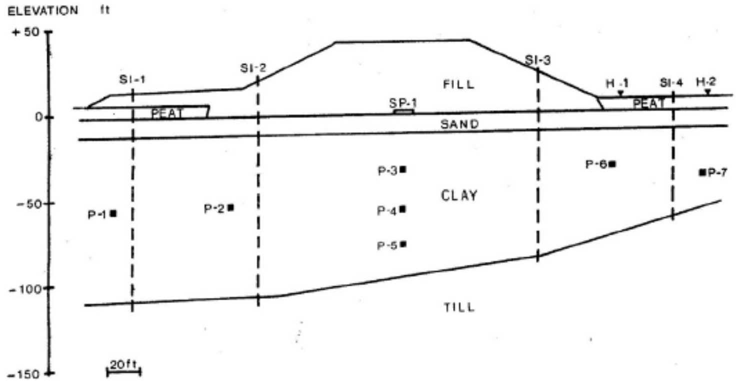

Fig. 1. MIT trial embankment, USA (1974) (WROTH [10], HERLE [3])

The predictions were submitted by ten groups. There was a large scatter of the numerical results (see the table). Although mostly linear and nonlinear elastic models were applied, one of the best predictions was based on the Modified Cam Clay model (WROTH [10]). This model was very good with respect to pore pressure but still proved less accurate in the case of deformations (predicted 4 cm at SP-1 and 4.1 cm at SI-3).

Table

Additional deformations due to 6 ft (1.8 m) of fill, (WROTH [10])

Item	Predicted [cm]	Measured [cm]
Settlement of SP-1	1.9. . . 34.8	1.7
Horizontal movement of SI-3 (at -30 ft)	0.4. . . 21.8	1.3
Heave of H-1	0. . . 12.2	–0.3

The second example presents a field experiment of “excavation in sand”, i.e., a sheet pile wall was driven into a homogeneous sand layer above the groundwater level and the task was to predict the embankment behaviour during a 5 m deep excavation (von WOLFFERSDORFF [9]). Slurry walls perpendicular to the sheet pile wall imposed plane strain conditions. For keeping the wall stable, struts were installed at the depth of 1.5 m. After the excavation an additional surcharge was placed at the ground surface behind the pit and the struts were loosened in order to reach the limit state.

In situ and laboratory soil investigations were performed prior to the excavation. The results from 43 predictions included horizontal displacements of the wall, vertical displacements at the ground surface, earth pressure on the wall and bending moments in the wall.

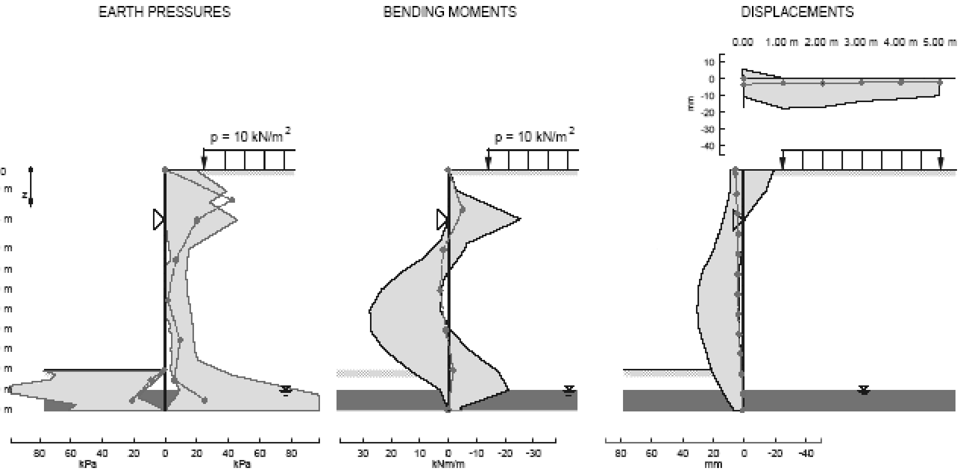

Fig. 2. Predicted (shaded range) and measured (line with points) values for the excavation in sand near Karlsruhe, Germany (1993) (von WOLFFERSDORFF [9], HERLE [3])

Most calculation methods are based on finite elements with different constitutive models. The comparison of calculated values with measured values was very disappointing (see figure 2 for final excavation stage with surface load, prior to the limit state). Especially disquieting is the fact that displacements have been predicted several times in the opposite direction than measured ones (von WOLFFERSDORFF [9]).

3. ELEMENTS OF PREDICTIONS

A geotechnical prediction task within the geomechanical computations process is represented by several important modelling steps:

- idealization, i.e., simplification of the reality and choice of important variables, geometry, domain, boundary conditions, construction details and stages, and so on,
- discretization process, i.e., element type, size and density, time step, type of loads, a.s.o.,
- qualification of constitutive equations, calibration of parameters, determination of initial state, framework for calculation of strains, model for interfaces, a.s.o.,
- numerical analysis of numerical methods for time and space integration, solution of algebraic equations, iteration schemes, well-posedness, a.s.o.

All steps are equally important and it is impossible to say a priori which aspect can be responsible for greater errors in predictions. These steps make a chain, which fails at the weakest link! Thus, for making predictions, it is necessary to have an insight into all of the topics mentioned. Computer software cannot yet replace the sound judgment based on the profound knowledge and makes automatic decisions based on several options interconnected with complex relations.

4. SOURCES OF ERRORS

We can mention many potential sources for errors in numerical calculations; the most important can be itemized as follows:

- hardware and software bugs,
- application of unsuitable theory/code,
- erroneous input (obvious misunderstanding/misinterpretation of data),
- lack of data (e.g., variability of geological conditions, loading scenarios),
- idealization of reality (neglecting important aspects),
- inappropriate constitutive models (e.g., linearization of significant nonlinear effects),
- determination of material parameters,
- description of initial state (initial values of state variables),
- mathematical and numerical problems.

Some of those error sources can be controlled, at least to a certain extent, by engineers; however, the other ones, like hardware/software bugs or the lack of data, are independent of their qualification and contribute to the uncertainty of the predictions. An expert on geoengineering should know about such problems, but another question arises how to wipe the slate clean.

5. THE ROLE OF CONSTITUTIVE MODELS

In geomechanical computations, constitutive models for soils play the crucial role. The mechanical behaviour of geomaterials is extremely complex, therefore the constitutive theory must always be a compromise between the well-fitting laboratory tests and a simple form of their application. It is a difficult task to assess the suitability of a constitutive equation for practical applications. There is always a checklist to be answered, e.g.:

- How to define the quality of a constitutive model? (KOLYMBAS [4]).
- What are the limitations of the constitutive model?
- How to check the model selected?
- How to apply/use the model selected?

- Is it possible to create the so-called “natural” material model, based on ANN and large DB?
- How to implement a promising model into a computer code attainable to an engineer?
- How to make the computer applications as simple as possible, but not simpler?
- Should/must be get-at-able the computer codes to the user (engineer)?
- What kind of numerical check-nodes should be mounted in order to get the correct solution of the boundary value problem from mathematical viewpoint?

Nevertheless, besides these general questions every forecaster should be aware of several substantial aspects which are of great importance for the application of constitutive models, mathematics and, last but not least, the programming code in geomechanical computation.

6. MATHEMATICAL AND NUMERICAL ASPECTS

Unfortunately, the use of more and more sophisticated models does not necessarily mean that we arrive at better results. More realistic elements of the simulation process are inevitably connected with more complicated mathematical structures. For most geotechnical problems it is difficult or practically impossible to guarantee well-posedness which is reflected in three aspects of the mathematical solution, i.e., existence, uniqueness, stability (i.e., small changes in the input produce finite changes in the output), (cf. SIKORA [8]).

Geotechnical calculations are considered to be a potential source of many mathematical and numerical difficulties. Material models are highly non-linear and the localized deformation is often related to bifurcations manifested themselves as shear localization and the loss of controllability. Shear bands represent also discontinuity of the solution in space and introduce remarkably different scales into the problem.

The mathematically correct solutions are by no means assured. Since several years scientists have realized that we live in a “chaotic” world full of bifurcations (cf. uniqueness) which can be extremely sensitive to small changes of initial and boundary conditions (cf. stability) (PRIGOGINE and STENGERS [6]).

However, in geomechanical computations, one has to take into account several easily accessible numerical conditions in order to guarantee the physical meaning of the numerically computed solution (SIKORA [8], CHAMBON and CAILLERIE [2]). Especially the latter author gives the tool for checking a local condition at Gauss-quadrature points. For a geotechnical engineer it is difficult to reject a fully deterministic approach, although he is often confronted with instabilities.

7. CONCLUDING REMARKS

The right choice and application of a constitutive model is not sufficient if the boundary value problem to be simulated does not include some essential aspects of the reality.

Prediction competitions and benchmarks in geotechnical engineering learn us the lesson that our ability to make reliable numerical prediction is very limited. Moreover, we still deal with many topics related to geotechnical simulations which are not discussed in this paper, e.g., averaging procedures in multiphase continua (partial saturation), soil dynamics (inertial and damping effects, wave propagation) or time- and rate-dependence. They further increase the difficulty level of calculations, (HERLE [3]).

The current situation may seem rather controversial. On one hand we need the models which involve the salient features of the soil behaviour (non-linearity, irreversibility, pressure-, density- and path-dependence), on the other hand the increasing complexity of material models poses additional mathematical difficulties which can be hardly overcome.

Anyway, at least the necessity to use better constitutive models should be accepted. One should abandon classical soil parameters like Young's modulus and Poisson's ratio (elastic formula) or angle of internal friction and cohesion (plasticity regime), which are not constants for any soil. Using them one implies linearity in many respects which contradicts the observed behaviours of soils. Unfortunately, this trend is still present today in many designing departments, and such computational technique is legitimate solely in education which has, probably together with standards and recommendations, the greatest inertia to keep conventional way of doing.

It was found that the quality of construction has a significant impact on the structure performance which may not be quantified and analyzed accurately during the design phase. The importance of the structure monitoring immediately after its completion should not be overlooked, as it can be useful for future back-analysis. Despite the fact that the numerical tools could analyze these complex problems, the analysts should still be able to distinguish between important and unimportant parameters. In the analysis of an unfamiliar problem, the validation process should be done incrementally. Perhaps the key to finding a validation method is to ask whether there are other ways to arrive at the solution without the use of numerical analysis tools. In many cases, these solutions can be found due to extensive literature search. But in other cases, laboratory tests and field observations will be the only alterative.

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