Geomechanical methods

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1 Introduction

The methods, available to solve geotechnical (geomechanical) tasks can be categorized as follows:

- Closed analytical solutions
- Semi-analytical solutions
- Numerical simulation techniques
- Empirical relations
- Physical models
- Lab investigations
- Field measurements and natural analogs

Within the following sub-chapters the different methods are shortly characterized, especially in comparison to the numerical modelling approaches, which will dominate in the future. Nevertheless, it should be stated clearly, that all methods have their right to exist and the choice of the appropriate method depends always on the specific task, available data, project phase and other circumstances. Often the combined and/or parallel use of several different methods is recommended. Also, it should be noticed, that there is no alternative to lab and/or field investigations. However, the closed analytical solutions, the semi-analytical solutions, the empirical solutions, the physical models and the numerical simulation techniques are in competition to each other and can, to a certain extend, replace each other.

2 Detailed description of methods

2.1 Closed analytical solutions

Closed analytical solutions of the underlying differential equations deliver exact solutions and have a high degree of generalization. Whole sorts of self-similar problems can be solved if closed analytical solutions are found. Analytical solutions can easily be reviewed and a lot of solutions are already available and published in textbooks and articles. Therefore, the use by the engineers and scientists is easy and results can be obtained fast.

Beside these advantages, closed analytical solutions are characterized by several severe limitations, because solutions can be obtained only for quite simple constellations. For more complex geometries, anisotropies, inhomogenieties, non-linear material behavior and coupled processes (e.g. hydro-thermal-mechanical coupling) closed analytical solutions can often not be found.

Therefore, in most cases closed analytical solutions can be used only for rough estimates, but play an important role during the verification process of numerical simulation tools.

<u>Typical example:</u> isotropic elastic stress and deformation state around a circular or elliptical hole (can be applied for boreholes, shafts, drifts, tunnels etc.).

2.2 Semi-analytical solutions

Within this document the term ‘semi-analytical solutions’ comprises all methods in respect to stress, strain and stability analysis witch go beyond the closed analytical solutions but do not show the complexity of the numerical simulation techniques. Semi-analytical solutions are obtained by solving differential equations, where closed solutions could not be obtained and more simple numerical solution parts have to be incorporated. Compared to closed analytical solutions they allow the consideration of much more complexity in respect to geometry, anisotropy and complex material behavior. They are already widely used in geotechnical engineering and have found their way into standards and regulations. They are easy to handle and results can be obtained within short time. However, compared to numerical simulation techniques they have also a few drawbacks. The semi-analytical solutions do not cover the whole spectrum of geomechanical information, instead each solution focus only on a certain aspect: e.g. solutions, which give only deformations, or solutions, which only consider the stability, or solutions, which only give stresses. Moreover, the semi-analytical solutions inhibit several simplifications in respect to the physics. Semi-analytical solutions will be replaced step by step by more advanced numerical simulation techniques.

<u>Typical example:</u> Support dimensioning in tunneling using the ‘bedded beam procedure’, prediction of settlement and consolidation by the using the ‘stiffness module or bedding module approach’ or using the ‘limit equilibrium approaches’ to determine the slope stability.

2.3 Numerical simulation techniques

Numerical simulation techniques are based on the discretization of the object under consideration and the ‘element’- or ‘point’-wise numerical solution of the underlying physical problem. Numerical simulation techniques can be distinguished in terms of the discretization in time (implicit versus explicit) and the discretization in space (mesh-based versus mesh-free). It is also possible to distinguish between continuum and discontinuum approaches. In principle, numerical approaches have no limitations in respect to the complexity in terms of geometry, nonlinearities, anisotropies, inhomogeneities or couplings. Therefore, even complex HTMC-coupled problems can be handled. Also, parameter studies, optimization, sensitivity and robustness analysis can be performed easily. The potential of numerical simulation tools are clearly superior to analytical or semi-analytical methods, but one should take into consideration, that the correct application of numerical simulation tools need highly educated stuff. Verification and validation of such powerful tools is complicated and elusive. Also, the set-up and testing of numerical models is still time-consuming and the pure computing time can reach hours, days or even weeks for standard engineering problems.

<u>Typical example:</u> Finite Element Method, Finite Difference Method, Discrete Element Method, Boundary Element Method, Smooth Particle Hydrodynamics

2.4 Empirical relations

Empirical relations are obtained through the generalization of experience. They exist for typical constellations only. The basis for empirical relations can be: practical in-situ experience obtained from mining or civil engineering projects or results from lab or field tests. The relations are phenomenological and have no physical background. Therefore, these relations do not allow any deeper insight into the underlying processes and consequently, profound conclusions or decisions are impossible. Also, caution is required, if such relations are applied to areas beyond the area of experience (area, from which the empirical relations were deduced). It should always be the aim to replace or at least to complement the empirical relations by physical-based solutions.

Typical example: Company-internal rules in mining or tunneling

2.5 Physical models

Physical models comprise the physical modelling of the object at reduced scale by using of equivalent materials under consideration of the laws of physical equivalence. Physical modelling allows the consideration of very complex situations in terms of geometry, loading conditions and material behavior. Also, boundary and initial conditions can be well defined and measurements can be performed with high accuracy at any location in the model. Therefore, compared to analytical and semi-analytical solutions, physical models can consider much more complexity, which is only comparable with numerical simulation techniques. On the other hand, the set-up of physical models is extremely time-consuming (weeks to months) and the model does allow only one test up to failure. Due to the huge costs and the fact, that parameter studies, sensitivity studies, optimization etc. is nearly impossible to conduct, physical models are replaced more and more by numerical simulation techniques.

Typical example: Dam models or tests in water or air channels

Physical equivalence is guaranteed by considering the similarity coefficients *SC*. The following holds:

$$\frac{SC_{\sigma}}{g \cdot SC_{\rho} \cdot SC_{L}} = 1, \quad \frac{SC_{U}}{SC_{\varepsilon} \cdot SC_{L}} = 1, \quad \frac{SC_{\sigma}}{SC_{\varepsilon} \cdot SC_{E}} = 1, \quad \frac{SC_{\sigma}}{SC_{C}} = 1, \quad SC_{\varepsilon} = SC_{\phi} = SC_{\nu} = 1$$

SC_{σ} similarity coefficient for stress
SC_{ε} similarity coefficient for deformation
SC_{ϕ} similarity coefficient for friction coefficient
SC_{C} similarity coefficient for cohesion
SC_{E} similarity coefficient for Young's modulus
SC_{ν} similarity coefficient for Poisson's ratio
SC_{ρ} similarity coefficient for density
SC_{L} similarity coefficient for geometry scale
SC_{U} similarity coefficient for displacement
G gravity

2.6 Lab investigations

The aim of lab tests is the investigation of the geomaterial under different loading conditions and the determination of corresponding parameters and constitutive relations, which are necessary for conducting empirical, analytical or numerical calculations. The advantage of lab tests consists in the fact, that measurements as well as boundary and initial conditions, like loading, temperature, water content etc. can be performed and specified, respectively, in a precise manner at reasonable costs and in short time. One should take into account, that lab samples are small in size. Therefore, in most cases data deduced from lab tests cannot be used directly for solving in-situ problems, but need a transformation due to the scale-effect. Rock mass classification systems can be used for this transformation process. Also one should keep in mind, that rock samples are disturbed to some extend due to sampling and sample preparation and therefore, parameter can deviate from those existing in-situ.

Typical example: Uniaxial and triaxial compression tests to deduce the strength criterion and the failure envelop, ultrasonic wave speed measurements to deduce dynamic elastic constants or Brazilian test to deduce tensile strength.

2.7 Field measurements and natural analogs

Field measurements and observations of natural analogs are performed under in-situ conditions: Normally they are more expensive and time-consuming than lab tests, but they deliver data at ‘real’ scale (size). Field data can be obtained at several points in time or phases during a project (monitoring) and can be used to calibrate or validate calculations. They can also be used during the back analysis to determine adequate parameters and constitutive relations (parameter identification).

Typical example: Dilatometer measurements to determine in-situ deformation modulus, big shear experiments to deduce the in-situ shear strength of joints, observation of geological sealing elements (layers)