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Back analysis of geomechanical parameters by optimisation of a 3D model of an underground structure

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ABSTRACT

One of the major difficulties for geotechnical engineers during project phase is to estimate the geomechanical parameters values of the adopted constitutive model in a reliable way. In project phase, they are normally evaluated by laboratory and in situ tests and, in the specific case of rock masses, by the application of empirical classification systems. However, all methodologies lead to uncertainties due to factors like local heterogeneities, representativeness of the tests, etc. In order to reduce these uncertainties, geotechnical engineers can use inverse analysis during construction, using monitoring data to identify the parameters of the involved formations. This paper shows the back analysis of geomechanical parameters by the optimisation of a 3D numerical model of the hydroelectric powerhouse cavern of Venda Nova II built in Portugal. For this purpose, two optimisation techniques were considered: one classical optimisation algorithm and an evolutionary optimisation algorithm. In the optimisation process, displacements measured by extensometers during excavation were used to identify rock mass parameters, namely the deformability modulus (E) and the stress ratio (K_0). Efficiency of both algorithms is evaluated and compared. Both approaches allowed obtaining the optimal set of parameters and provided a better insight about the involved rock formation properties.

1. Introduction

Design and construction of underground works are many times based on the observational method (Terzaghi and Peck, 1948) in which field measurements are used in order to overcome uncertainties related to the complexity and unpredictability of geological/geotechnical features. Hence, during construction and in some cases also in the exploration stage, displacements and stresses of the geological formations surrounding the underground structure are monitored. Nowadays, observational information can be used by practitioners and researchers to validate or update the input data (like the geomechanical parameters) allowing a deeper understanding of the formations/underground structure behaviour providing a sound basis for the adaptation of the initial design and construction method.

The procedure of using field measurements in order to obtain input material parameters is called back analysis. This procedure was introduced in tunneling engineering by Gioda (Gioda and Maier, 1980), Gioda and Maier (1980) and Cividini et al. (1981) for the sophistication of the observational method and constitutes an essential tool for assessing design parameters in underground structures.

In Fig. 1 a scheme of the observational method that takes advantage of back analysis is presented. After the geotechnical survey, one or more constitutive models have to be chosen for the formations and a set of values have to be established for each parameter. Numerical models are then developed to predict displacements and stresses and for safety assessment. During construction monitoring data can be collected and used in a back analysis process to obtain an updated and more reliable geotechnical model that can optimise the design and construction process. In this sense, it is important to develop reliable back analysis procedures that can provide the optimum set of parameters. This work tries to contribute to this goal.

Modelling softwares are not prepared to compute geomechanical parameters from measured data. Consequently, an iterative procedure has to be adopted in order to obtain the required output. Depending on the way the identification problem is solved, the available back analysis methodologies can be divided in two main categories: the inverse and the direct approach (Cividini et al., 1981; Gioda and Sakurai, 1987).

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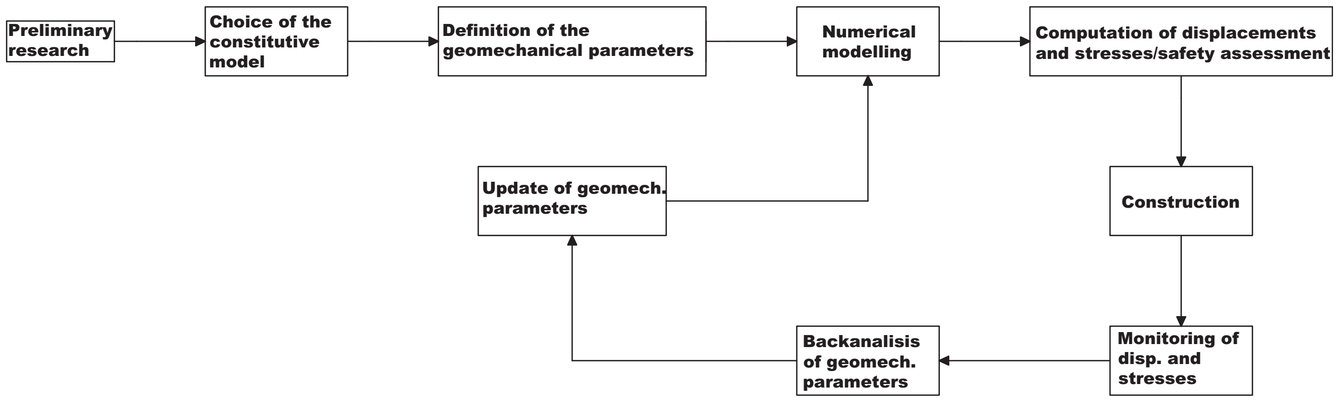

Fig. 1. Scheme of the observational method using back analysis in the process.

In the inverse approach the equations which describe the system behaviour are rewritten/inverted in such a way that the material parameters appear as outputs and the measured quantities as inputs. The first application of the inverse approach was carried out by Gioda and Maier (1980) to identify elastic parameters and earth pressure in a tunnel lining. This approach, in spite of normally being more efficient (demands less iterations to converge), raises however some computational issues. For instance, in order to invert the governing equations, and when a numerical model is used, it demands the access to the software code which most of the times is not possible.

In the direct approach the numerical model is not modified. It is used together with an error function (like the least squares), also called cost function, which measures the difference between the observed and computed quantities. This function, which is normally non-linear, is minimised in an iterative process using an optimisation algorithm. The direct approach is more flexible then the previous since the optimisation routine can be programmed independently from the numerical model and the coupling can be carried out using simple programming. However, the iterative process can be time-consuming and convergence to the global minimum is not assured. In the developed studies, the direct approach was used since it is a far more flexible methodology.

In this paper, the main components and methods of back analysis are summarized with special emphasis to the type of algorithm used in the optimisation process. Afterwards, a brief state of the art concerning the use of classical and innovative optimisation algorithms in back analysis applied to underground structures is presented. A real case study of back analysis of geomechanical parameters in an underground structure built in Portugal using an algorithm based on classical optimisation techniques and an innovative algorithm based on evolutionary computation techniques is carried out. The main results are presented and the strengths and drawbacks of each approach are pointed out.

2. Main components and methods of back analysis

In geotechnical engineering, inverse analysis has been used mainly to estimate rock or soil parameters based on field monitoring (Ledesma et al., 1996). In the particular case of underground works, the measurements performed in the first excavation stages can be used to back analyse the parameters which then can be employed to modify/optimise the design and excavation process.

The main components necessary to perform back analysis through the direct approach are the following (Oreste, 2005):

- a representative calculation model that can determine the stress/strain field of the formation;
- an error function;
- an optimisation algorithm to reduce the difference between the computed results and the observed values.

The error function can take several forms. Its appropriate definition is very important to obtain good results in the back analysis process (Yang and Elgmal, 2003). The most used error functions in geotechnics are (Ledesma et al., 1996; Tavares, 1997):

- Least-square method: the parameters are obtained by minimising a function depending on the squared difference between the measured and computed values.
- Maximum likelihood approach: a probabilistic formulation that can be applied when the probability density function of the measurement errors is known.

The probabilistic approach is well suited to incorporate previous knowledge about the parameters and treat observation errors in a consistent way. However, it is usually difficult to determine the distribution parameters of the involved random variables.

There are two main approaches to minimise the error function: iterative optimisation algorithms form the field of classical optimisation theory such as the Simplex, the Levenberg–Marquardt or gradient methods (Gens et al., 1996; Ledesma et al., 1996; Lecampion et al., 2002; Calvello and Finno, 2004); optimisation methods from the evolutionary computation and artificial intelligence (AI) field like neural networks (ANN), genetic algorithms (GA), evolution strategies (ES), simulated annealing, etc. (Haupt and Haupt, 1998; Hashash et al., 2004).

Concerning the classical optimisation methods, the main differences and their applicability are related with the use or not of the first and second derivatives of the error function. The methods that use these derivatives are normally more efficient that the others. However, in some cases, the error function is not differentiable or the computation of its gradient involves high computational costs. Also, the success of the procedure is strictly connected to the ability of the numerical and constitutive models to accurately predict ground behaviour and to the quality and quantity of measurement data (Mattsson et al., 2001; Sakurai et al., 2003).

These algorithms do not search in the entire parameter space for the optimal solution. They are characterised by a local search for a minimum of the error function, which is possible to attain only under some specific conditions. A highly non-linear error function, which is common in geotechnical problems, may contain several local minima. In this case, different solutions can be identified depending on the initial estimation of the parameters (Calvello and Finno, 2002; Miranda, 2007). There is no way to determine whether the set of obtained parameters is also the global minimum