NUMERICAL MODELLING IN ROCK ENGINEERING

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12.1 Modelling in rock engineering design

Modelling is simply the operation of a numerical tool. The behaviour of rock mass complex and is distinguished from other engineering materials by the presence of inherent discontinuities such as joints, bedding planes and faults that control its behaviour. Hence, the prediction of the response of rocks and rock masses derives largely from their discontinuous and variable nature. The highly complex and non-linear behaviour of rock mass depends on the degree of jointing and also on the degree of confinement. Therefore, a universal constitutive law may not be appropriate even if it is non-linear. The understand and analyse rock mass behaviour, different modelling techniques have been developed and now one can find wide spectrum of modelling approaches. They are categorization into eight approaches based on four methods and two levels, (Hudson, 2001).

A categorization into eight approaches based on four methods and two levels is illustrated in Fig. 12.1 (after Hudson, 2001). The modelling and design work starts with the objective, the top box in Fig. 1. Then there are the eight modelling and design methods in the main central box. The four columns represent the four main modelling methods:

Method A - design based on previous experience.
Method B - design based on simplified models.
Method C - design based on modelling which attempts to capture most relevant mechanisms.
Method D - design based on ‘all-encompassing’ modelling.
Figure 12.1 Eight different approaches to rock mechanics modelling for rock engineering design

All geotechnical/rock mechanics problems broadly can be divided into 3 types of problems, namely equilibrium or stability, stress and deformation behaviour and drainage (Fig.12.2).

1. Equilibrium/stability
2. Stress and deformation behavior
3. Drainage
Burland (1999) provided a triangle for the Geotechnical / Rock engineering design and is known as Burland triangle. As per Burland (1999),

1. Geotechnical design requires a clear understanding of the ground profile established from a site investigation.
2. Soil/rock behavior provided from field and laboratory measurements and
3. Application of this understanding through the use of modelling.

Two important features of this triangle: first, that all three steps are interlinked and second, they are all tied together by experience.
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Figure 12.3: Burland Triangle (Anonymous 1999)
12.2 Numerical techniques for rock mechanics

✓ Finite element method (FEM)
✓ Finite difference method (FDM)
✓ Boundary element method (BEM)
✓ Distinct element method (DEM)
  --Discontinuous deformation analysis (DDA)
  --Key block approach
  --Lattice models
✓ Discrete fracture network method (DFN)
✓ Hybrid methods
✓ Neural Networks

Finite difference method
The FDM is a direct approximation of the governing PDEs by replacing partial derivatives with differences at regular or irregular grids imposed over problem domains, thus transferring the original PDEs into a system of algebraic equations in terms of unknowns at grid points. The solution of the system equation is obtained after imposing the necessary initial and boundary conditions. This method is the oldest member in the family of numerical methods, one that is widely applied and is the basis of the explicit approach of the DEMs. FDM procedure recognizes the multidimensional continuity of rock masses and doesn’t require separate interpolation for extension to other parts. Software uses FDM method are FLAC2D & FLAC3D.

Finite element method
The FEM requires the division of the problem domain into a collection of sub-domains (elements) of smaller sizes and standard shapes (triangle, quadrilateral, tetrahedral, etc.) with fixed number of nodes at the vertices and/or on the sides—the discretization. Trial functions, usually polynomial, are used to approximate the behaviour of PDEs at the element level and
generate the local algebraic equations representing the behaviour of the elements. The local elemental equations are then assembled, according to the topologic relations between the nodes and elements, into a global system of algebraic equations whose solution then produces the required information in the solution domain, after imposing the properly defined initial and boundary conditions. The FEM is perhaps the most widely applied numerical method in engineering today because its flexibility in handling material heterogeneity, non-linearity and boundary conditions, with many well developed and verified commercial codes with large capacities in terms of computing power, material complexity and userfriendliness.

FEM yields solution at fixed point in the domain of interest and may need additional interpolations for solution at other points. Most of the softwares uses FEM like, PLAXIS, ABAQUS, ANSYS, PHASES etc.

**Boundary element method**

The BEM, on the other hand, requires discretization at the boundary of the solution domains only, thus reducing the problem dimensions by one and greatly simplifying the input requirements. The information required in the solution domain is separately calculated from the information on the boundary, which is obtained by solution of a boundary integral equation, instead of direct solution of the PDEs, as in the FDM and FEM. It enjoys greater accuracy over the FDM and FEM at the same level of discretization and is also the most efficient technique for fracture propagation analysis. It is also best suited for simulating infinitely large domains due to the use of fundamental solutions of the PDEs in such domains.

**Discrete element method**

The DEM for modelling a discontinuum is relatively new compared with the three methods described above and focuses mostly on applications in the fields of fractured or particulate geological media. The essence of the DEM is to represent the fractured medium as assemblages of blocks formed by connected fractures in the problem domain, and solve the equations of motion of these blocks through continuous detection and treatment of contacts between the blocks. The blocks can be rigid or be deformable with FDM or FEM discretizations. Large displacements caused by rigid body motion of individual blocks, including block rotation, fracture opening and complete detachments is straightforward in the DEM, but impossible in the FDM, FEM or BEM.
Discrete fracture network method (DFN)
An alternative DEM for fluid flowing fractured rock masses is the DFN method that simulates fluid flow through connected fracture networks, with the matrix permeability either ignored or approximated by simple means. The stress and deformation of the fractures are generally ignored as well. This method is conceptually attractive for simulating fluid flow in fractured rocks when the permeability of the rock matrix is low compared to that of the fractures, and has wide applications in groundwater flow for civil engineering, reservoir simulation in petroleum engineering and heat energy extraction in geothermal engineering.

Discontinuous Deformation Analysis method
Implicit DEM—Discontinuous Deformation Analysis method: block systems DDA originated from a back analysis algorithm for determining a best fit to a deformed configuration of a block system from measured displacements and deformations (Shi and Goodman, 1985). It was later further developed to perform complete deformation analysis of a block system (Shi, 1988) [231]. The early formulation used a simple representation of block motion and deformation, with six basic variables (three rigid body motion and three constant strain components) and is not suitable for irregularly shaped blocks. The applications focus mainly on tunnelling, caverns, fracturing and fragmentation processes of geological and structural materials and earthquake effects (see, for example, Yeung and Leong, 1997; Hatzor and Benary, 1998; Ohnishi and Chen, 1999; Pearce et al., 2000; Hsiung and Shi, 2001).

Hybrid models
Hybrid models are frequently used in rock engineering, basically for flow and stress/deformation problems of fractured rocks. The main types of hybrid models are the hybrid BEM/FEM, DEM/BEM models. The hybrid DEM/FEM models are also developed. The BEM is most commonly used for simulating far-field rocks as an equivalent elastic continuum, and the FEM and DEM for the non-linear or fractured near-field where explicit representation of fractures or non-linear mechanical behaviour, such as plasticity, is needed. This harmonizes the geometry of the required problem resolution with the numerical techniques available, thus providing an effective representation of the effects of the far-field to the near-field rocks.
Artificial Neural Networks

Artificial Neural Networks are computational systems whose architecture and operation are inspired from our knowledge about biological neural cells (neurons) in the brain. ANNs can be described either as mathematical and computational models for non-linear function approximation, data classification, clustering and nonparametric regression or as simulations of the behavior of collections of model biological neurons. Idea of ANNs is not to replicate the operation of the biological systems but to make use of what is known about the functionality of the biological networks for solving complex problems. Attractiveness of ANNs comes from the characteristics of the biological system such as non-linearity, high parallelism, robustness, fault and failure tolerance, learning, ability to handle imprecise and fuzzy information and their capability to generalize (Jain et al. 1996). The main objective of ANN based computing is to develop a mathematical algorithm which will enable model to learn by mimicking information and knowledge acquisition in the human brain. They can be used in a variety of powerful ways, to learn and reproduce rules or operations from given examples; to analyze and generalize from sample facts and make predictions from these, or to memorize characteristics and features of given data and to match or make associations from new data to the old data. ANNs are able to solve difficult problems in a way that resembles human intelligence. What is unique about neural networks is their ability to learn by example. Traditional artificial intelligence (AI) solutions rely on symbolic processing of the data, an approach which requires a priori human knowledge about the problem. Also neural networks techniques have an advantage over statistical methods of data classification because they are distribution-free and require no a priori knowledge about the statistical distributions of the classes in the data sources in order to classify them. Unlike these two approaches, ANNs are able to solve problems without any a priori assumptions. As long as enough data is available, a neural network will extract any regularity and form a solution.