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DISCRETE ELEMENT MODELLING OF ROCK ENGINEERING STRUCTURES FOR SEISMIC SAFETY ANALYSES

PhD thesis research plan of Margarida Espada

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DISCRETE ELEMENT MODELLING OF ROCK ENGINEERING STRUCTURES FOR SEISMIC SAFETY ANALYSES

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Abstract

This document presents the research plan for the doctoral thesis of LNEC's Junior Research Fellow Margarida Espada. This work, to be submitted to the Faculty of Engineering of the University of Porto (FEUP), will be developed in the Modelling and Rock Mechanics Unit of the Concrete Dams Department, and it is part of the on-going P2I research project DEMRock6m.

This work aims at developing more efficient methodologies to perform safety studies and seismic analysis of rock engineering structures, based on discrete element models and in the integrated use of probabilistic models for the geometric and shear strength parameters and for the water pressures in rock discontinuities. This will allow a more realistic definition of the rock mass in discrete element models and an adequate identification of the potential failure mechanisms.

Keywords: Rock discontinuities / Discrete element models / Discontinuities generation tool / Safety analysis / Probabilistic analysis / Seismic analysis / Dam foundations

UTILIZAÇÃO DE MODELOS DE ELEMENTOS DISCRETOS PARA A ANÁLISE SÍSMICA DE ESTRUTURAS EM MACIÇOS ROCHOSOS

Plano de tese de doutoramento de Margarida Espada

Resumo

Neste documento apresenta-se o plano de tese de doutoramento da Bolseira de Iniciação à Investigação Científica Margarida Espada. O trabalho será realizado no Núcleo de Modelação e Mecânica das Rochas do Departamento de Barragens de Betão, integrado no projeto de investigação P2I designado por DEMRock6m, e a tese será submetida para apreciação na Faculdade de Engenharia da Universidade do Porto (FEUP).

Com este trabalho pretende-se contribuir para o desenvolvimento de metodologias mais eficientes para realizar estudos de estabilidade e análises sísmicas de obras em maciços rochosos, com base em modelos de elementos discretos e no uso integrado de modelos probabilísticos para os parâmetros geométricos e de resistência das descontinuidades e para as pressões de água nas juntas. Estas metodologias irão permitir gerar modelos geométricos do maciço mais realistas e uma melhor identificação dos mecanismos de rotura mais relevantes.

Palavras-chave: Descontinuidades do maciço rochoso / Modelos de elementos discretos / Ferramenta para geração de descontinuidades / Análise da segurança / Análise probabilística / Análise sísmica / Fundações de barragens

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1 | Introduction

This document presents the research plan for the doctoral thesis of LNEC's Junior Research Fellow (JRF) Margarida Isabel Ramalho Espada, entitled *Discrete Element Modelling of Rock Engineering Structures for Seismic Safety Analyses.*

Margarida Espada obtained her Master Degree in Civil Engineering (Structures) in January 2010 at the Polytechnic Institute of Lisbon - Instituto Superior de Engenharia de Lisboa (ISEL). Her master thesis concerned the development of two and three-dimensional numerical models for dynamic analysis applied to concrete dams and appurtenant works. It was done during a 4-month traineeship at LNEC under the supervision of Dr Sérgio Oliveira.

She worked for two years as a structural engineer in a design company (P2S - Estudos e Projectos de Engenharia L$^{\underline{da}}$), in the analysis, calculation and design of concrete structures and she was also responsible for the acoustic laboratory and for building acoustic tests.

Margarida Espada joined the LNEC as a Junior Research Fellow in September 2011, and she has been developing her research activity in the Modelling and Rock Mechanics Unit of the Concrete Dams Department (NMMR/DBB), under the supervision of Dr Luís Lamas. During this period, she obtained solid background knowledge in theoretical aspects of rock mechanics, in field and laboratory tests and in numerical modelling of rock masses. In order to complement her background, she attended several courses of the Diploma of Advanced Studies (DFA) in Geotechnical Engineering organised by LNEC, the IST of the University of Lisbon and the Faculty of Sciences and Technology of the New University of Lisbon.

She has participated as a main researcher in several studies related with the measurement and estimation of the state of stress in rock masses, the deformational behaviour of underground caverns and the safety evaluation analysis for foundation failure scenarios of concrete dams. These studies resulted in a number of technical reports and publications to conferences and journals.

Margarida Espada's detailed scientific *curriculum vitae* is presented in the Annex.

The thesis work will be developed mainly at LNEC, integrated in the on-going research project DEMRock6m – Discrete element modelling of rock engineering structures for seismic safety analyses, included in LNEC's Research and Innovation Plan (P2I). The thesis will be submitted to the Faculty of Engineering of the University of Porto (FEUP), where the required ECTS credits will be obtained.

The thesis supervisors will be Dr José Muralha and Dr José Vieira de Lemos from LNEC, and Professor José Couto Marques from FEUP.

2 | Relevance of the theme

The Portuguese government established in 2007 the national strategy for the increase of clean and renewable energies production, comprising the construction of new hydroelectric schemes or the refurbishment of existing schemes. The new large concrete dams and underground structures for this purpose require comprehensive studies to support the design and to ensure the safety during the construction and operation stages. These studies generally include a complete site investigation for the rock mass characterisation, which supports the numerical models used for the structural safety assessment.

The development of sophisticated numerical models to support the safety analysis studies of rock engineering structures (e.g., dam foundations, underground works, rock slopes) has been, for a long time, an active research topic in LNEC's Concrete Dams Department (DBB). LNEC's experience in safety assessment of large rock engineering projects, allowed LNEC to improve the ability of using discrete element models to take into account the discontinuous nature of the rock masses, which constitutes its major structural feature.

Realistic representations of rock mass by discrete element models require three-dimensional analyses including the most important rock discontinuities. Computational tools implemented in discrete element models that allow the representation of complex jointing patterns in rock masses based on statistical distributions already exist (Dershowitz and Einstein, 1988), but their practical use for safety stability analysis has not yet been addressed. Jointing geometric modelling procedures usually consist in the representation of the major faults, which may be inserted in the model with their known orientations and at their recognised locations, but the choice of the joints that can contribute to the occurrence of failure mechanisms is still much based on the practitioner's experience. Additionally, the manual procedure for introducing the rock discontinuities in discrete element models is a highly time-consuming task. One of the goals that is to be attained in this work is the development of an efficient joint generation tool specially intended for mechanical stability analysis, which will allow a more realistic definition of the rock mass, including the representation of the non-persistency of the discontinuities, and will contribute to expedite the procedure of manually introducing the discontinuities in numerical models.

Once a geometric model of the rock mass has been defined, safety assessment studies with the appraisal of potential failure mechanisms, typically defined by natural rock discontinuities or concrete-rock interfaces, are usually performed considering strength reduction methods for computing global safety factors. Strength parameters for the discontinuities considered in these studies are frequently obtained from laboratory shear tests. The number of laboratory tests conducted is usually scarce, and the average values obtained may not be representative of the global mechanical behaviour of the discontinuities. Even with a statistically sound number of tests, the results may be surprising in terms of their wide variability. Consequently, it is important to consider the shear strength variability of the discontinuities in safety studies, in order to analyse its influence on the failure modes. Another important factor that also impacts the failure modes of structures in or on rock masses concerns the water pressures. Though some studies introducing joint fluid flow in discrete element models have already been performed (e.g., Farinha *et al.*, 2012), simplified assumptions are often made concerning water pressure distributions along the joints. So, for each joint pattern realisation of the rock mass (provided by the joint generation tool that will be developed), the variability of the shear strength parameters and of the water pressures in discontinuities will be considered in this work, assuming specific statistical distributions, aimed at the identification of potential failure modes.

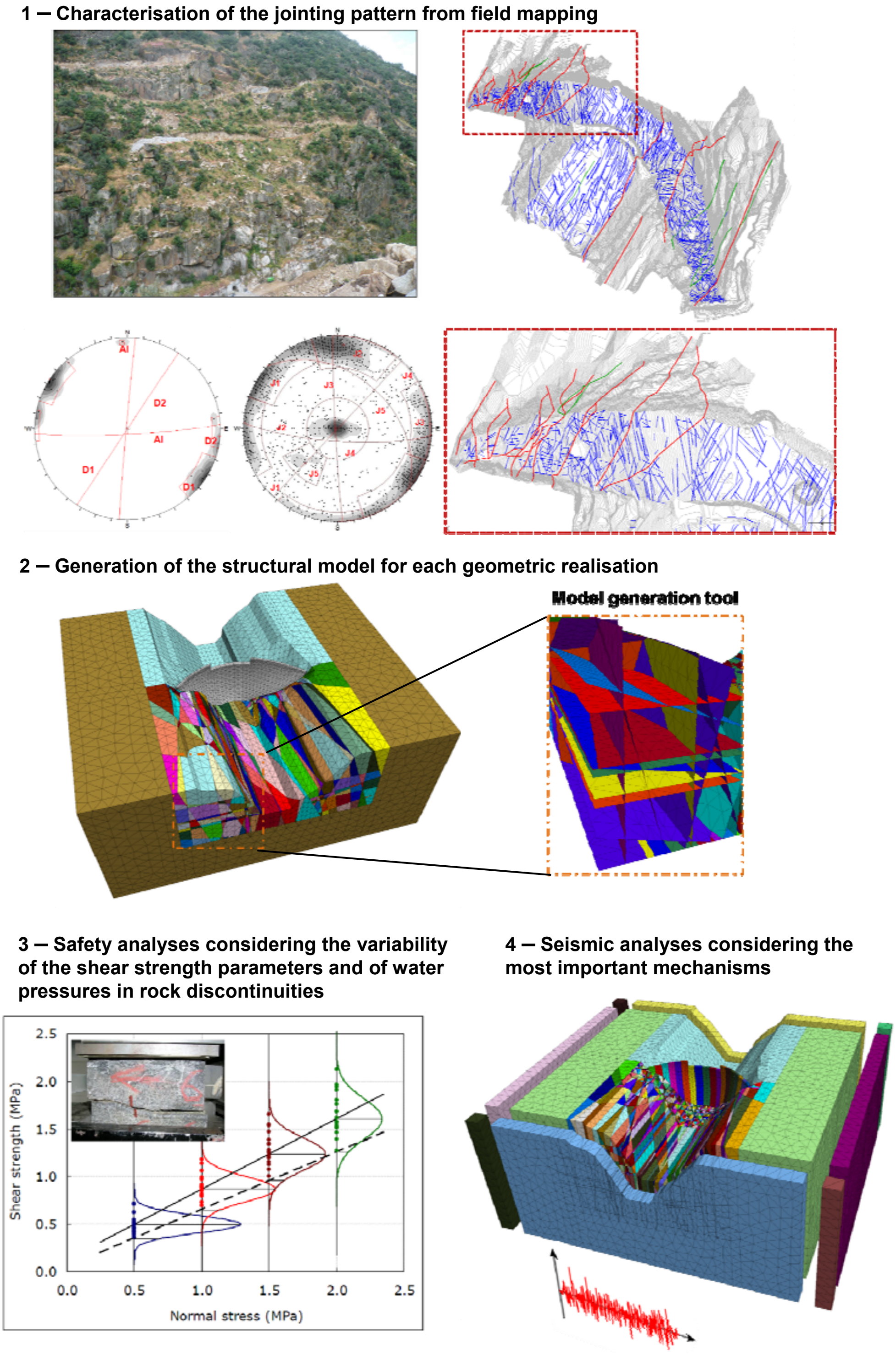
Combined consideration of the variability of the geometric and shear strength parameters and of the water pressures in rock discontinuities, will allow to adequately identify the most relevant failure scenarios and which discontinuities are involved in them. Considering just these discontinuities, with the corresponding mechanical properties and water pressures, it will be possible to build simplified models to perform efficient seismic analyses, due to the high computation effort that this type of analyses entails.

Figure 2.1 displays a scheme with the identification of the main steps to be followed in the safety assessment. It starts with the development of an efficient methodology that allows to define realistic rock mass geometrical models given the *in situ* characterisation of the jointing pattern; then, for each geometric model realisation, safety analyses will be performed and the potential failure mechanisms will be identified, considering the variability of the shear strength parameters and of the water pressures in rock discontinuities; finally, for the key failure mechanisms identified, involving specific rock discontinuities with the corresponding mechanical properties and water pressures, it will be possible to perform efficient seismic analyses.

The theme of this thesis falls in the scope of LNEC's research activities related to modelling and analysis of rock engineering structures for their design and safety assessment. In what concerns concrete dams, these activities will improve LNEC’s expertise to fulfil its supporting role to the national regulatory agency – Agência Portuguesa do Ambiente (APA) – in assuring adequate safety conditions during construction and operation stages, and to provide high-level consultancy to private owners in making sound decisions concerning the design and construction. This is a research topic of great interest to LNEC, which deserved special emphasis in recent years, with several research works, theses and scientific papers in this field, owing to the high potential risk associated to large engineering structures in and on jointed rock masses.

Recently, LNEC performed several studies for the design and construction of new large dams and for the refurbishment of existing hydroelectric projects, including *in situ* rock mass characterisation and numerical modelling for the stability analysis of dam foundations, underground works and rock slopes. The Foz Tua hydroelectric scheme, owned by EDP, located in the north of Portugal, is one of these new projects, which includes the construction of a 108 m high concrete arch dam, an underground powerhouse and several underground tunnels. Construction started in 2011 and it is expected to end in 2016. Foz Tua dam will be used as one of the case studies in this thesis for the application of the resulting methodologies for failure analysis under static and seismic conditions.

On-going cooperation between LNEC and the State Key Laboratory of Geomechanics and Geotechnical Engineering (SKLGGE) of the Chinese Academy of Sciences in Wuhan (China) started in January 2015. SKLGGE is involved in several studies for two very large Chinese arch dams (over 250 m high) currently under construction in seismic regions. One of these, the Baihetan dam, will be also used as a case study in this thesis.



1 – Characterisation of the jointing pattern from field mapping

2 – Generation of the structural model for each geometric realisation

3 – Safety analyses considering the variability of the shear strength parameters and of water pressures in rock discontinuities

4 – Seismic analyses considering the most important mechanisms

Figure 2.1 – Integrated use of probabilistic models for the geometric and shear strength parameters and for the water pressures in discontinuities, for safety studies and seismic analyses

3 | Failure analysis in rock engineering structures

3.1 General

The design of rock engineering structures involves two basic requirements that must be simultaneously satisfied – serviceability and safety. Serviceability criteria concern the ability of the structure to perform its function satisfactorily under the normal operating conditions. Safety criteria demand that the structure does not originate unacceptable risks for those who directly use it or the public in general.

According to the Portuguese national regulations for dams (NPB, 1993; RSB, 2007), these requirements must also be assured considering two different design situations: current scenarios and failure scenarios. Each scenario involves the definition of the various factors that contribute to the design process namely loads, construction or operating procedures and materials behaviour.

At a preliminary stage of design, the knowledge of rock mass properties, of the main discontinuities and of the stress field or the presence of water is usually limited. At this stage, the use of empirical methods, such as rock mass classification systems, can be very useful to provide initial estimates of the strength and deformation properties of the rock mass and to provide an idea of the support requirements. Rock mass classification systems, such as the RMR system of Bieniawski (1976, 1989) or the Q system of Barton, Lien and Lunde (1974), are widely used in the field of tunnels and mines, where experience gained in similar preceding projects provides some degree of confidence in their application.

Limit equilibrium methods and probabilistic analyses have also been used in rock engineering problems. However, for complex geometries or when it is necessary to assess complex failure mechanics or the relative weight of several parameters, numerical models have been increasingly used. Nowadays, the fast increase in computational power and affordability has reinforced the tendency to employ larger and more complex numerical models to directly support design and safety analyses. There is a variety of numerical techniques suitable for rock engineering problems, such as finite elements (Zienkiewicz, 1967), boundary elements (Crouch and Starfield, 1983), discrete elements (Cundall, 1971) and combinations of these methods (von Kimmelmann *et al.*, 1984, Lorig and Brady, 1984). Owing to the difficulties of having a full characterisation of the various parameters, for instance the geometry and location of the discontinuities, numerical models generally contain a number of unavoidable simplifications and occasionally arbitrarily chosen details. Hence, it is important to perform multiple analyses to assure the validity of conclusions derived from particular representations of rock masses.

3.2 Modelling failure modes using discrete element models

3.2.1 Discontinuous modelling

Numerical methods, based on finite elements or discrete elements, have been widely used to assess failure mechanisms in rock engineering structures, replacing classical analytical techniques. The finite element method is the most common tool for equivalent continuum analysis, but it is also capable of addressing discontinuous models by means of joint, interface or gap elements (e.g., Alonso *et al.*, 1994). The development of the distinct element method aimed at a straight representation of a discontinuum. Presently, the designation of “discrete elements” (DE) covers a wide family of numerical methods (distinct elements, discrete finite elements, discontinuous deformation analysis – DDA, etc.), all sharing the concept of representing a discontinuous medium as an assembly of blocks or particles.

DE models are adequate to identify and analyse failure mechanisms, given their ability to represent the rock mass discontinuities, as well as other intervening structures, such as concrete dams or rock support elements in underground works. At the scale of large civil and mining engineering works, DE deformable block models, with internal finite element meshes in the blocks, are the most suitable to employ, thus allowing stress analyses to be carried out and a better representation of deformability and load distribution (Lemos, 2011). These deformable DE models differ from finite element models with joint elements more from the numerical than the conceptual points of view, namely: contact logic based on point contacts, suitability for large displacements; ease of generation of complex block patterns with automatic contact detection; and explicit solution algorithms using dynamic relaxation, instead of matrix solutions (Lemos, 2012).

The 3DEC code - Distinct-Element Modelling of Jointed and Blocky Material in 3D (Cundall, 1988; Itasca, 2013), applicable to rigid and deformable blocks, has been extensively used in the rock mechanics field to model engineering structures in and on jointed rock masses.

In the next sections, two modelling issues, concerning the use of DE models for the stability analysis of rock engineering works, which are intended to be addressed in this work, are presented.

3.2.2 Joint network modelling

One of the main challenges in rock mass modelling is the development of 3D numerical models for mechanical stability analysis capable of a reliable and realistic representation of the rock mass structure based on the data collected during the site investigation (Lemos, 2001).

Typically, there are several faults and a considerable number of joints identified at the site. The common procedure for the rock mass generation is to insert in the numerical model the main faults or other major geological structures, which are generally persistent and well-defined, with their known orientations and at their recognised locations. The representation of the joint sets in numerical models is more complicated, because they are usually in large number and it is not feasible to represent in the model all the joints identified due to the required computational effort. So, the selection of the joint planes that might intervene in the occurrence of failure mechanisms is still very much based on the practitioner's experience. Usually, the methodology consists in the evaluation of the most important joint sets, according with the identified potential failure mechanisms, and to represent only a few joint planes. However, these manual procedures for the introduction of faults and joints in 3D numerical models are generally quite laborious. During the last years, LNEC performed several stability studies for the analysis of failure mechanisms of dam foundations (e.g., Farinha and Lemos, 2011; Leitão, 2011; Farinha, 2011; Espada *et al.*, 2015), and has improved its experience in modelling jointed rock masses using discrete element models. For the rock mass generation, manual procedures were adopted in these studies for the introduction of the main faults and joint sets, which is a time consuming task.

Especially for the joint sets, an alternative is the stochastic representation using statistical distributions of their geometric properties (e.g., orientation, spacing, size, shape, aperture) to reproduce their random nature. Joint data can be sampled from exposed surfaces (e.g., different oriented outcrops) and boreholes, and can then be used to synthesise a 3D stochastic joint model. Statistical descriptions for the geometric parameters of the joints, which fit satisfactorily with the observations, have already been proposed (e.g., Grossmann, 1993). However, the generation of a realistic 3D stochastic joint model that complies with the statistical descriptions is still a difficult problem, especially in three dimensional problems (Lemos, 2001).

Dershowitz and Einstein (1988) describe several joint system models or discrete fracture network (DFN) models developed to characterise, in an aggregate way, the various joint characteristics. The authors mention that *"there are so many geometric joint characteristics and thus a seemingly infinite number of combinations"* but, *"on the other hand, reality shows a relatively limited number of predominant rock mass geometries".* Hence, they present five general joint system models which can represent most of the real joint geometries found in nature. Rock jointing patterns evolved from the earliest deterministic models proposed by Irmay (1955) or Snow (1965), based on the assumption that all joints can be defined by three sets of unbounded orthogonal joints, to fully stochastic ones, such as the Baecher disk model (Baecher and Lanney, 1978) and models based on Poisson plane-line processes proposed by Veneziano (1978) and Dershowitz (1984).

Models based on Poisson plane-line processes were derived from the similarities between the geometry of rock joint systems with the geometries of Poisson planes and lines studied by mathematicians in the field of stochastic geometry (Priest and Hudson, 1976).

The fundamental feature of Baecher and Lanney model (1978) is the assumption of circular or elliptical joint shapes, as can be seen in Figure 3.1. The joint locations, shapes, sizes and orientations are defined stochastically, and the results of these models are joints terminating in intact rock or intersecting each other as shown.

The generation process of the rock joint system model proposed by Veneziano (1978) is illustrated in Figure 3.2. It starts with the generation of joint planes as Poisson planes with a uniform distribution of orientations. Then a Poisson line process on each joint plane divides joint planes into polygonal regions, and finally a portion of these polygons is randomly marked as jointed, while the remainder is defined as intact rock, according with the defined persistence parameter. With this model, joint shapes are polygonal, and joint sizes are defined by the intensity of the Poisson line process and the proportion of polygons defined as joints.

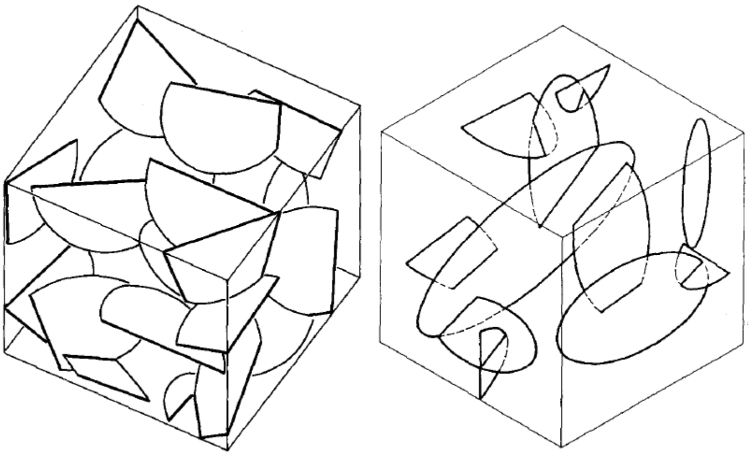


Figure 3.1 – Baecher and Lanney joint system model (in Dershowitz and Einstein 1988)

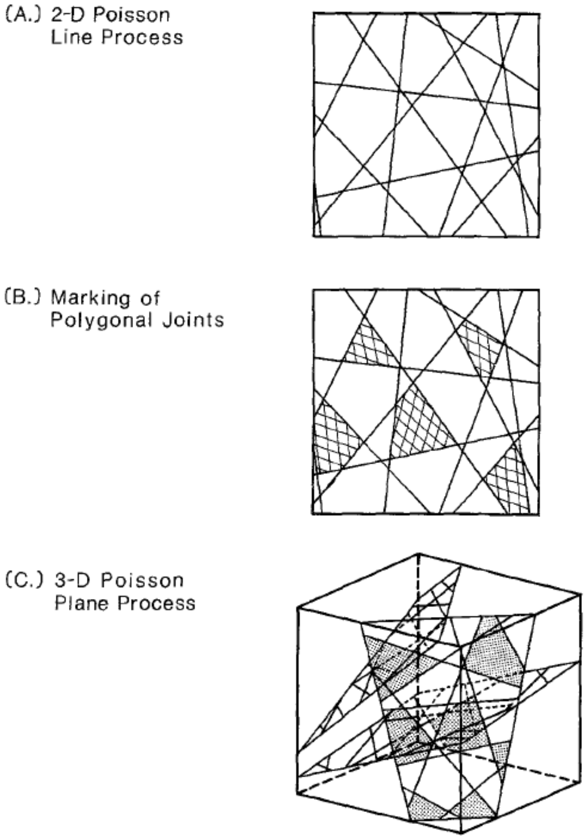


Figure 3.2 – Generation of a Veneziano joint system model (in Dershowitz and Einstein 1988)

The Dershowitz model (1984) is also based on a Poisson plane process for the representation of the joint planes, but is an update of the Veneziano model, since it overcomes the drawback that the joint intersections and joint edges do not match. Figure 3.3 shows the process of a Dershowitz rock joint system model. The first step is the generation of joint planes by a Poisson plane process of uniformly distributed locations, and by orientations following a specified distribution. The intersections between these planes define a process of lines on each joint plane, which divides each plane into polygons. The second step is the marking of a persistent portion of polygons on each plane as joints, and the remainder as intact rock. Since all joint intersections occur at joint edges, the joints correspond directly to the faces of the polyhedra defined by the joint planes, and the rock blocks are easily obtained with this model.

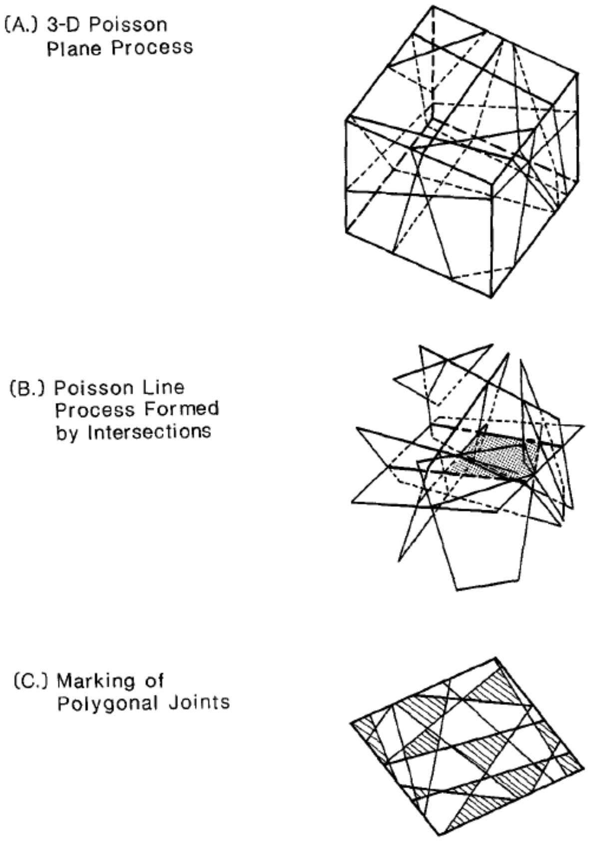


Figure 3.3 – Generation of a Dershowitz joint system model (in Dershowitz and Einstein 1988)

Dershowitz (1993) further explored the Poisson plane-line approach and later implemented many of the existing joint system models into the FracMan code (Dershowitz *et al.,* 1993; Golder, 2014), which evolved into the most widely used DFN software (e.g., Elmo, 2006; Pine *et al.,* 2006).

Presently, three DFN models are available in FracMan software: i) the Enhanced Baecher, a development of the original Baecher disk model (Baecher and Lanney, 1978); ii) the Nearest Neighbour, which is very similar to the Enhanced Baecher model, except for its assumptions in terms of spatial distribution of fractures (Geier *et al.*, 1988); and iii) the fractal model Levy-Lee (Geier *et al.*, 1988). In Elmo (2006) a complete description of these DFN models is presented.

The geometric characteristics of the fractures needed for a stochastic generation DFN model in FracMan software are the orientation, termination (e.g., T-type joint surfaces terminating against those of another set or X-type joint surfaces crossing those of another set), the fracture shape and size, and the intensity. The choice of a specific DFN model is typically based on assumptions made from field data and geological observations. Logically, the merit of DFN models depends on the quality of the field mapping that sometimes can be difficult to achieve even with a good amount of data.

Two important factors in joint generation procedures are the interdependence of the various joint sets and the hierarchical sequence in which the joints are generated. For instance, the FracMan software recognises T-type terminations, which is the common case found in nature. Besides, the hierarchical sequence of joint generation incorporated in computer codes must take into account the natural process of fracture development deriving from the chronology of the geological events (Heliot, 1988).

Several DFN formulations and computer codes have been continuously developed during the last years with many applications in civil, environmental and reservoir engineering and other geoscience fields, such as the BLOCSTAB (Song *et al.*, 2001), RESOBLOK (Heliot, 1988; Merrien-Soukatchoff *et al.*, 2012), NAPSAC (Stratford *et al.*, 1990; Wilcock, 1996), and GEOFRAC (Ivanova *et al.,* 2014).

Recently, Itasca (2013) also incorporated in 3DEC software version 5.0 its own DFN module, based on the assumption that the discrete fractures are disk-shaped. The geometric characteristics currently supported by this DFN module are the distributions of fracture size (disk diameters), of densities (or intensities), of orientation and of position. Users are able to modify or include code blocks into their modules using the *fish* language in 3DEC software. On the whole, the main differences between the various DFN computer codes fall in the definition of distribution laws used to simulate the geometric characteristics of the joints.

It has to be stressed that most of these codes have been developed for fluid flow simulations, and requirements in flow problems are quite different from those in mechanical stability analyses. In contrast to flow problems, where connectivity of the network is dominant, in stability studies it is not sufficient for the joints to be connected: kinematically removable blocks have to be generated. Even the RockBlock module in FracMan software, which allows mechanical stability analyses, is more frequently used for hydraulic purposes then for mechanical analyses. In fact, references in literature to stability analysis applications using RockBlock are scarce, and are mostly related with roof stability problems of underground works (e.g., Starzec and Andresson, 2002). Merrien-Soukatchoff *et al.* (2012) present the module BSA incorporated in RESOBLOK software for block stability analysis, which allows 3D analysis of unstable blocks during excavations of underground works by simple computations based on limit equilibrium approach or energy-based analysis. However, as referred by the authors, this module has some limitations in terms of the failure modes that can be identified and so the presented application examples are relatively simple.

So far, the use of DFN formulations for analysis of failure modes in rock mass foundations, rock slopes or underground works is very limited. Most of the examples have relatively simple geometries, with a complex network with many fractures, which sometimes are not realistic, and therefore the analysis of potential failure modes may not be conservative, as small rock bridges may prevent the development of a particular failure mode.

3.2.3 Non-persistent joints

An important factor that strongly determines the stability of rock engineering structures is the persistence of discontinuities. Instability and failure are more likely to occur if discontinuities are fully persistent, owing to the usually much higher strength of intact rock when compared to the discontinuities. In the case where discontinuities are not totally persistent, fracture through the intact rock bridges, between discontinuities, is necessary to occur for the development of a failure mechanism, as is illustrated in Figure 3.4.

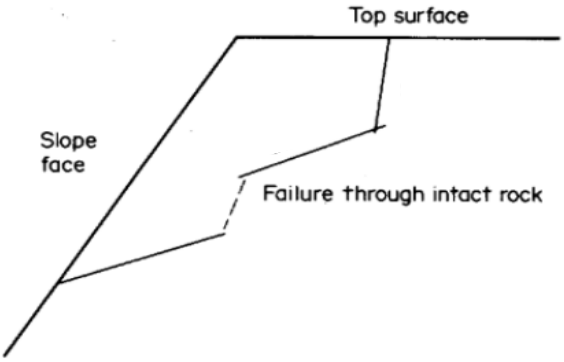


Figure 3.4 – Failure through the intact rock bridges (adapted from Einstein 1993)

As already stated, for the development of failure mechanisms in rock masses it is not enough the discontinuities to be connected, kinematic conditions must also be satisfied to form a failure mechanism. Figure 3.5 illustrates this idea. As can be seen in Figure 3.5 a), sliding failure along the discontinuities is not kinematically possible, even though they are fully connected. On the other hand, in the case displayed in Figure 3.5 b), failure can actually occur since kinematic conditions are satisfied.

The representation of non-persistent joint sets in stability calculations using 3D DE models still poses some difficulties. In failure studies, the simplest but highly conservative option is to disregard the shear strength of the rock bridges, assuming joints and faults to be continuous. While major faults are clearly continuous, assuming infinite persistency for the joints is questionable. However, if an acceptable safety margin can be ensured, there is no need for more elaborate models. If this is not the case, the non-persistence of the joint planes has to be taken into account.

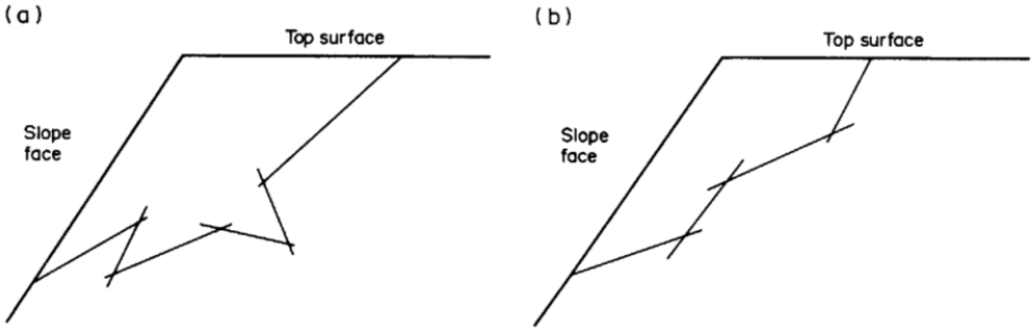


Figure 3.5 – a) Interconnection exists but top block cannot slide along discontinuities; b) interconnection exists and top block can slide along discontinuities (in Einstein 1993)

Polygonal block patterns such as the Voronoi tesselation, which is implemented in UDEC software (Itasca, 2011), has been extensively used by several authors to simulate fracturing processes through intact rock (e.g., Kazerani and Zhao, 2010). The application of this technique in the analysis of laboratory tests on rock samples has successfully allowed the simulation of progressive cracking and fragmentation processes. However, the applicability of Voronoi patterns in rock mass jointing is not suitable, especially in the case of sliding modes, as the sliding path of the joint sets is not captured.

On one hand, the use of stochastic models for the generation of the joint patterns can lead to a non-conservative scenario, since the large number of generated fractures produce many small rock bridges that may prevent the development of a failure mode. On the other hand, even with a simplified DFN model, involving the simulation of non-persistent joints, the breakage of rock bridges has to occur to provide a sliding surface. A simpler alternative is to pre-define the potential failure paths through rock bridges, assigning them cohesive strength, and to check if they actually fail in the simulations (Lemos, 2014).

Einstein (1993) presents some methodologies to identify potential fracture paths, capable to form a failure mode in 2D numerical models. Fractures that were identified as relevant for the stability analysis, and therefore included in the pre-defined fracture paths, are called effective discontinuities. Non-effective discontinuities that do not contribute to the occurrence of a failure mechanism are sequentially eliminated. This can be a valid procedure for the simplification of DFN models; however, non-effective discontinuities must be carefully eliminated (some non-effective discontinuities must be preserved), or else the final model may be similar to a model with continuous joints.

3.2.4 Final remarks

DFN tools that allow the representation of the complex jointing patterns in rock masses already exist, but their practical use for 3D safety stability analyses in DE models, as are performed using manual procedures for introduction of the main faults and joints, has not yet been adequately addressed. Continuing research is still needed in this field, aimed at simplifying the computer representations of rock masses obtained from the DFN tools, in order to have some measure of realism and, at the same time, to have suitable representations for mechanical stability analyses (Lemos, 2001). In this work a 3D generator tool that encompasses these features will be developed, in order to be implemented in discrete element models of rock engineering structures, thus allowing the automation of the procedure of introducing the discontinuities in numerical models.

3.3 Safety evaluation methods

3.3.1 Introduction

Safety assessment and performance of rock engineering structures, according with the defined safety and serviceability criteria, is an activity that takes place during the design, construction, operation and demolition stages.

At the design stage, besides the verification of the proposed solution according with the required criteria, activities related with observation and evaluation of the behaviour during construction and operation are planned. Construction and operation stages involve monitoring, verification of criteria and, eventually, decision making. It is essential, at this stage, to follow a monitoring plan, which includes the tasks of data collection and interpretation for understanding the structural behaviour, and subsequent judgement on the performance (e.g., Mata, 2013). This procedure will allow the early detection of any abnormal behaviour and to act promptly. Detailed safety evaluation studies may have to be performed at different stages of the structure's lifetime due to, for instance, the development of deterioration processes (e.g.,, Piteira Gomes, 2008) or anomalies in the observed behaviour, changes in the actions or regulatory requirements. The same numerical models that supported safety analysis studies before construction are frequently used, at later stages, to validate and calibrate the models used for structural behaviour monitoring during operation stages.

Safety evaluation during these stages is then performed by comparing the effects of the actions with the resistance capacity of the structure, using one of the three following available methodologies (Cardoso, 2002), which are briefly described in the next sections:

- The conventional approach, based on deterministic methods, with the definition of a global safety factor, usually defined as a reduction factor of the friction angle and/or of the cohesion (e.g., Alonso *et al.*, 1996).
- The semi-probabilistic approach using partial factors, which incorporates the inherent variability of the parameters introducing the concept of characteristic values (e.g.,, Eurocode 7, EN 1997-1, 2004).
- The probabilistic approach considering failure probabilities instead of using safety factors (global or partial), based on structural reliability concepts (e.g.,, Duncan, 2000).

3.3.2 Deterministic approach with a global safety factor

The conventional approach to the quantification of safety is based on the evaluation of a safety factor *F*, defined by the relationship between the resisting forces or moments (R) and the acting or disturbing forces or moments (S), *F* = R/S. Failure is considered to occur when *F* is less than one. Two different methods are commonly used in numerical analysis programs to compute the safety factor in geomechanics, namely the strength reduction method and the limit equilibrium method.

The strength reduction method consists in the progressive reduction of the shear strength of the materials or discontinuities, leading to a limiting equilibrium state. This method is usually applied with the Mohr-Coulomb failure criterion (e.g., Matsui and San, 1992; Alonso *et al.*, 1996; Espada *et al.*, 2015), reducing the cohesion and/or the friction angle until failure takes place, along an *a priori* unknown surface. An example of the application of this method is the study presented in Lemos (2012) to evaluate the failure mechanisms defined by rock discontinuities in the foundation of an arch dam, in which safety factors were calculated by means of the reduction of the tangent of the friction angle of discontinuities.

Limit equilibrium methods assume that failure occurs by sliding movements or rotations along pre-existing discontinuities or weakness planes, where the equilibrium conditions are analysed on the basis of statics (e.g., Janbu, 1968; Morgenstern and Price, 1965). The objective is to find the shape of the failure surface and its most critical position. This approach has been widely used for preliminary stability analysis and is suitable for simple cases, as the stability of a rock slope, to analyse the different failure mechanisms, such as planar or circular mechanisms, and wedge or toppling failure (e.g., Londe, 1973; Alejano *et al.*, 2011).

3.3.3 Semi-probabilistic approach with partial factors

The evolution from the concept of a single global safety factor to the use of partial factors represents the introduction of probabilistic concepts, as it allows the consideration of different levels of uncertainty for the various actions and material properties.

In the field of geotechnical engineering design, Eurocode 7 (EC7) is employed. EC7 is based on limit state design principles (ultimate and serviceability limit states) wherein, for each particular design situation, all the possible limit states for a structure shall be verified and the likelihood of any limit state being exceeded must be proved to be sufficiently small.

Geotechnical design according to EC7 can be carried out using one or a combination of the following methods: use of calculations, prescriptive measures, experimental models and load tests, and the observational method. The first method of safety verification, using calculations, is by far the most used one, and involves using characteristic values of actions, ground properties and geometrical data. Design values of actions and of geotechnical parameters are obtained from their corresponding characteristic values affected by partial factors. The partial factors for actions and material properties include an allowance for minor variations in geometrical data and, in such cases, no further safety margin on the geometrical data should be required. In cases where deviations in the geometrical data have a significant effect on the reliability of a structure, design values of geometrical data shall be derived from nominal values plus or minus a certain tolerance.

Regarding characteristic values for ground parameters, EC7 presents rules for obtaining them based on experimental results from laboratory or *in situ* tests, and based on the experience of geotechnical engineers. EC7 refers that characteristic values of geotechnical parameters *"shall be selected as a cautious estimate of the value affecting the occurrence of the limit state"*. This value depends on the volume of ground governing the behaviour of the geotechnical structure or the area of the failure surface. Usually it is much larger than the volume affected in an *in situ* or laboratory test, and the characteristic value should be *"a cautious estimate of the mean value"* or of the range of values covering that whole ground volume. However, if the behaviour of the geotechnical structure is governed by the lowest or highest value of the ground property, the characteristic value should be *"a cautious estimate of the lowest or highest value"*. If statistical methods are used, the characteristic value is *"a selection of the mean value of the limited set of geotechnical parameter values, with a confidence interval of 95%"*, in the first case, *or "a 5% fractile"* in the second case. In what concerns of characteristic values for actions, they are obtained according with Eurocode 0 (EN 1990, 2002) and with several parts of Eurocode 1 (EN 1991).

It is important to mention that the current version of EC7 is widely recognised as more adequate to soil problems, whereby the geotechnical aspects of the design in soils are clearly dominant in the code (Lamas *et al.*, 2014). In fact, the applicability of the semi-probabilistic approach of EC7 to rock engineering poses additional difficulties, especially due to the essential feature of rock masses, which is their discontinuous nature. This has a number of major implications regarding, for instance, the definition of failure modes, the validity of the assumption of the aleatory nature of rock mass parameters, or the consideration of the important geometric variability of rock discontinuities. Hence, in 2011 the European Committee for Standardisation, CEN, responsible for EC7, established an evolution group assigned to review the rock mechanics aspects of the code for further applicability in rock engineering (Harrison, 2014).

3.3.4 Probabilistic approach

The uncertainties associated with the inherent variability of the rock mass properties, including the geometric and mechanical parameters of discontinuities, or with the definition of the actions and the limitations introduced in numerical models for safety evaluations, led several authors to suggest that probabilistic analyses with evaluation of failure probabilities should be included in safety analysis studies (Priest and Brown, 1983; Muralha, 1995; Cardoso, 2002).

The concept of structural reliability states the probability of fulfilment of the requirements of safety and serviceability. These requirements can be defined by a limit state equation (Schneider, 1997), in terms of basic random variables X_i, representing the actions and material parameters:

$$G(X_1, X_2, ..., X_i) = 0 \tag{1}$$

As inferred from the limit state equation, the failure or the unsafe zone corresponds to the domain Df in which $G \leq 0$ and the safe zone is characterised by $G > 0$. Therefore, the probability of failure for an ultimate limit state or the probability of a given serviceability state being reached is defined by:

$$P_f = P(G \leq 0) = \int_{Df} f(X_1, ..., X_i)\, dX_1 ... dX_i \tag{2}$$

Owing to the difficulties in obtaining the solution of expression (2), simpler approximation methods of the failure surface must be applied. These methods involve the computation of a reliability index, which is then converted into the probability of failure. For a linear approximation of the limit state function, first order reliability methods (FORM) are used (e.g., Hasofer and Lind, 1974). In the case of second order approximations of the limit state function, which includes additional information about its curvature, second order reliability methods (SORM) are applied (e.g., Fiessler *et al.*, 1979).

Simulation techniques, which have their origin in the Monte Carlo method (MCM), have been widely used to overcome the limitations of the approximation methods, for instance, when the limit state function is not defined analytically or is too complex. The MCM consists in generating a large number of limit state evaluations, with the approximation of the true value of the probability of failure being the proportion of evaluations falling into the failure domain. However, this method usually demands a high number of simulations (or limit state evaluations) for complex problems, requiring, consequently, a high computational effort. To improve the computational efficiency of the MCM, variance reduction methods can be applied (e.g., the importance sampling method), but when the limit state function has an implicit form, response surface methods (RSM) are an efficient technique to be used (e.g., Bucher and Bourgund, 1990).

3.3.5 Final remarks

In rock engineering, calculation of probabilities of failure poses serious difficulties, due to the complexity in adequately considering the probability distributions for the discontinuities' parameters (geometric and shear strength parameters, water pressures), which are the main factors that govern the failure modes in rock masses. Statistical descriptions of the joint patterns and properties are already available, but the generation of numerical models in accordance with these statistical descriptions still needs further research. Additionally, the high safety levels required imply that most problems fall into the range of low probabilities, where satisfactory accuracy is difficult to attain.

In spite of all difficulties in quantifying the probabilities of failure in rock engineering problems, probabilistic approaches can be useful for comparisons between different mechanisms aimed at evaluating the influence of each input parameter (e.g., orientation, persistence, water pressures, friction angle of discontinuities, etc.) on the control parameters (e.g., safety factor, total maximum displacement, number of failed blocks, etc.), indicating the occurrence of possible failure modes (Londe, 1993).

In this work probabilistic analyses will be performed using 3D discrete element models, in order to take into account the combined variability of geometric and shear strength parameters of discontinuities and of water pressure distributions. For the defined statistical distributions of each parameter, numerical simulations will be carried out using advanced techniques based on the Monte Carlo simulation method, to reduce the number of calculations without affecting the results. In order to analyse the effects of the variability of these parameters on the equilibrium conditions, various control parameters will be examined during the analysis, including the computation of global safety factors, and allowing to identify the most relevant failure mechanisms.

3.4 Seismic analyses

3.4.1 Discrete element models for seismic analysis

The seismic analysis of engineering structures considering the assumption of linear elastic material behaviour, based on well-established techniques of structural analysis, is performed routinely in design procedures. However, for rock engineering structures the rock mass has to be considered as a discontinuous medium, and the rock discontinuities must display a non-linear behaviour for the identification of potential failure modes that may be induced by a seismic event, involving slip and separation along rock discontinuities.

Safety evaluation of rock engineering structures under seismic loads by means of DE models requires time domain analysis and a proper representation of the structure and the rock mass, taking into account the most important factors that affect the seismic response (e.g., water-structure dynamic interaction, damping, support system, etc.).

The explicit solution algorithms used by most DE codes for quasi-static analysis, such as the 3DEC software, perform the integration of the equations of motion of the system. In the case of seismic analyses, it is necessary to introduce the correct values for damping, instead of the large values used to obtain static solutions, and to consider real masses, i.e., not applying mass scaling techniques that are frequently used in quasi-static analysis to improve convergence.

Deformable blocks must be used in seismic analyses to simulate more accurately the wave propagation in the jointed medium. An important aspect in this type of analysis using DE models is the mesh element size. Meshes should be fine enough to allow about eight internal elements per wavelength for the highest relevant frequencies (Lemos, 1999).

For seismic analyses, special dynamic boundary conditions must be considered in DE models. The bottom boundary must have an absorbing nature, to avoid reflections of outgoing waves back into the model, in order to allow correct energy dissipation, thus simulating a semi-infinite model in the vertical direction. The viscous boundary formulation proposed by Lysmer and Kuhlemeyer (1969), implemented in 3DEC, is frequently used to represent the non-reflecting (or absorbing) boundaries. In this formulation, independent viscous dashpots are attached to the bottom boundary in the normal and tangential directions, providing the corresponding reaction tractions. The seismic input is applied as a vertically propagating stress wave obtained from the velocity records derived by integrating the accelerations. The stress wave can be defined by three components of accelerations, namely a vertical component and two horizontal components. For the dynamic conditions at the lateral boundaries, auxiliary free-field meshes proposed by Cundall *et al.* (1980), also implemented in 3DEC, have to be used to calculate the dynamic stresses to be applied to the main model. The concept of free-field is used to represent the behaviour of the site that would exist in the absence of the structure. The lateral boundaries of the main model are coupled to the free-field meshes by viscous dashpots to simulate the non-reflecting boundaries, and at the base of the free-field the stress wave is applied in the same way as in the main model (see Figure 3.6). In 3D, the free-field model consists of four plane free-field meshes on the side boundaries of the model and four column free-field meshes at the corners (see Figure 3.7), in which there is a correspondence between the free-field and the main model gridpoints.

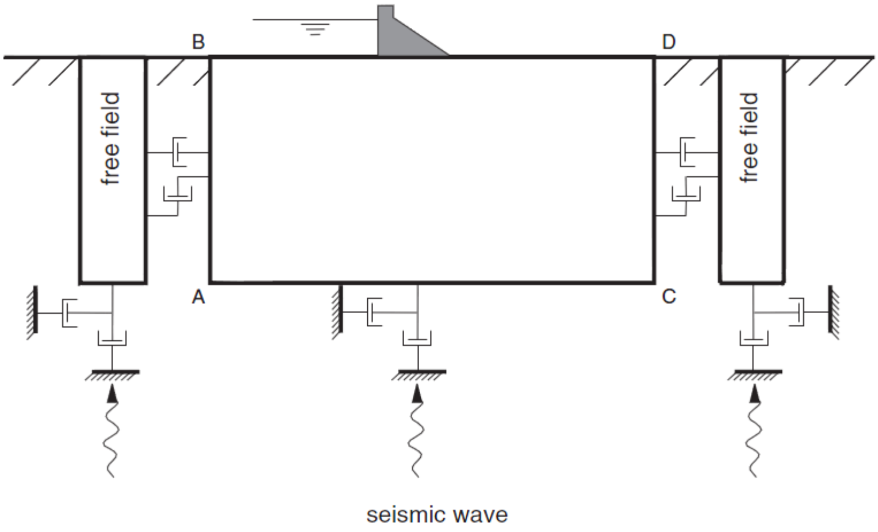


Figure 3.6 – Scheme with the dynamic boundary conditions for seismic analysis with the representation of the free-field blocks (in Itasca 2013)

The operating basis earthquake (OBE) and the maximum design earthquake (MDE) are, respectively, considered in current and failure scenarios. The former refers to the analysis for the main combinations involving the service actions. The latter comprises the analysis for potential failure scenarios, but is also used for post-seismic stability analyses resulting from the occurrence of local damaged zones (e.g., efficiency reduction of the drainage system) or permanent displacements. The earthquake input can be defined by generating acceleration records from response spectra (for OBE and MDE) or from fault failure models (e.g., Carvalho, 2007), and using acceleration records from nearby occurring seismic events.

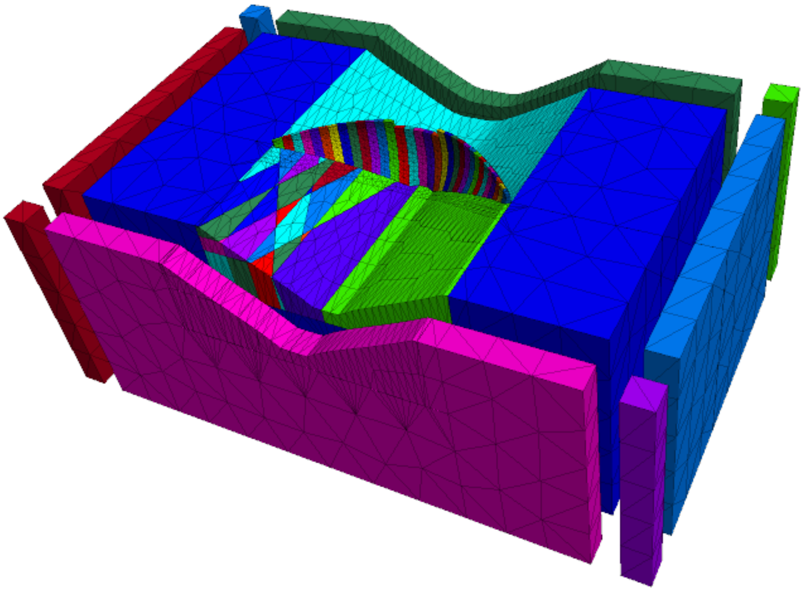


Figure 3.7 – Representation of free-field meshes in the Baixo Sabor dam model (in Lemos 2012)

Dynamic analysis with block models is highly time consuming, as the time step required by explicit algorithms is usually quite small since it depends on the minimum dimension of any tetrahedral element, which cannot be controlled by the user since the mesh is automatically generated for the irregular polyhedral blocks. So, simplifications in 3D DE models, such as reducing the number of discontinuities only to those that have major influence on the seismic behaviour, are particularly important to reduce the computational effort.

The next sections present two important issues that are related with the modelling of concrete dam-reservoir-rock mass foundation systems for seismic analysis, due to the particular characteristics of this type of systems.

3.4.2 Water-structure dynamic interaction

The water-structure dynamic interaction plays an important role in the global dynamic behaviour of the dam-reservoir-foundation system. Therefore, seismic analyses of concrete dams require a proper representation of the reservoir to take into account this dynamic interaction (Câmara, 1989).

A common and well-established procedure is to use the Westergaard formulation (1933), which is implemented in 3DEC software, considering extra masses in the gridpoints on the dam upstream surface, based on the solution for the dynamic forces that an incompressible fluid exerts on a moving vertical wall. However, it is well known that the use of Westergaard's added masses in arch dams often leads to overestimating the water dynamic action and, consequently, to decreasing the calculated natural frequencies with numerical models, which is not confirmed by the results obtained from monitoring data. For instance, Houqun (2014) proposed a reduction of about 50% to the

Westergaard's added masses, considering it to be more appropriate to seismic studies of Chinese arch dams. Moreover, Oliveira *et al.* (2014) also verified that using a reduction of about 70% of the Westergaard's added masses is more suitable to adjust the calculated and the observed natural frequencies in the dynamic evaluation of Cabril dam, in Portugal.

The reservoir can also be discretised into finite elements, assuming that the water behaves like a degenerated solid, with null shear modulus. However, using finite elements with null shear modulus to simulate the reservoir often leads to unstable numerical solutions, and is usually computationally inefficient.

Recent developments presented by Oliveira *et al.* (2015) suggest that the reservoir can be discretised into pressure finite elements, considering pressure waves propagation in the water, which allows the simulation of the water-structure dynamic interaction and of the radiation effects by establishing the main interfaces: water-water, water-air, water-concrete and water-foundation. This methodology was applied to the Luzzone (Switzerland) and Cabril arch dams, and a good agreement between calculated and monitoring results was obtained for the Cabril dam.

The water pressure variations along pre-existing cracks and joints or the development of new cracks that can be formed during an earthquake is also a relevant issue in dynamic studies. Moreover, the uplift pressures at the concrete-rock interface can change during a seismic event. Their variation can be considered according to different dam safety guidelines (Javanmardi *et al.*, 2005) and goes from full reservoir pressure to zero. In the Portuguese codes, the uplift pressures in the concrete-rock interface, prior to a seismic event, are assumed to remain constant during the earthquake. Additionally, the efficiency of the drainage system can be reduced or even disrupted during an earthquake (Alliard and Léger, 2008). Opening and closing cycles of the joints can also modify the pre-seismic water pressure distributions in rock masses.

3.4.3 Damping

Energy dissipation phenomena during a seismic event may be represented by various types of damping: i) viscous damping, proportional to the velocity; ii) hysteretic damping through non-linear constitutive equations of the material, suitable to represent the behaviour under cyclic loadings; and iii) frictional damping due to the sliding of discontinuity surfaces (e.g., Mohr-Coulomb model).

In linear dynamic calculations, using the concept of modal superposition, it is possible to define an equal damping value for all vibration modes, in terms of a certain percentage of the critical damping. In non-linear dynamic calculations, the Rayleigh damping is typically employed, which is proportional to the mass (M) and stiffness (K) matrices by using damping coefficients, α and β ($C = \alpha M + \beta K$). In practice, the coefficients α and β are determined assuming the damping values for two known natural frequencies (typically corresponding to the first and second vibration modes). It is also possible to consider only the term of mass-proportional damping, assuming $\beta = 0$, or the term of stiffness-proportional damping, considering $\alpha = 0$.

This hypothesis of classical damping, i.e., the Rayleigh damping, is generally used as a good approximation in engineering structures. However, several authors suggest that in the case of dynamic water-structure interaction phenomena, this hypothesis may not be suitable (e.g., Chopra, 1995; Oliveira *et al.,* 2012). Therefore, the generalised damping hypothesis can be considered (non-classical damping, i.e., non-proportional to the mass and stiffness), using a space state formulation in displacements and velocities (Veletsos and Ventura, 1986), in which the eigenvalues and eigenvectors are complex values consequently leading to non-stationary vibration modes with complex components.

3.4.4 Final remarks

Seismic studies in jointed rock masses using DE models can be found in literature for various fields of application, such as concrete dams (e.g., Pina *et al.*, 2006; Lemos, 2012; Zenz *et al.*, 2012), rock slopes (e.g., Noorzad *et al.*, 2008; Liu *et al.*, 2014; Hatzor *et al.*, 2004), and underground excavations (e.g., Hsiung and Shi, 2001; Ma and Brady, 1999). Most of these studies comprise 2D models or relatively simple 3D models, with simple geometries in which only a few joint sets are represented. On one hand, this is due to the high computational effort that an earthquake analysis entails for complex block models with 3D geometries, because the dynamic time step required is usually quite small. On the other hand, a better understanding of the key elements and rock discontinuities that effectively influence the dynamic response and are relevant for the seismic analysis has still to be handled, in order to simplify the 3D DE models to become computationally viable. The identification of the most important failure mechanisms, using probabilistic approaches, will allow to have simplified 3D DE models to perform efficient seismic analyses. A methodology to conduct seismic analyses of dam-reservoir-foundation systems will be developed based on these simplified 3D DE models and with the essential features for a dynamic analysis.

4 | Objectives and work plan of the thesis

4.1 Objectives

This work aims at improving the methodologies for failure analysis of engineering structures in and on jointed rock masses, which support the safety studies developed during the design, construction and operation stages, as well as contributing to the enhancement of discrete element models capable of a more realistic representation of rock masses, including the most important discontinuities, and to perform efficient seismic analyses. Figure 4.1 displays a workflow with the tasks and the expected results of the thesis.

Firstly, a procedure for numerical generation of discontinuity sets in DE models, intended for mechanical stability analyses of jointed rock masses, will be developed. This tool, based on statistical distributions of the geometric parameters of discontinuities, defined according with the field mapping information, will allow to represent, in a more appropriate way, the geological conditions of the rock mass, including the representation of the rock bridges, defined by the non-persistence of discontinuities. It will be essential to automate the procedure of introducing the discontinuities in the numerical models, thus allowing to easily test the importance of the different discontinuity sets.

Then, for each 3D geometric model realisation, probabilistic analyses will be performed considering the shear strength variability of the rock joints and the effect of the variation of joint water pressures, using efficient simulation techniques based on the Monte Carlo method. The consideration of the combined variability of geometric and shear strength parameters and of water pressures in rock discontinuities will allow the identification of the most important failure mechanisms, assessing the respective influence of each parameter on the stability conditions. This will contribute to improve the current methodology employed by LNEC for safety analysis studies.

At this stage, it is expected to identify the most relevant failure scenarios enabling to perform efficient seismic analyses considering simplified 3D DE models only with the most relevant mechanisms, with the discontinuities involved in them, with the corresponding mechanical properties and water pressure distributions. This will allow to have 3D DE models with the essential features to analyse the dynamic behaviour of dam-reservoir-foundation systems, since seismic analyses are usually computationally demanding. Seismic analysis will allow structural safety evaluation and the identification of possible failure modes or local damaged zones due to the seismic events.

The resulting methodologies for safety assessment and seismic analyses will be applied to the Foz Tua and Baihetan arch dams.

It is relevant to mention that the three topics described above are the range of possibilities intended to be examined in this thesis and, with the progress of the work, the actual scope of the studies may become more focused on a few particular topics.

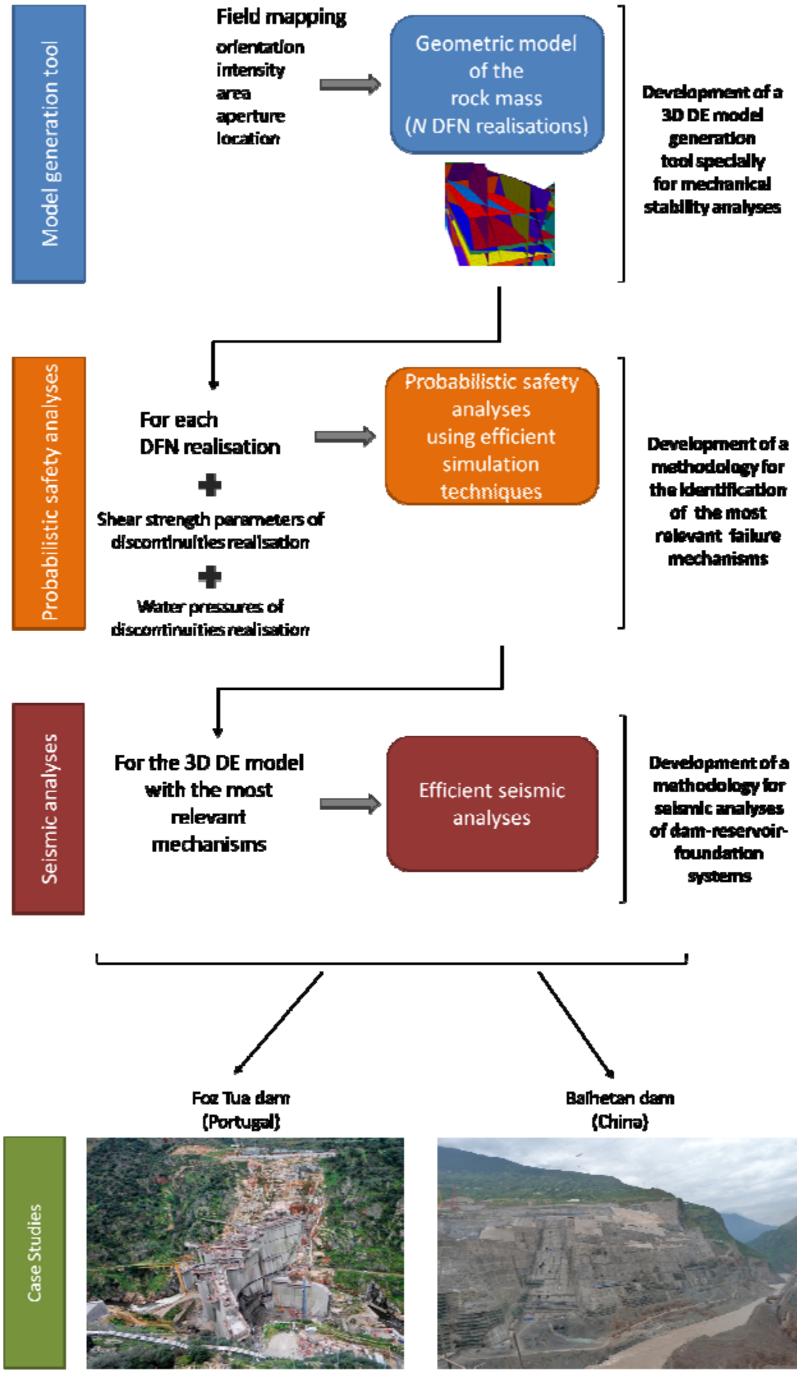


Figure 4.1 – Workflow with the summarised tasks and expected results of the thesis

4.2 Work plan

4.2.1 Model generation tool

A 3D discrete element model generator tool, specially intended for mechanical stability analyses, will be developed using statistical distributions of the geometric properties of the joints, allowing a realistic, while still computationally viable, representation of the rock mass.

The analysis of the geological information from the studies conducted at the site, allows the definition of the main discontinuity sets' geometric parameters, such as the orientation, intensity, area, aperture or location. These parameters will be used to further characterise the geometric statistical distributions for the discontinuity sets. Based on these statistical distributions, geometrical models of the rock mass are generated, using the tool that will be developed. Parametric studies will be performed, in order to assess the significance of the various geometric parameters on failure modes (e.g., effect of joint spacing, orientation and location, number of failure blocks, etc.). Geometric simplifications of the resulted discrete fracture networks, such as the combination of nearly co-planar fractures, deleting or extending incomplete fractures, etc., are among the topics that will be examined.

In 3D DE models the hypothesis of infinite persistence of all joints usually considered is an overly conservative simplification. So, procedures to effectively represent the non-persistency of the discontinuities in stability analyses will be investigated. A simple methodology that will be tested consists in creating through-going planar cuts, and simulating breakable rock bridges by assigning cohesive strength to some sections of the joint plane. Therefore, methodologies to identify potential failure paths through rock bridges in pre-existing fractures will be investigated.

The 3DEC software (Itasca, 2013) and its available tool for generating stochastic discontinuities will be used for the numerical tests. 3DEC has an embedded programming language enabling the user, if necessary, to modify and incorporate other code blocks into their modules. This will allow routines developed during this research for model generation, constitutive modelling, safety analysis, etc., to be made public and shared with other researchers.

4.2.2 Probabilistic safety analyses

For the geometric models of the rock mass generated with the tool that will be developed, probabilistic approaches will be performed, using simulation techniques, to analyse the joint effect on the equilibrium conditions of the variability of the geometric and shear strength parameters and of water pressure distributions in the discontinuities. In order to mitigate the high computational effort usually required in traditional random sampling of the Monte Carlo simulation method, advanced simulation techniques, such as the surface response methods will be examined.

The main objective of using probabilistic approaches is to compare different mechanisms, aimed at identifying the most relevant failure mechanisms to be considered in subsequent seismic analyses, and to evaluate the influence of each input parameter concerning the rock discontinuities (various geometric parameters, friction angle, cohesion and water pressures) on the control parameters that will be defined for each numerical example. These control parameters will be monitored during the analyses and can be defined, for instance, as global safety factors, total maximum displacements of the structure and of the rock mass, maximum compressive and tensile stresses in the dam body, indicators of probable damage in the drainage systems or loads applied by the structure to the rock mass.

4.2.3 Seismic analyses

The identification of the most relevant failure scenarios using probabilistic approaches enables to consider more simplified 3D DE models to perform efficient seismic analyses, aimed at evaluating the structural safety for both current and failure scenarios considering, respectively, the operating basis earthquake and the maximum design earthquake.

3D DE models of dam-reservoir-foundation systems will be used to conduct the seismic analyses, considering adequate dynamic boundary conditions and the hydrodynamic water-structure interaction. In what concerns the latter, the Westergaard formulation will be considered, since it is already implemented in 3DEC software, and it is not intended in this work to develop a new code for the implementation of other type of hydrodynamic interaction formulation in 3DEC.

During the seismic analysis, damage indicators such as the occurrence of permanent displacements, existence of cracking zones in the dam body and damage of the drainage system will be investigated. Some factors will also be examined, in terms of their influence on the global seismic behaviour of the dam-reservoir-foundation system and on the occurrence of damaged zones, namely the effect of different seismic intensities, the influence of near and far seismic action, damping, the distance of boundary conditions and the reduction of Westergaard's added masses.

4.2.4 Case studies

Methodologies and techniques resulting from the work developed in the previous sections will be applied to the safety stability analysis of real engineering works using 3D DE models. For this purpose, two case studies of concrete arch dams have already been established (Foz Tua and Baihetan dams). Prior to these studies, validation of the methodologies and techniques using literature cases, where the failure mechanisms are well defined or rock engineering works with known failure surfaces, is envisaged.

The first case study is the Foz Tua arch dam, which is at its final construction stage. Recently, the safety assessment study for foundation failure scenarios using the current methodologies employed by LNEC for this type of analysis was performed (Espada *et al.*, 2015). The JRF was fully involved in it. Three discrete element models were developed using 3DEC software, considering the geological and geotechnical conditions actually encountered during the excavation works, in order to evaluate different foundation failure scenarios, in accordance with Portuguese regulations. The first numerical model was developed to analyse the failure of the dam-rock interface, assuming a homogeneous rock mass. In the second model, failure along the main geological structures of the rock mass in both banks was analysed. Finally, the third model was developed to analyse failure scenarios in the left bank, where a particular joint set was included. These numerical models will be further explored to conduct probabilistic analyses during the research work.

The second case study is the Baihetan arch dam, located in the Jinsha River, a tributary of the Yangtze River, in southwest China. It is the result of the on-going cooperation project between LNEC and SKLGGE of the Chinese Academy of Sciences in Wuhan, China. Baihetan is a very large arch dam (over 280 m high), currently under construction in a seismic region. Its rock mass foundation consists of basalt layers intersected by several faults and shear bands, more or less persistent and thick, generally filled by impervious volcanic soil (tuff). During the meetings with the dam owner China Three Gorges (CTG) and researchers from LNEC and SKLGGE, two interesting studies about the Baihetan project were identified and were integrated as part of this doctoral thesis. The first study refers to the stability analysis of the left bank during excavation, assessing the behaviour of the main shear bands and faults in this zone. The second study relates to the seismic analysis of the dam-reservoir-foundation system, considering the most important discontinuities in both banks. During the period that the JRF stayed in Wuhan, at the SKLGGE, work already started on the development of the geometry of the 3D numerical model to perform the analysis of the slope stability of the left bank.

4.2.5 Tasks

For the development of the thesis works the following tasks are considered:

Task 1 – Achievement of the ECTS credits required for the PhD degree.

Task 2 – Literature review and state of the art.

Task 3 – Development of a 3D DE model generation tool specific for mechanical stability analyses:

> **Sub-task 3.1** – Study of the statistical distributions of the geometric parameters of discontinuities.
>
> **Sub-task 3.2** – Study of the procedures to effectively represent the non-persistency of the discontinuities in stability analyses.
>
> **Sub-task 3.3** – Development and implementation of a 3D DE tool dedicated to mechanical stability analyses.

Task 4 – Development of a methodology for identification of the most relevant failure mechanisms:

> **Sub-task 4.1** – Study of the statistical distributions of shear strength parameters and of water pressures in rock discontinuities.
>
> **Sub-task 4.2** – Study of simulation methods to reduce the number of simulations in the probabilistic analyses.
>
> **Sub-task 4.3** – Development and implementation of a numerical procedure for combined variability of geometric and shear strength parameters and of water pressures in discontinuities.
>
> **Sub-task 4.4** – Implementation of a procedure for the identification of the most important failure mechanisms and the discontinuities involved in them.

Task 5 – Development of a methodology for seismic analyses of dam-reservoir-foundation systems:

Sub-task 5.1 – Study of the national codes (Portuguese and Chinese) to perform seismic analyses applied to arch dams.

Sub-task 5.2 – Study of the main features of performing seismic analyses using 3D DE models.

Sub-task 5.3 – Development and implementation of a procedure to perform efficient seismic analyses of dam-reservoir-foundation systems.

Task 6 – Numerical modelling of two arch dams (case studies):

Sub-task 6.1 – Development of 3D DE models using the tool for the rock mass generation.

Sub-task 6.2 – Application of probabilistic analyses to identify the most relevant failure mechanisms.

Sub-task 6.3 – Seismic analyses of Baihetan and Foz Tua dams.

Task 7 – Writing papers and thesis text.

Table 4.1 presents the schedule for the execution of the tasks.

Table 4.1 – Task execution schedule

Tasks	**1st year**				**2nd year**				**3rd year**				**4th year**			
Task 1			▨	▨			▨	▨			▨	▨				
Task 2	▨	▨	▨	▨												
Task 3			▨	▨	▨	▨	▨									
Task 4						▨	▨	▨	▨							
Task 5							▨	▨	▨	▨	▨					
Task 6					▨	▨	▨	▨	▨	▨	▨	▨	▨			
Task 7					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	

4.3 Thesis outline

The expected structure of the thesis is the following:

Chapter 1 – Introduction and thesis relevance.

Chapter 2 – State of the art about available joint generation techniques/software and about probabilistic and seismic analyses applied to rock engineering structures.

Chapter 3 – Discrete fracture networks intended for mechanical stability analyses in 3D DE models:

- Statistical distributions of the geometric parameters of discontinuities

- Consideration of the non-persistency of discontinuities
- Procedures to adapt the existing DFN tools to mechanical stability analyses
- Simple application examples

Chapter 4 – Methodology for the identification of failure modes in rock masses based on probabilistic analyses:

- Statistical distributions of the shear strength parameters and of water pressures in discontinuities
- Efficient simulation techniques based on the Monte Carlo simulation method
- Implementation of a procedure for the combined variability of the geometric and shear strength parameters and of water pressures in discontinuities
- Simple application examples with the identification of potential failure modes

Chapter 5 – Seismic analyses of dam-reservoir-foundation systems:

- Regulations for seismic analysis in Portugal and China
- Seismic analyses using discrete element models
- Simple application examples

Chapter 6 – Applications and result analysis:

- Foz Tua arch dam
- Baihetan arch dam

Chapter 7 – Conclusions.

4.4 Available resources to be used

4.4.1 Statistical distributions

The statistical distributions that will be used and analysed regarding the geometric parameters of discontinuities are available in national and international literature. LNEC has experience in the definition of geometrical models, based on field mapping of geological structures, using suitable statistical distributions (e.g., Grossmann, 1993).

In what concerns statistical distributions of shear strength parameters and water pressures in rock discontinuities, experience from previous works developed at LNEC will be used (e.g., Muralha, 1995).

4.4.2 Software

The main software that will be used in this work is 3DEC from Itasca (2013). The DFN module from 3DEC will be tested in order to explore the fracture networks generated from this module. The dynamic module from 3DEC will also be used to perform the seismic analyses. Both licenses of DFN and dynamic modules are available at LNEC.

3DEC software will be used for the implementation of all numerical models expected to be carried out during this thesis. Since 3DEC has an embedded programming language, it is possible to create or modify code blocks into their modules. For the probabilistic analyses, other software can be used in this work, such as MatLab (2011).

5 | Supervision

This work will be mainly developed at LNEC for a period of 4 years. The thesis will be submitted at FEUP - Faculdade de Engenharia da Universidade do Porto, in which the JRF will achieve the required ECTS credits for the PhD degree.

The supervision of this work will be done by Dr José Muralha and Dr José Vieira de Lemos from LNEC, and by Associate Professor José Couto Marques from FEUP.

Senior Researcher José Muralha has been developing his activity on the mechanical and geometric statistical characterisation of the rock jointing with the objective of performing probabilistic safety studies of structures in or on rock.

Principal Researcher José Vieira de Lemos has a vast experience in the development and application of numerical models to support stability studies of rock engineering structures in and on jointed rock masses, and in the use of discrete element codes for the seismic analysis of concrete dams and stone masonry structures.

Professor José Couto Marques is widely experienced in numerical modelling of geotechnical problems, including non-linear static and dynamic analysis of dams, and application of discrete elements to foundation analysis.

6 | International cooperation

The SKLGGE of the Institute of Rock and Soil Mechanics of the Chinese Academy of Sciences in Wuhan (China) and LNEC established a scientific cooperation project starting in January 2015, entitled *Discrete element numerical modelling of dam foundation failure mechanisms*. The scientific cooperation project, financed by SKLGGE, covers several activities related to the theme of the doctoral thesis that the JRF is expected to develop in the coming years. Other researchers from LNEC, namely José Muralha, José Vieira de Lemos and Luís Lamas, are also participating in the project.

Since SKLGGE is involved in several studies of large arch dams, currently under construction in southwest China, where the seismic action is very relevant, it was decided that Baihetan dam, currently under construction, would be used as a case study in the doctoral thesis of the JRF. So, according to the activities foreseen in the project for 2015, the JRF stayed for 2 months at SKLGGE in Wuhan, at the end of 2015, in order to gather relevant data about the Baihetan hydroelectric project. During the stay in China, a one week visit to the dam construction site allowed to establish contact with the dam owner, CTG.

In the scope of the on-going cooperation project between SKLGGE and LNEC the following activities are expected to occur in 2016 and 2017:

- One week visit to LNEC of SKLGGE researcher Prof. Quan Jiang to interact with local researchers and visit on-going dam projects in Portugal.
- Two months stay of the JRF at SKLGGE to continue the research and visit the Baihetan dam site.
- Organisation of a final workshop for presentation of results of the project, by researchers of SKLGGE and LNEC.
- Preparation of two papers to international journals and one paper to an international symposium related to the studies that will be developed.

7 | Funding

The JRF will participate in the new calls *for PhD Studentships, PhD Studentships in Industry and Post-Doctoral fellowships* of the Fundação para a Ciência e a Tecnologia (FCT), aimed at obtaining financing from FCT.

As previously mentioned, financing from SKLGGE was obtained according to the approved *Scholarship for Visiting Scholars of the State Key Laboratory of Geomechanics and Geotechnical Engineering (Research No. Z014003*), in December 2014. This project includes financing for flights between Lisbon and Wuhan, visits to Wuhan and Baihetan dam site, living allowance during the stay at the institutions, travel expenses and registration in an international symposium to be designated.

LNEC funding results from the allocation of the resources involved in the on-going research project “DEMRock6m”, established in DBB-NMMR.

Lisbon, LNEC, July of 2016

APPROVED

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ANNEX
Curriculum Vitae of Margarida Espada

Name: Margarida Isabel Ramalho Espada

Education: M.Sc. in Civil Engineering - Structures (Instituto Superior de Engenharia de Lisboa - ISEL), January 2010

Complementary education

Attendance to three subjects of the Diploma of Advanced Studies (DFA) in Geotechnical Engineering organised by LNEC, the IST of the University of Lisbon and the Faculty of Sciences and Technology of the New University of Lisbon, in 2011-2012.

Professional experience:

From September 2009 to September 2011

Structural engineer in a design company (P2S - Estudos e Projectos de Engenharia L^{da})

Analysis, calculation and design of concrete structures. Responsible for the acoustic laboratory of the company, having been involved in several building acoustic tests and in the development of the respective reports.

Since September 2011

Junior Research Fellow at the Concrete Dams Department (DBB), Modelling and Rock Mechanics Unit (NMMR)

Participation in the following studies at the LNEC:

- Analysis and interpretation of the small flat jack tests results conducted in the Salamonde II rock mass, 2012.
- Implementation of a global methodology for evaluation of the stress field in the Salamonde II rock mass from *in situ* stress measurements, using a large 3D numerical model developed with the FLAC3D software, 2012 (Espada *et al.*, 2013a; Espada *et al.*, 2013b; Lamas *et al.*, 2014b; Espada and Lamas, 2014a).
- Analysis of the deformational behaviour of the rock mass during the excavation of the new underground powerhouse cavern of Salamonde II, using a 3D numerical model developed with the FLAC3D software, 2013 (Espada and Lamas, 2014b; Espada and Lamas, 2014c; Espada and Lamas, 2015).
- Development of a VBA tool for the representation of the measured displacements of the road bridge in the Foz Tua hydroelectric scheme, 2013.
- Technical report describing the activities carried out during the eleventh visit to the surface excavations and powerhouse works in 15 and 16 July 2014, of the Foz Tua hydroelectric scheme, 2014.
- Analysis of the global behaviour of the Castelo de Bode hydraulic tunnel during the five-year period from 2009 to 2013, using quantitative interpretation models, 2014.
- Safety evaluation analysis for foundation failure scenarios of the Foz Tua arch dam, using three discrete element models, developed with the 3DEC software, 2015 (Espada *et al.*, 2016).
- Technical report describing the activities carried out during the fourteenth visit to the surface excavations and powerhouse works in 20 and 21 May 2015, of the Foz Tua hydroelectric scheme, 2015.
- Plan for the first filling of the power conduit of the Venda Nova III reversible hydroelectric scheme and for the start of operation of the electromechanical groups, 2016.

M.Sc. thesis:

- Espada, M., 2010 – **Desenvolvimento de modelos para análise dinâmica de estruturas. Aplicação a barragens de betão e estruturas auxiliares.** M.Sc. thesis, ISEL.

Publications in national and international conferences:

- Espada, M., Mendes, P., Oliveira, S., 2010a – **Observação e análise do comportamento dinâmico da torre das tomadas de água da barragem do Cabril.** 8º Congresso Nacional de Mecânica Experimental, Universidade do Minho, Guimarães.
- Espada, M., Mendes, P., Oliveira, S., 2010b – **Análise do comportamento dinâmico da barragem do Cabril sob excitação ambiente: influência da torre das tomadas de água. Estudo sísmico da torre.** Sísmica 2010 - 8º Congresso de Sismologia e Engenharia Sísmica, Universidade de Aveiro, Aveiro.
- Espada, M., Mendes, P., Oliveira, S., 2011a – **Dynamic monitoring of Cabril dam under ambient vibration. Influence of the intake tower dynamic behaviour.** Proceedings of the 6th International Conference on Dam Engineering, LNEC, Lisbon.
- Espada, M., Lamas, L., Leitão, N., 2013a – **Modelo tridimensional para análise global dos ensaios de medição de tensões *in situ* no maciço rochoso da caverna da central de Salamonde II.** Congress on Numerical Methods in Engineering - CMN 2013, Bilbao, Spain.
- Espada, M., Lamas, L., Leitão, N., Figueiredo, B., 2013b – **Global methodology for evaluation of the stress field in a rock mass from *in situ* tests. Application to the Salamonde II powerhouse cavern.** In Kwasniewski & Łydzba (eds), Rock Mechanics for Resources, Energy and Environment; Proc. Eurock 2013, Wroclaw: 425-430. Taylor & Francis.
- Espada, M., Lamas, L., 2014a – **Modelo tridimensional do estado de tensão *in situ* num maciço rochoso.** Congresso Nacional de Geotecnia, Covilhã. Sociedade Portuguesa de Geotecnia.
- Espada, M., Lamas, L., 2014b – **Monitored and calculated deformational behaviour of a large cavern during excavation.** In Alejano, Perucho, Olalla & Jiménez (eds), Rock Engineering and Rock Mechanics: Structures in and on Rock Masses; Proc. Eurock 2014, Vigo, Espanha: 983-988. Taylor & Francis.
- Espada, M., Lamas, L., 2014c – **Comportamento deformacional de uma estrutura subterrânea durante a escavação.** 5as Jornadas Portuguesas de Engenharia de Estruturas (JPEE 2014), Lisboa, Portugal.
- Espada, M., Lamas, L., 2015 – **Rock mass behaviour analysis of the Salamonde II powerhouse.** Proceedings of Second International Dam World Conference - DW 2015, Lisbon, Portugal.
- Espada, M., Muralha, J., Lemos, J.V., Plasencia, N., Paixão, J., 2016 – **Avaliação da segurança para cenários de rotura pela fundação da barragem de Foz Tua.** 15º Congresso Nacional de Geotecnia - 15CNG, Porto, Portugal.
- Lamas, L., Muralha, J., Espada, M., Figueiredo, B., 2014b – ***In situ* stress field estimation for underground structures design.** Proceedings of VI Brazilian Symposium on Rock Mechanics (SBMR 2014) – ISRM Specialized Conference, Goiânia, Brasil.
- Oliveira, S., Espada, M., Câmara, R., 2012a – **Long-term dynamic monitoring of arch dams. The case of Cabril dam, Portugal.** Proceedings of 15th World Conference on Earthquake Engineering, Lisbon.

- Oliveira, S., Espada, M., Câmara, R., 2012b – **Monitoring and modeling the dynamic behavior of arch dams.** 54º Congresso Brasileiro do Concreto. Dam World Conference, Brasil.
- Oliveira, S., Silvestre, A., Espada. M., Câmara, R., 2012 – **Monitorização e modelação do comportamento dinâmico de barragens de betão. Interação barragem-fundação-albufeira.** Encontro Nacional Betão Estrutural (BE2012), Faculdade de Engenharia da Universidade do Porto, Porto.
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- Espada, M., Lamas, L. – **Back analysis procedure for identification of anisotropic elastic parameters of overcored rock specimens.** Rock Mechanics and Rock Engineering (*submitted, under revision*).
- Espada, M., Lamas, L., Plasencia, N. – **Assessment of the stress field and analysis of the deformational behaviour of the Salamonde II powerhouse cavern.** Tunneling and Underground Space Technology (*to be submitted*).
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Other technical and scientific activities:

- Lecturer in three training courses at LNEC and ISEL about MatLab programming with applications to static and dynamic analyses to civil engineering structures.
- Lecturer in one course at LNEC related with VBA programming.
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