Numerical modelling of masonry gravity dams considering the internal structure of the material

BRETAS, E.M.[1], LEMOS, J.V.[2], LOURENÇO, P.B.[3]

ABSTRACT: Frequently, numerical models of masonry dams disregard the discontinuous nature of the material. In some cases, those discontinuities control the structural and hydraulic behaviour of the masonry dam. The masonry proprieties are influenced by the quality of the material and the laying scheme of the stones on the external faces as well as in the inner material. The Discrete Element Method (DEM) has been used on analyses of gravity masonry dams. The capacity to model the discontinuities explicitly and the ability to perform coupled analyses are two significant benefits of the DEM. The DEM application used in this paper is presented, stressing the description of the calculation cycle. Seven examples of numerical analyses of gravity masonry dams are presented. Three of them consider the discontinuous nature of the dam body, in order to study the loss of cohesion scenario, the crack propagation scenario and the seismic performance of a masonry dam. The remainder four examples are aimed at stress analysis, global stability, hydromechanical analysis and the permanent sliding resulting from a seismic event.

Keywords: *Masonry gravity dams, Numerical models, Discrete Element Method*

1 INTRODUCTION

During the second half of the 19th century, stone masonry was used in the construction of most large dams, both in Europe and America [1]. Many of these structures have been subjected to rehabilitation works, and remain in use. The structural problems of masonry dams result from aging and are different from those that occur in concrete dams. Most of the problems are related to the cohesion loss of masonry due to the chemical and physical effects of the water. The structural safety analysis of masonry dams through numerical models, demands the use of appropriate tools, which take into account the non-linear behaviour of the structure and the hydromechanical interaction, resulting from water seepage through the dam. Regarding the numerical models of masonry gravity dams, an important aspect concerns the representation of the internal structure of the masonry. This representation must be able to characterize the behaviour of the structure subjected to static and dynamic loads, including its permeability and discontinuities, taking into account that failure mechanisms like cracking, sliding and overturning may take place. This work presents a set of examples of masonry dams, considering different discretization techniques of the numerical model, making use of the Discrete Element Method.

[1] Postdoctoral Researcher, National Laboratory for Civil Engineering, Concrete Dams Department, eduardombretas@gmail.com
[2] Researcher, National Laboratory for Civil Engineering, Concrete Dams Department, vlemos@lnec.pt
[3] Professor, ISISE, University of Minho, Department of Civil Engineering, pbl@civil.uminho.pt

2 CONSTRUCTIVE ASPECTS OF MASONRY DAMS

The majority of the masonry dams were constructed with cut stones, rubble and concrete [2]. The inner parts were built with a combination of large stones and rubble, surrounded by concrete. In the stones laying, special measurements were taken in order to create break joints in all directions, avoiding horizontal courses. Figures 1a to 1d show different degrees of interlocking, from the non-interlocking case (a), vertical interlocking (b), horizontal interlocking (c) and the full interlocking case (d). In the latter case, different blocks size must be employed. Because of its highest price, the cut stone was used only on the upstream and downstream faces and on ornamental works. In many cases the cut stones were laid normal to the faces (Figure 1e), but some cases are found in which the stones were laid horizontal to the faces (Figures 1f to 1h). According to the analysis objectives, some of those aspects should be considered on the discretization of the numerical model.

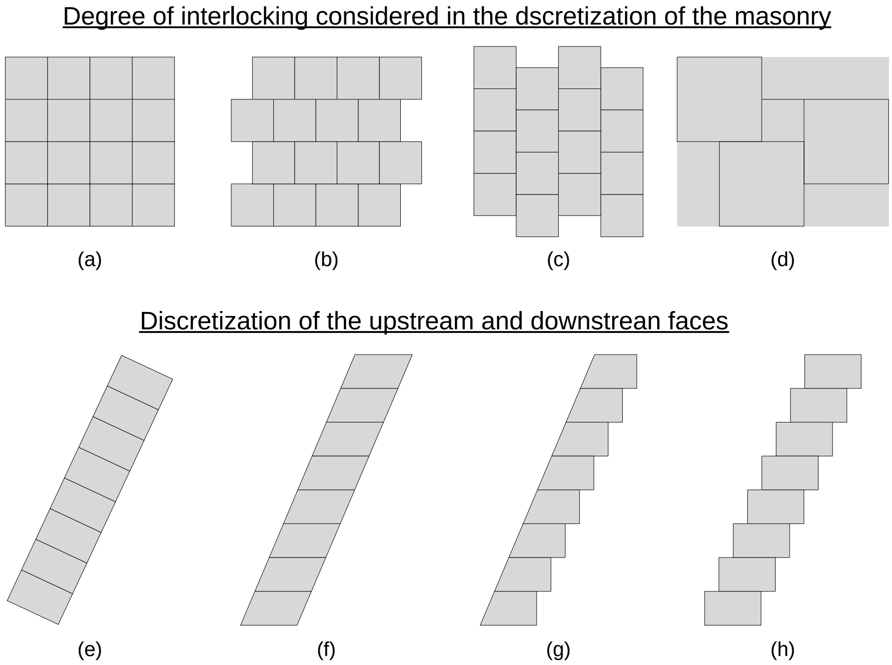

Figure 1. Different arrangements of the masonry

3 NUMERICAL MODELING USING THE DISCRETE ELEMENT METHOD (DEM)

The Discrete Element Method (DEM) proves to be suitable for the analysis of gravity dams, because it allows an explicit modelling of the discontinuities. These discontinuities control the structural behaviour of the system dam-foundation-reservoir and are found in the masonry of the dam body, in the foundation surface itself and in the rock mass foundation. The numerical application used in this paper is described briefly next, see [3] for details. The model is an assemblage of blocks. The blocks could be deformable or rigid. In the case of deformable blocks, each block is discretized by a Finite Element mesh. Between the blocks, numerical contacts are established with a specific constitutive law. Sliding among blocks is allowed, including full separation, as well as new contacts can be found during the analysis. In numerical terms, the computation cycle embodies the solution of the movement equations of each degree of freedom by means of the central difference method. In fact, it is a dynamic analysis, whose static solution is gained through the dynamic relaxation scheme. This solution presents a numerical restriction related to the time step and, for this reason, extremely stiff contacts and stiff or small blocks, should be avoided because this increases the total calculation time.

The calculation cycle is represented in Figure 2. The seismic analysis (D steps), the flow analysis (H steps) and the structural strengthening analysis (R steps) are integrated in the mechanical cycle (M steps), sharing the same model data and allowing full coupled analysis. In the initial phase, forces are computed and added to each independent degree of freedom (steps M3, M4, M5, M12, D1, H1 and R1). Next, the movement equations are established and solved (steps M2, M6, M7 and D2). Subsequently, absolute and relative position of all blocks is updated (M8, M9, M10, M11 and R2), where the verification of active contacts and the attempt to detect new ones (step M1) takes place. In the meantime, the new flow rates and new pressures are computed closing the flow cycle (step H2). The convergence criterion depends on the objectives proposed by the analysis. Usually, the analysis is stopped when the unbalanced force reaches some specific minimum threshold (step M13). This numerical application has been used in the analyses of existing masonry gravity dams, particularly in the evaluation of structural safety conditions, involving the assessment of rehabilitation and reinforcement works.

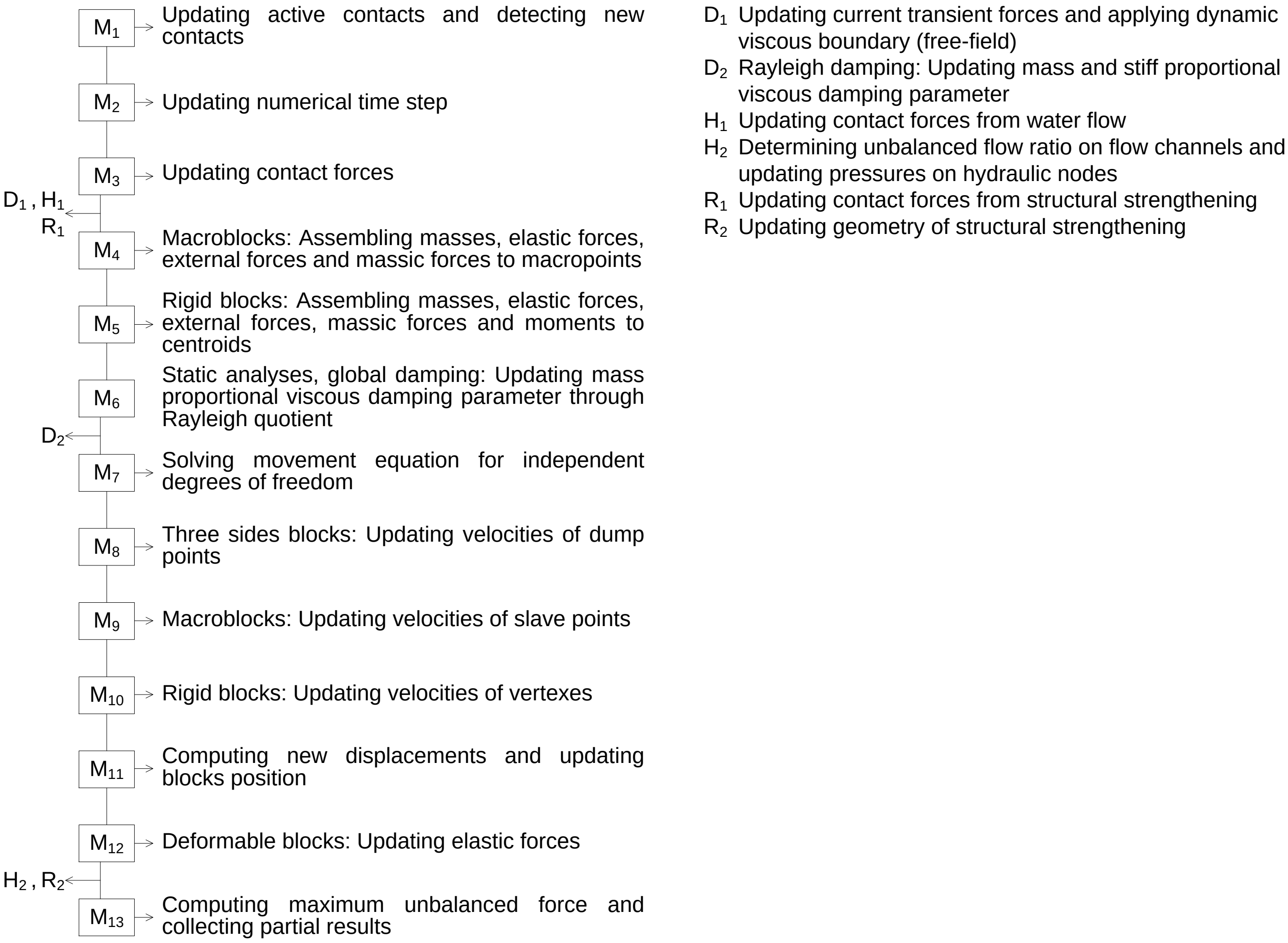

Figure 2. Description of the calculation cycle of the numerical application

4 EXAMPLES OF NUMERICAL MODELS OF MASONRY GRAVITY DAMS

4.1. Stress analysis of the body of a masonry gravity dam

The stress analysis of the dam body of a gravity masonry dam is the aim of this first example shown in Figure 3 [4]. The dam is about 31 m high, with a base 23 m wide. An equivalent continuous model of the dam and the foundation was adopted, using a Finite Element (FE) mesh. An elastic joint between the dam and the foundation was assumed. The foundation is represented by a mesh 47.4 m high and 86.5 m wide, in which a box boundary condition was applied. The loads considered in this model were the self-weight and the hydrostatic pressure. The stress field is represented through the main stresses. For those loads, the dam is under compression, with a maximum of -0.96 MPa at the downstream toe. The safety factor is defined from the main stresses and the material properties according the Mohr-Coulomb criterion. Three different scenarios for the material strength were analysed, varying the cohesion and the tensile strength, considering a friction angle of 55º and a compression strength of 10 MPa. For all cases, the shear failure is the main mechanism as shown in Figure 3. For the weakest material, characterized by a tensile strength t= 0.25 MPa and a cohesion c= 0.79 MPa, the lowest safety factor (1.9) is archived at the downstream toe. For a gravity masonry dam in reasonable conditions, the failure by overstress is not the main concern.

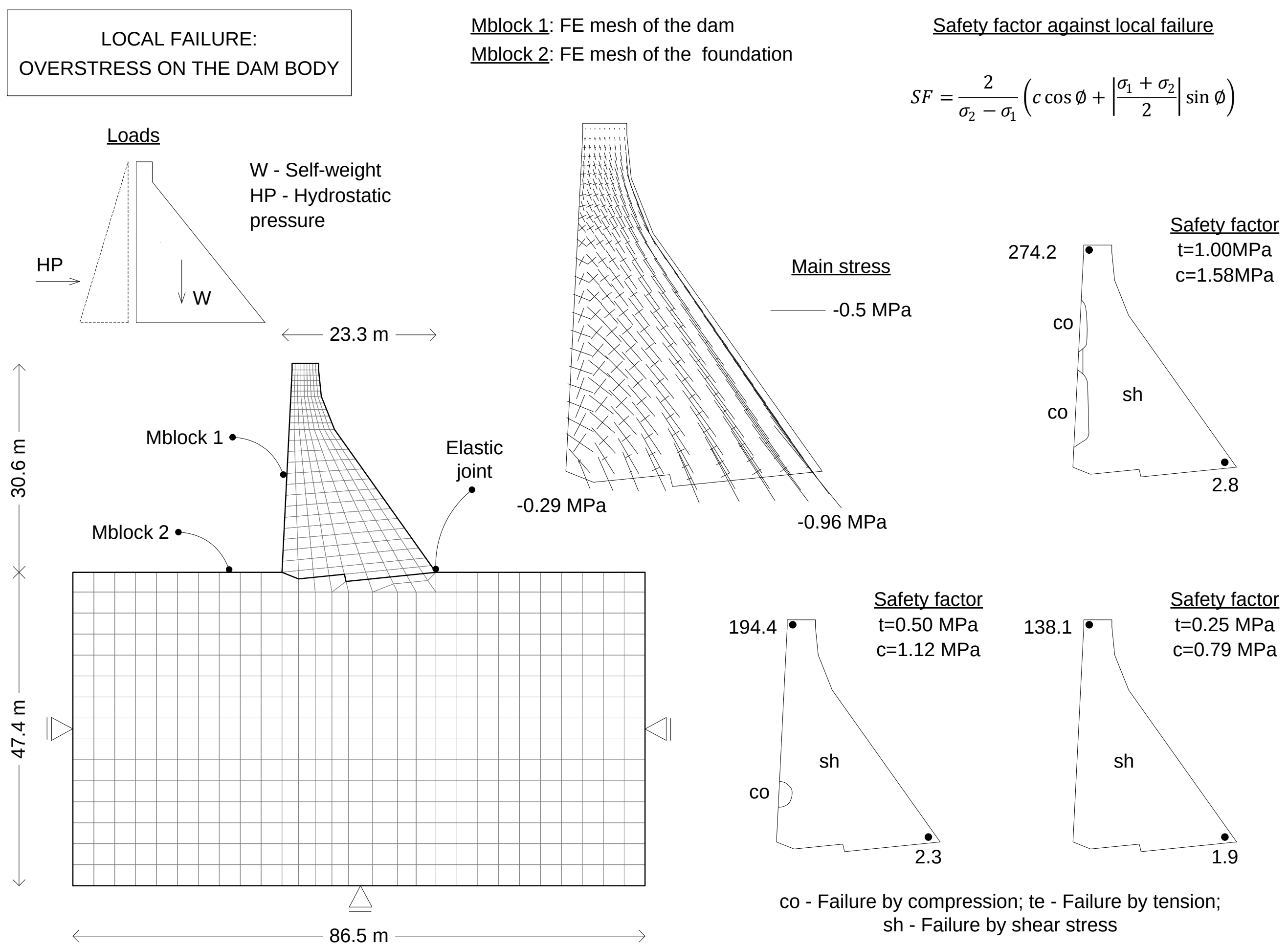

Figure 3. Stress analysis of the body of a masonry gravity dam

4.2. Assessment of the loss of cohesion scenario of a masonry dam

The main failure mechanism of a masonry gravity dam is the loss of cohesion due to the chemical and physical attack of the water leakage. This problem is more dramatic on dams subject to severe climatic conditions, with long and cold winters. For this reason the rehabilitation works carried out in many masonry dams were focused in reducing the permeability of the material and increasing the stiffness of the dam body. The example presented in this section is aimed to evaluate this scenario (Figure 4) [4]. This dam is already analysed in the first section for the overstress case. The model comprises two blocks type. The first is a quadrangular block to model the upstream and downstream faces. The other type is a Voronoi block, to model the masonry structure into the dam body. Each Voronoi is composed by triangular elements which share one point, coincident with the centroid of the Voronoi element. The dam is subjected to the self-weight and the hydrostatic pressure, in addition to the internal pressure, from the leakage through the masonry joints. The internal pressure was established by means of a hydromechanical analysis. The boundary condition was applied directly at the base of the dam, avoiding a foundation block. Between the masonry blocks, a non-linear constitutive model was assumed. A parametric study was carried out, reducing the friction angle, and considering null cohesion and null tensile strength. Three different discretization were tested, designated as Model A, B and C. For Model A, a failure on the crest was observed for a friction of 18º. A similar failure mechanism was found for Model B for a friction angle of 17º. For Model C, for a friction angle of 15º, a global collapse of dam was observed.

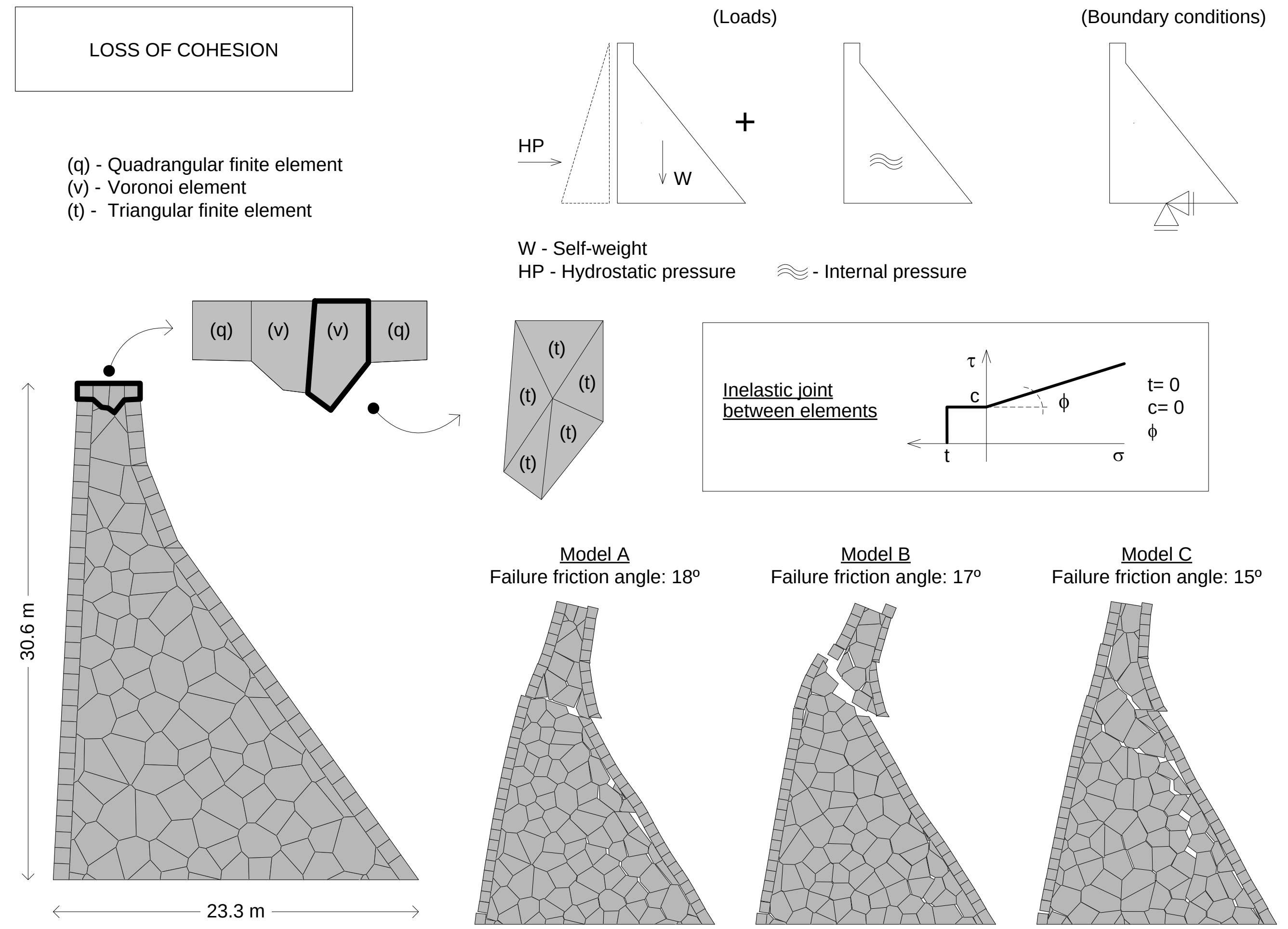

Figure 4. Assessment of the loss of cohesion scenario of a masonry dam

4.3. Static analysis considering the global stability of a masonry gravity dam

The actual failure of a gravity dam is a composed mechanism, including overstress, sliding and overturning scenarios. For the sake of simplicity those scenarios are tested separately. The global dam sliding and overturning are widely accepted as important scenarios to consider for gravity dams safety assessment. These failure mechanisms can be observed in discontinuities into the dam body, through the foundation, as well inside the rock mass foundation. The next study (Figure 5) [4] was applied to the same dam analysed in the last two sections. The model is similar to the first model, section 4.1, except for the joint between the dam and the foundation, which the constitutive model assumes now a non-linear behaviour. Both dam and foundation were modelled using a continuous and elastic Finite Element mesh. For the sliding scenario, through the foundation surface, a parametric study was developed. The initial properties with null tensile strength and null cohesion were adopted. The friction angle was reduced step by step from an initial value of 45º. The dam sliding started for a friction angle of 27º. From this result, a sliding safety factor (SSF) of 2.0 was established. The dam overturning around downstream toe was analysed considering a flood scenario. The dam proved to be stable even when the water level was raised until 5 m above the normal design reservoir elevation. Global failure was not reached, but the failure mechanism can be figured out in Figure 5.

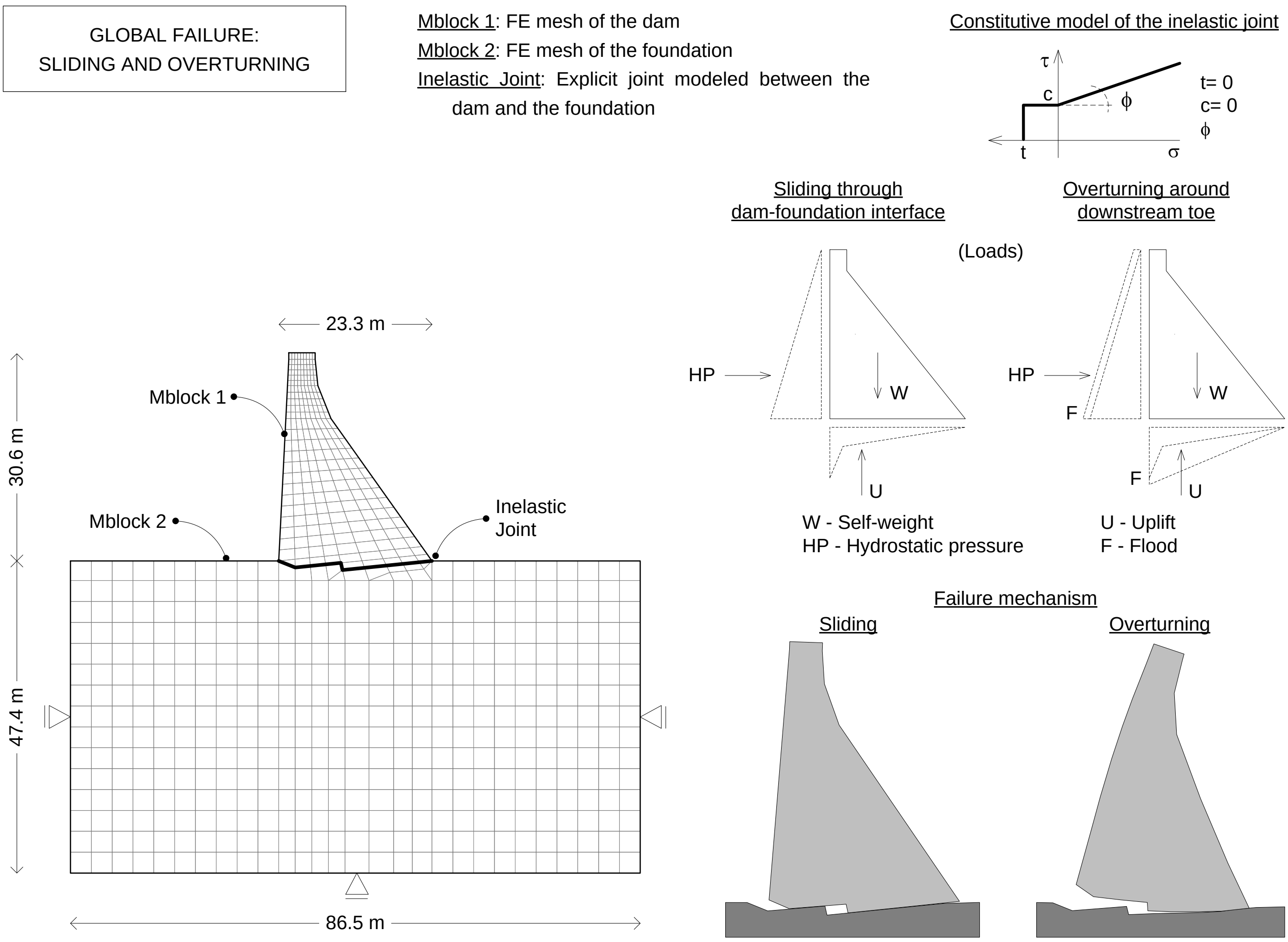

Figure 5. Static analysis of a masonry gravity dam assessing the failure mechanisms of global sliding and overturning

4.4. Analysis of crack propagation in the dam body of a masonry gravity dam

One important criterion on the design of a gravity dam is to avoid tensile stresses in any region of the dam body and as well on the contact between the dam and the foundation. On the water side of the dam, on the upstream face, the stress field of compression must be greater than the hydrostatic pressure in each point, in order to keep the integrity of the dam body. Generally the origin of a crack is associated with unexpected loads, like earthquakes or construction deficiencies. The progress of a crack is connected with the water leakage and increment of uplift inside the discontinuity. Figure 6 shows the crack propagation analysis of a large masonry gravity dam, 82 m high [5]. This dam was subjected to a severe crack incident, detected from the upstream face to the downstream toe. The dam model comprises triangular elements, laid out on the foundation block modelled by a continuous and elastic Finite Element mesh. The loading includes the self-weight and the hydrostatic pressure on the upstream side. An elastic joint on the dam-foundation interface was adopted. Between the triangular elements of the dam model, three different set of properties were tested (models A, B and C), giving rise to distinct failure mechanisms. In all models, the crack was initiated on the upstream face, by reducing the properties of the first numerical contact and was developed by adding uplift, simulating the water leakage until the complete failure. Model C seems to give a correct overview of the phenomena, reaching crack path propagation similar to the path actually detected in the dam [5].

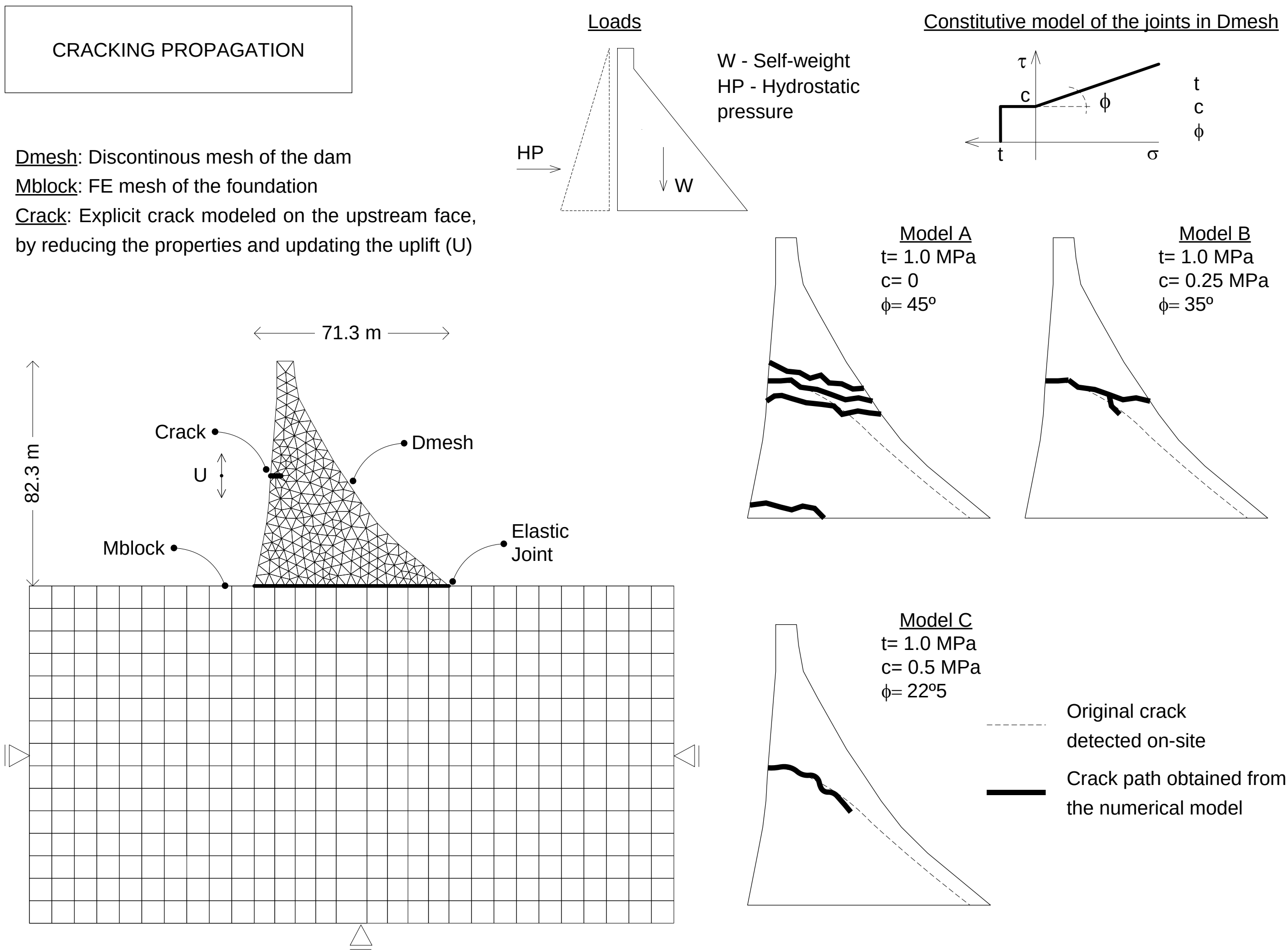

Figure 6. Analysis of crack propagation on the dam body of a masonry gravity dam

4.5. Seismic analysis of a masonry gravity dam

In many countries, the dam safety against seismic events is a central issue. Portugal presents moderate seismic hazard, which justifies special considerations. The scenarios to check include global and local failures. In the first group, among global failures, the permanent sliding is a standard assessment. Figure 7 shows a seismic analysis of a masonry gravity dam, considering the permanent sliding case [6]. The model is composed by two Finite Element meshes, both continuous and elastic meshes, representing the dam body and the foundation rock mass. Between the dam and the foundation, a nonlinear joint was assumed, with null cohesion and null tensile strength, and a friction angle of 45º. The dynamic load was applied using a free-field boundary condition. In this case, the load is applied by means of shear and vertical histories of stresses directly on the base of the block foundation. Simultaneously, the histories are also applied on the base of two unitary columns established on the lateral sides of the block foundation. The roles of those columns are to absorb the waves reflected by the surface of model and to apply the infinite stress condition on the block foundation. Other oversimplified solutions are alternatives to the free-field scheme. A history of velocities can be applied directly on the points of the foundation block, which assumes a rigid behaviour or a history of stresses can be applied at the base of a deformable foundation, in combination with viscous boundaries. The self-weight, the hydrostatic pressure, the uplift, in addition to the seismic loads, are part of the load combination. The histories of displacements are plotted in Figure 7 in parallel with the accelerogram, using rigid foundation, deformable foundation and the free-field boundary conditions. The maximum permanent displacement is around 10 cm, obtained by the rigid foundation model.

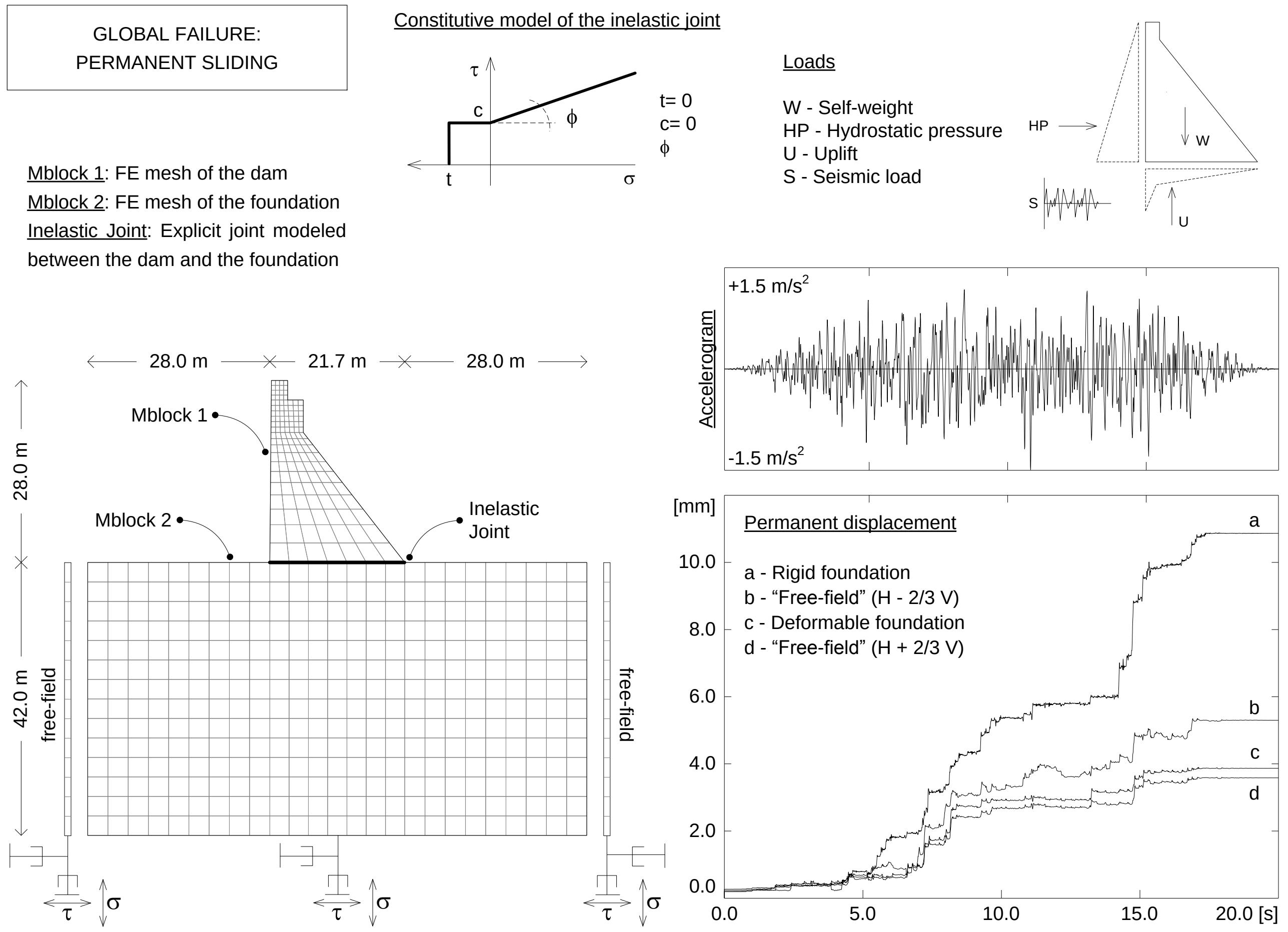

Figure 7. Dynamic analysis of a masonry gravity dam assessing the permanent sliding

4.6. Seismic analysis considering the discontinuities in the dam body of the masonry gravity dam

For masonry dams, the discontinuities existing on the dam body should be taken in consideration during an earthquake. The analysis developed in the previous section was repeated, superseding the dam mesh by a discontinuous and non-linear model. The joint between the dam and the foundation presents now an elastic behaviour. The model was composed by quadrangular elements disposed in vertical layers. This approach aims to represent the structural dam features characterized by a set of heightening works. In the last rehabilitation work, a new concrete plate was erected on the upstream face, which was also considered in the model. The load combination includes the self-weight, the hydrostatic pressure, the uplift and the seismic load using the free-field boundary condition. During the seismic analysis, sliding movements were detected between the horizontal masonry layers, as shown in Figure 8. The internal pressure was not applied in the dam body, which would decrease the safety conditions. Many regulations preconize a post-seismic analysis, taking in consideration potential damages raised from the earthquake. One of this is the uplift increment on the dam body, established from the leakage through the masonry discontinuities and cracks.

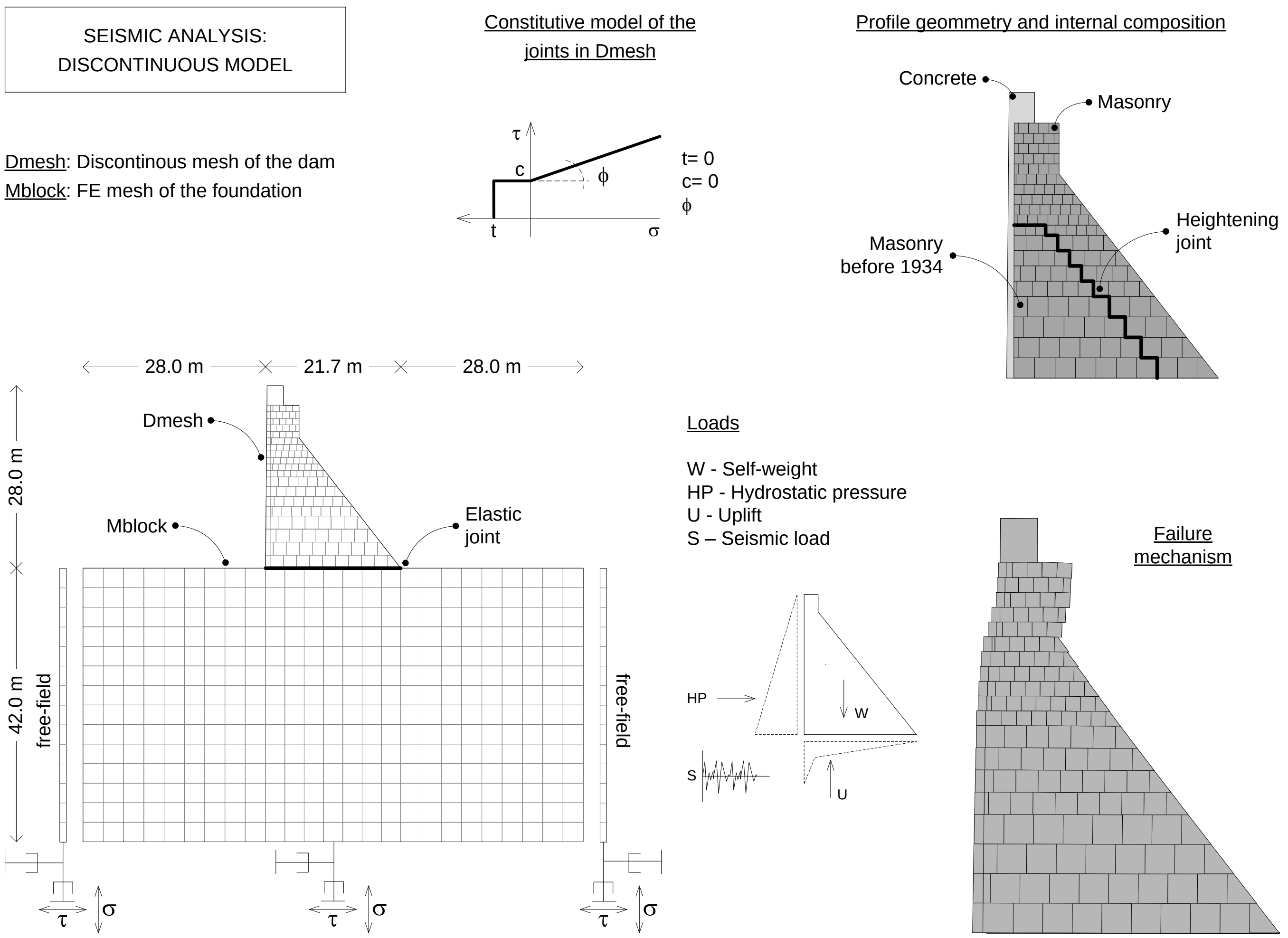

Figure 8. Seismic analysis of a masonry gravity dam considering the discontinuities on the dam body

4.7. Assessment of a rehabilitation project to improve the hydraulic behaviour of a masonry dam and its foundation

Many of the rehabilitation works carried out on masonry dams are triggered by leakage problems. As mentioned before, reduction of the permeability mainly on the water side is the foremost goal. The leakage of water from the reservoir has long term consequences to the dam, reducing its structural integrity, but also consequences in short term, related to the stability, because of the internal pressure of the water into the dam body. The water is responsible to increase the uplift inside of the discontinuities, causing crack propagation. For this reason, actual studies of these phenomena must include a coupled analysis between the mechanical and the hydraulic calculations. Figure 9 shows an example of this type of analyses [7]. It describes the assessment of a rehabilitation project, which includes the use of grouting on foundation, trough the dam body, the opening of new drains on the foundation and on the dam, and the excavation of a new drainage gallery. A continuum elastic Finite Element mesh was modelled, representing the dam and the foundation. Hydraulic properties were applied considering the current permeability and the predicted permeability after the rehabilitation works. The drains were modelled setting the pressures at the nodes along their development. Inside each drain, the hydrostatic pressure is assumed. The changes on the hydraulic performance are showed by the equipotential lines. The uplift diagrams are also plotted on Figure 9. Between the current situation and the expected conditions after the rehabilitation works, a reduction of around 60% on the total uplift is predicted.

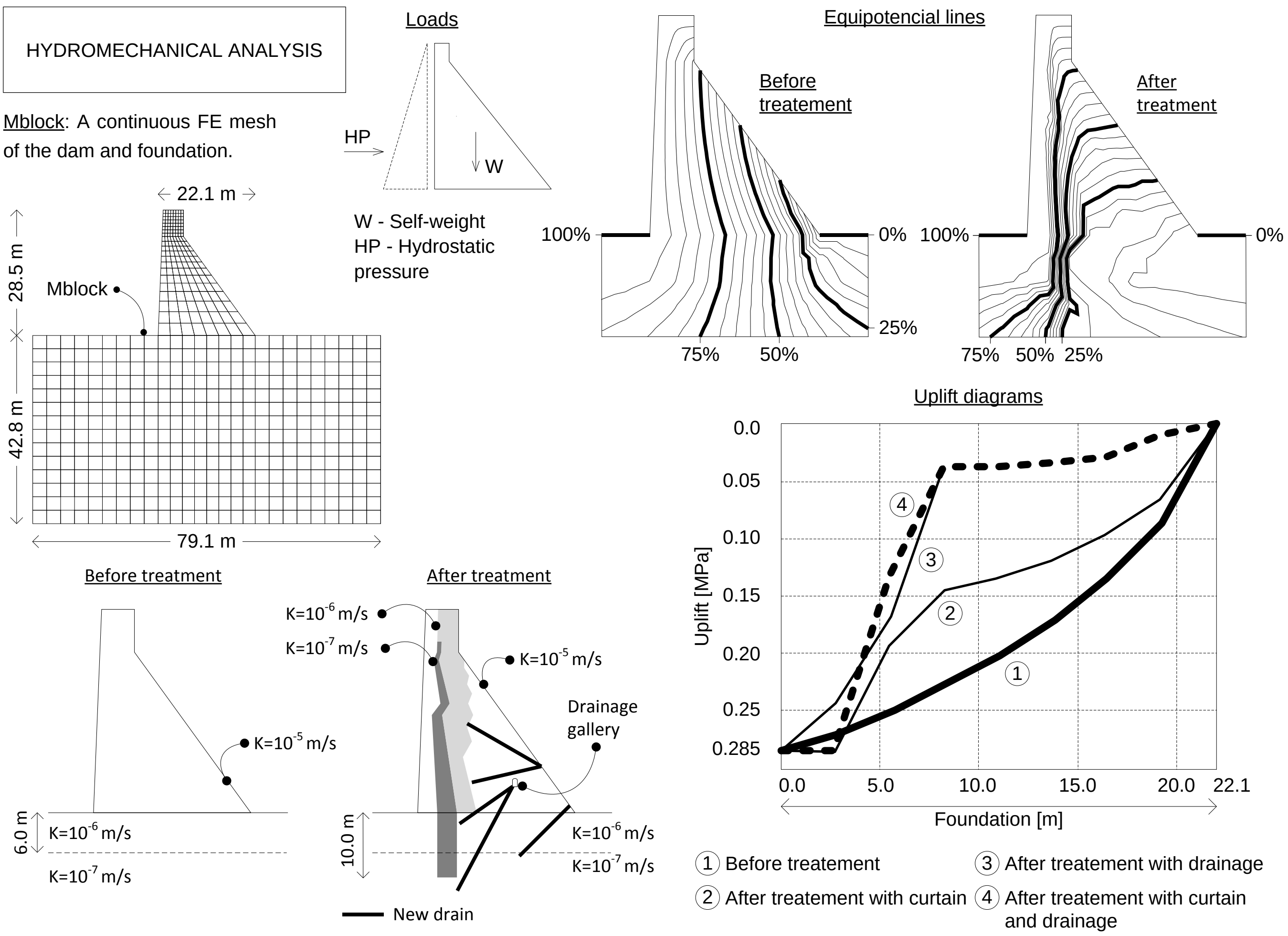

Figure 9. Hydromechanical analysis of a masonry gravity dam considering the rehabilitation measurements

5 CONCLUSIONS

A detailed representation of masonry dams should be adopted according to the analyses objectives. Failure mechanisms involving the masonry discontinuities are clear examples in which the use of discontinuous models is mandatory. In some cases, equivalent continuum model is a fair alternative. The global stability problem is a typical case in which continuous models of the dam fit well. Other relevant characteristics of the model, i.e. boundary conditions, loads, analysis procedure and stop criterion, should be selected following the same strategy.

The Discrete Element Method is able to manage all loads in a consistent way, giving straight answers to the main failure mechanisms. Its ability to assemble continuous and discontinuous meshes simultaneously (and independently) in the same model is a very good characteristic, keeping the focus on the failure mechanism under analysis.

This work showed three examples of discontinuous meshes of the dam body. Voronoi elements were employed in the loss of cohesion scenario. Triangular elements were used on the crack propagation model. The last discontinuous model was comprised by rectangular elements to carry out the seismic analysis. The latter alternative, with quadrangular elements, is the most time consuming solution, regarding the discretization process, among the alternatives discussed here. All those solutions proved to be reasonable choices for the selected applications.

REFERENCES

[1] Bretas, E.M., Lemos, J.V., & Lourenço, P.B.: Masonry Dams – Analysis of the Historical Profiles of Sazilly, Delocre and Rankine. *International Journal of Architectural Heritage*, 6 (2012) 1, 2012.

[2] Bulletin 143: *Historical review on ancient dams*, ICOLD: Paris 2013.

[3] Bretas, E.B.: *Development of a Discrete Element Model for Masonry Gravity Dams Analysis* (In Portuguese.). PhD-Thesis, Universidade do Minho, 2012.

[4] Bretas, E.M., Lemos, J.V., & Lourenço, P.B.: A DEM based tool for the safety analysis of masonry gravity dams. *Engineering Structures*, 59 (2014), 248-260.

[5] Bretas, E.M., Lemos, J.V., Léger, P., Lourenço, P.B.: Structural analysis of the rehabilitation works of Bhandardara Dam, India (In Portuguese.). *XXVIII Seminário Nacional de Grandes Barragens*, Rio de Janeiro 2011.

[6] Bretas, E.M., Batista, A.L.; The role of the behaviour report on the structural safety of dams. The example of Lagoa Comprida dam, Portugal. *XXIX Seminário Nacional de Grandes Barragens*, Porto de Galinhas 2013.

[7] Bretas, E.M., Lemos, J.V., & Lourenço, P.B.: Hydromechanical analysis in masonry gravity dams and their foundations. *Rock Mechanics Rock Engineering*, 46 (2013) 2, 327-339.