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MASONRY DAMS: DETERIORATION, MODELLING AND REHABILITATION

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EXTENDED ABSTRACT

In 1853, J. Sazilly published the first scientific paper on the field of Dam Engineering, with the title *Note sur un type de profil d'égale résistance proposé pour les murs de réservoirs d'eau*. In this paper, Sazilly proposed a novel method to define the profile of gravity masonry dams, based on stress analysis, taking into accounting the self-weight of the structure and the hydrostatic pressure on the upstream face, due the reservoir. Almost forty years later, in 1895, after the accident of Bouzey Dam, M. Lévy published the report titled *Quelques considérations sur la construction de grands barrages*, which describes the great effect of the uplift in the global stability of gravity dams. Only in 1962, R. Clough and E. Wilson developed the first analyses of dams by means of the Finite Elements Method to solve thermal and seismic problems (Bretas et al. 2011).

This historical introduction describes the period of time along which the majority of gravity masonry dams were constructed. Many of these dams present some structural fragility that reflects the knowledge available in the period of time that dams were designed. Other problems should be considered mainly related with deterioration phenomena.

Nowadays, the operation of these dams, represents a relevant challenge for the professionals, since the structural safety should be achieved according to modern regulations. One important step is the monitoring activity based on field data, resulting from the monitoring system, whose results must be verified by numerical models. The majority of commercial applications in the market, does not allow to model actual rupture mechanisms typical of gravity masonry dams since it was developed for the analysis of general structures. In this context, related to the PhD project of the first author, a numerical application using the Discrete Element Method (DEM) was developed, designated as DEC-DAM, which is described in this paper.

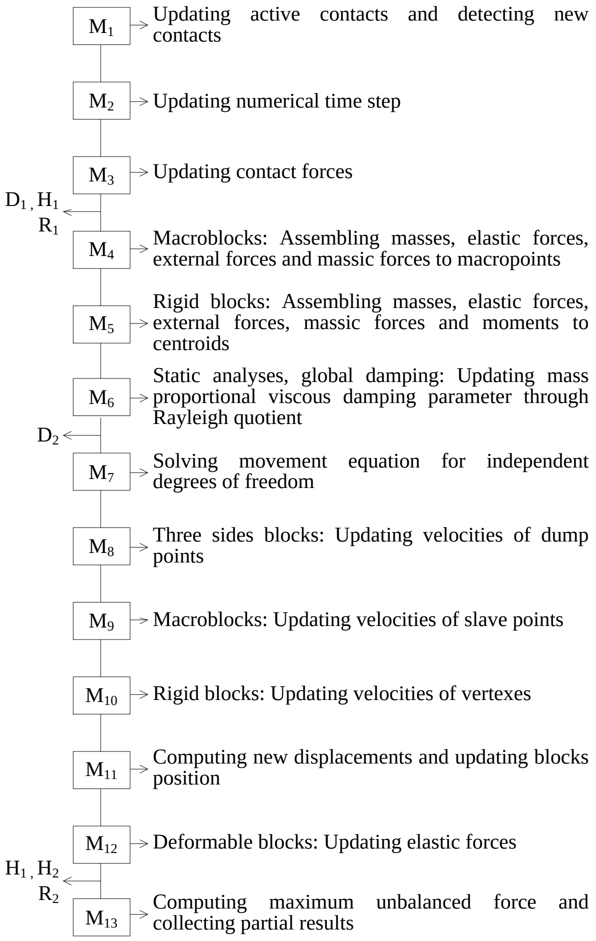
A DISCRETE ELEMENT METHOD IMPLEMENTATION

The DEM prove to be suitable for the analysis of gravity dams, since it allows an explicit modeling of the discontinuities. These discontinuities control the structural behavior of the system dam-foundation-reservoir and are found in the masonry of the dam body, on the surface foundation itself and inside the foundation.

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, very small blocks or extremely stiff contacts and stiff deformable blocks, should be avoided since this increases the total calculation time.

The calculation cycle, implemented in this project, is represented in Figure 1. 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.



- D_1 Updating current transient forces and applying dynamic viscous boundary (free-field)
- D_2 Rayleigh damping: Updating mass and stiff proportional viscous damping parameter through Rayleigh quotient
- H_1 Updating contact forces from water flow
- H_2 Determining unbalanced flow ratio on flow channels and updating pressures on hydraulic nodes
- R_1 Updating contact forces from structural strengthening
- R_2 Updating geometry of structural strengthening

Figure 1: Integrated calculation cycle

In the initial phase, forces are computed and added to each independent degree of freedom (steps M_3, M_4, M_5, M_{12}, D_1, H_1 and R_1). In the sequence, the movement equations are established and solved (steps M_2, M_6, M_7 and D_2). Subsequently, absolute and relative position of all blocks is updated (M_8, M_9, M_{10}, M_{11} and R_2), where the verification of active contacts and the tentative to detecting new ones (step M_1) take 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 M_{13}).

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. One example is the analysis of Bhandardara Dam, located in India, in which a solution including active and passive anchors was implemented, as a consequence of existing severe cracking. Extensive static and dynamic analyses (Bretas et al. 2011a) were carried out. The possible cracking origin was sought and the rehabilitation works were validated.

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