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An improved numerical manifold method for simulation of sequential excavation in fractured rocks

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ABSTRACT

We improve the original numerical manifold method (NMM) capability to correctly model the stability of underground openings embedded in discontinuous rock masses under high *in situ* stress conditions by implementing an algorithm which models the excavation sequence during NMM simulations, starting with a domain with no opening at all and progressively adding openings according to the planned construction phases. The significance of this improvement is demonstrated using the case of Zedekiah cave underneath the old city of Jerusalem, excavated 2000 years ago at a shallow depth in a highly discontinuous rock mass and still stands unsupported. The results clearly show that modeling underground openings in discontinuous rocks without consideration of the excavation sequence is overly conservative. We proceed with developing a new procedure to impose high initial stresses in NMM for accurate deformation modeling of deep underground excavations, and verify our suggested approach using the analytical Kirsch solution. Finally, we apply our enhanced NMM code to the Jinping hydroelectric project tunnels in Sichuan Province, China. Using very accurate sliding micrometer data obtained during the excavation of a research tunnel within the Jinping tunnel complex we constrain the *in situ* stress field at depth by inversion of the measured displacement data using the modified NMM code. The results provide a quantitative assessment of the *in situ* stress field in Jinping tunnels at a depth of 2525 m below ground surface, where the execution of *in situ* stress measurements by conventional procedures proves an extremely challenging task.

1. Introduction

In this paper, we present several important enhancements to the numerical manifold method (NMM) originally proposed by Shi [1], and apply those enhancement to perform stress inversion based on accurate sliding micrometer data obtained *in situ* at the 2525 m deep Jinping tunnels located in Sichuan province, China.

The NMM inherits the strengths of the numerical, discrete element, discontinuous deformation analysis (DDA) method proposed earlier by Shi [2] for block kinematics analysis, and retains its excellent contact detection algorithm, its unique open-close iteration procedure that guarantees that at the end of every time step there is no tension and no penetration between discrete blocks, and its fully dynamic formulation. Both DDA and NMM can therefore deal with the mechanical response of a block system under general loading and moving boundary conditions when body movement and large deformation occur simultaneously. But in addition, the NMM incorporates a mathematical cover over the DDA block system thus enabling accurate calculation of stress and strain distributions within block elements as well as everywhere else in the analysis domain. Therefore, when the displacement of the blocky rock mass is of concern, DDA can be used safely and can be trusted to provide accurate results, both for static and dynamic cases, as has been shown in multitude validation and verification studies [3] and can be effectively applied for underground engineering [4–8]. However, when accurate stress or strain distribution in a discontinuous domain is sought the NMM will provide much more accurate results, particularly when the blocks are large with respect to the modeled domain dimensions, due to DDA's simply deformable blocks assumption. The NMM can be viewed, therefore, as a natural bridge between the continuum and discrete representations, by combining the DDA and FEM methods in a united form [9]. The essentials of the numerical manifold methods are discussed by many authors [10–14] and will not be repeated here, for brevity.

Previous NMM research has mainly focused on theoretical implementations and improvements of the NMM rather than

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application to real case studies. The main developments of the NMM can be categorized into three groups: (1) improvement of the approximation accuracy [10,11]; (2) extension of the NMM for crack propagation problems [14–16]; and (3) development of 3D NMM [12,13,17]. An important limitation of the original NMM code when applied to underground mining is that in the original program developed by Shi [1], and also in the original DDA code [2], the excavation is open from the beginning of the simulation—before the stresses have reached their ultimate value everywhere in the modeled domain. It has been shown [18] that the number of time steps it takes for the stresses to attain their theoretical value everywhere in the modeled domain increases with the increasing number of blocks in the mesh. In reality, however, when tunnels are excavated, initial compressive stresses have already developed to their full extent in the rock mass, and the rock column has already experienced elastic deformation over geologic times under the overburden and tectonic stresses. Realizing this is important when analyzing the stability of underground openings in discontinuous rock masses using DDA or NMM as ignoring this numerical artifact may lead to overly conservative design. We demonstrate the significance of modeling sequential excavation using a real case study of a historic 40 m span cavern which was excavated more than 2000 years ago underneath the old city of Jerusalem and still stands unsupported.

Another important issue which is addressed in this paper is how to correctly impose the initial *in situ* stresses with NMM when analyzing deep tunnels. We discovered that with the available "initial stresses" option in the original NMM code the specified initial stresses are dissipated in the course of the simulation and are not maintained at their original value before the excavation material has been removed by means of the new sequential excavation algorithm. This could be the result of a numerical artifact possibly associated with the contact algorithm in the original NMM code which may be improved in the future as the method matures. At present we overcome this problem by applying tractions on the boundaries of the modeled domain in addition to the existing "initial stress" option thus imposing the desired initial stresses on the modeled domain. The detailed procedure for imposing initial stresses in NMM using tractions on the boundaries is described and verified in this paper.

Finally, our enhanced NMM code, with imposed initial stresses and sequential excavation algorithm, is applied to the case of the Jinping hydroelectric project in China in order to find the best fit *in situ* stresses at the site by inversion of accurate sliding micrometer data obtained at the site during tunnel excavation.

2. Simulating the excavation sequence with NMM

In the original NMM underground openings are modeled as an existing cavity in the mesh from the first time step and throughout the simulation. It has been observed by many researchers however [e.g. [19]] that gravity is not immediately "turned on", both in DDA and in NMM, and so the numerical values of the stresses at a given depth in the mesh approach the theoretical value only after a significant number of time steps has elapsed, the number of which has been shown to increase with the increasing number of blocks in the mesh [18]. Naturally, the theoretically available frictional resistance across the discontinuities, defined by the assigned friction angle and the level of normal stress acting on the joints, is not fully mobilized until gravity is completely turned on and the stresses acting on the joints attain their ultimate magnitude. Consequently, blocks that are free to move from the rock mass into the excavation space from a kinematical stand point will tend to do so from the first time step of the simulation, when the frictional resistance is much lower than the theoretical level. This will obviously lead to exaggerated block displacements and as a result to overly conservative design.

The original NMM code is modified here to enable modeling tunnel excavation during the NMM simulation after the initial stresses are fully developed and the corresponding elastic deformation has already taken place. The modified NMM code contains two stages: (1) at the beginning of the simulation a single or few blocks replace the tunnel and "static" simulation (in a "static" simulation the initial velocity at the beginning of every time step is set to zero everywhere in the domain) is executed until equilibrium is attained. Then, (2) the tunnel blocks are removed so as to simulate tunnel excavation, and a "dynamic" or "static" computation is executed (in a "dynamic" simulation the terminal velocity in the previous time step is inherited in the new time step everywhere in the domain). Here the excavation sequence is not modeled by reducing the elastic constants (e.g. Young's modulus, Poisson's ratio) or by assigning zero stress in all elements inside the tunnel, because blocks that are free from a kinematical stand point to fall into the tunnel space may cause numerical instabilities when in contact with tunnel elements having zero or very small stiffness. A procedure to overcome this difficulty by introducing a softening block approach has been suggested recently [20].

The block removal process requires careful preprocessing at every excavation sequence which includes the removal of manifold elements inside every block that is to be removed and their corresponding star nodes, as well as the detachment of contacts

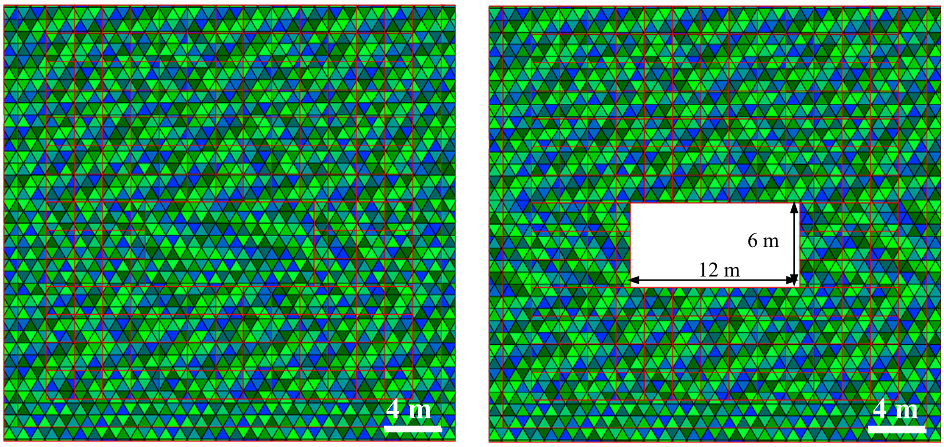

Fig. 1. NMM model for testing the significance of the proposed sequential excavation algorithm: modified (left) and original (right) NMM model at the beginning of the simulation.