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#### Physical modelling of underground excavations in a random fractured rock mass

<sup>1</sup>Abi Aad Emilio, <sup>1</sup>Deck Olivier, <sup>1</sup>Conin Marianne, <sup>2</sup>Al Heib Marwan, <sup>1</sup>Gaillard Laura,

<sup>1</sup>Université de Lorraine, CNRS, GeoRessources, Ecole des Mines de Nancy, 54042 Nancy Cedex, France, <u>emilio.abi-aad@univ-lorraine.fr</u>

<sup>2</sup>Ineris, The French National Institute for Industrial Environment and Risks, 54042 Nancy Cedex, France

#### ABSTRACT

The purpose of this study is to investigate the feasibility of performing a small-scale 1-g physical model of an underground excavation in a stochastic fractured rock mass with fully controlled geometrical and mechanical properties. To do this, we are developing a unique tri-axial 1-g device called "DIMITRI". The rock-like material is printed with a 3DP based on sand and a liquid binder, to control the fractured network geometry, the joints and matrix mechanical properties. The phasing of this modeling includes the following steps : (i) mechanical characterization of 3DP material; (ii) geometrical description and mechanical characterization of the printed fractures taking into account scale factors; (iii) geometric modelling of the fully 3D physical model with a random (realistic) fractured network; (iv) integration of a monitoring system with embedded stress sensors and fiber optic; (v) construction of the final 3D physical model and performance of the physical tests that include the galleries excavation; (vi) comparison with numerical modeling of the same configuration. This paper is dedicated to steps i) to iv). Uniaxial compressive, three bending and shears tests on 3DP specimens and shears tests are presented. Results allow to define which prototype can be modelled with the investigated sand-3DP technology taking into account the scale factors. Preliminary results of the embedded fiber optic are also presented.

Keywords: 1-g physical modelling, underground excavation, Sand-3D printing, fractured rock mass, optic fiber.

#### **1 INTRODUCTION**

Underground construction in fractured rock mass is often tied to complex operations and frustrating situations regarding the security and safety. Many collapse accidents have been observed, resulting in dramatic situations. Most of these accidents are related to an unpredicted or misunderstood behavior of the rock mass. Several research works have focused on modeling the behavior of fractured rock masses subject to different mechanical solicitations. They used different approaches: numerical modelling (Hauquin, 2016; Thanh & Hoang, 2013) in situ monitoring of stress and strain in the environment of the excavation (Tao et al., 2019; Xu et al., 2021), ng small-scale physical model (Stone & Taylor, 1965) or under normal gravity (1-g).

To date physical models under normal gravity have been widely investigated to simulate the stability of underground constructions in rock mass. The simulations usually simplify the problem into 2D dimensional problem (Fuenkajorn & Phueakphum, 2010; He et al., 2010; Z. Li et al., 2005). Previous researches in replicating fractured rock masses have mainly concerned the use of mixtures of cementitious material like gypsum, and fine aggregates such as sand (Yingjie et al., 2014). However, while these models are useful for producing continuous rock masses, they failed to model fractured rock masses. Efforts to replicate a jointed rock mass have been made by Fuenkajorn & Phueakphum, 2010; Son & Park, 2014 by building "brick" concrete block models. In these models the discontinuities network is limited to two set, most often orthogonal, and their mechanical properties (cohesion, friction angle, dilation, etc.) are not constrained nor repeatable, which restricts the representativeness of the natural fractured rock mass.

In this paper we propose an innovative approach to model a fractured rock mass with a realistic small-scale (1-g) 3D physical model of random jointed rock mass, subjected to different mechanical solicitations. An analogous material with weaker mechanical properties than rocks must be used to comply with scaling relationships. For this purpose, the 3D printing technology based on sand and phenolic liquid binder was adopted to simulate the rock mass-like (Nyembwe et al., 2016; Perras & Vogler, 2019) because of its high accuracy and repeatability (Jacques-hulin, 2019). The questions, then are: (i) will the present model be able to replicate the behavior observed in naturally fractured rock mass subjected to mechanical solicitations? To do so, the first step will be to characterize the used material by several mechanical tests. (ii) What are the uncertainties, and can they be quantified.

#### **2 DIMITRI DEVICE**

**DIMITRI** is an experimental device developed at GeoRessources laboratory consisting in a large-scale triaxial tool with an effective volume of 2.25 m<sup>3</sup> (L x W x  $H = 1.5 \times 1.5 \times 1m$ ) (Fig. 1). Controlled pressure and / or displacements can be applied in all three spatial directions through jacks, on 3 moving faces. The remaining horizontal faces are fixed, and equipped with windows, where an excavation tool can be used for drilling underground excavations of a maximum section equal to  $10 \times 10$  cm<sup>2</sup>. The ultimate stress and maximum displacement applied on the edges are 1.5MPa and 10cm respectively, thus allowing to generate threedimensional stress fields and to extend to deep applications. Concurrently, an innovative monitoring system is being developed with: (i) fiber optics to measure strains and (ii) embedded stress snorers to measure the stress field.



Fig. 1. Photography of Dimitri device

# 3 ARTIFICIAL MATERIAL: 3D- PRINTING MATERIAL

#### 3.1 3D-printing: Binder jetting process

In this paper, the rock-like are constructed from artificial material based on liquid binder and sand using Binder Jetting 3DP process. This process applies a selective binder through the inkjet head to bind sand and shape the required forms. In this study, a 3D sand printer VX1000 from Volxejet is used to manufacture specimens. The type of used sand is silica with reference GS140, and a phenolic resin as binder. The printed layer thickness is between  $250\mu m$  and  $300 \mu m$ . The properties of the material depend on the level of binder saturation, the printing direction, the storage time and conditions, and the curing time and temperature (Jacques-hulin, 2019).

#### 3.1 Artificial intact 3DP rock

A series of uniaxial compressive and three-point bending tests were performed to characterize the macro mechanical behavior of the 3D printed rock. Two types of specimens: cylinder (D=38mm, H=76mm), and bar (l=e=34mm, L=150mm) were printed. Since the 3D printing process involves possible mechanical anisotropy, the specimens are printed in three perpendicular X, Y and Z directions (

Fig. 2), with three different levels of binder saturation 6.5% (stander percentage), 5.7% (intermediary percentage) and 5% (minimum percentage to assure the cohesion of the material).



Fig. 2. 3DP Cylindrical and bar specimens printed in X -

During the uniaxial compressive tests, all specimens are loaded (strain) at the controlled rate of 0.2mm/s until failure, while a loading rate of 0.1mm/s or 0.05mm/s is applied during the three points bending tests. All specimens are tested at room temperature and after the same storage time (two months). The uniaxial compressive strength (UCS) is taken as the peak stress that the specimens can sustain during the test, and the Young's modulus (E) as the slope of the linear component of the stress-axial curve. The tensile strength  $(\sigma_t)$  of the material is determined with three points bending test as the peak stress which the specimens can withstand. In 90% of cases, brittle behavior is observed for all specimens printed in X and Y direction, while ductile behavior is performed for Z. Results confirmed that UCS,  $\sigma_t$ , and E of the 3DP specimens are highly dependent on the saturation binder rate (W) and the printing direction. In details, UCS,  $\sigma_t$ , and E increase with the increasing of the saturation binder rate and the maximum properties are systematically measured for specimens printed in the Y direction, therefore the material behavior is considered to be anisotropic ( Fig. 3 and



Fig. 3. UCS and Yong's Modulus (E) of 3DP specimens function of the binder rate (W)



Fig. 4. Tensile strength ( $\sigma_t$ ) of 3DP specimen's function of the binder rate (W)

The scaled factors calculation between prototype model and the scaled physical model are based on the Vaschy-Buckingham theorem (Buckingham, 1914; Jaber, 2020), (Table 1) where  $P^* = P_p/P_m$  with  $P_p$  the value of the prototype parameters (real scale) and  $P_m$  the value of the model parameters (reduced scale). For those calculations, we measured an average bulk density of the 3DP material of 13kN/m<sup>3</sup> with a standard deviation equal to 0.5kN/m<sup>3</sup>. This value is independent of the printing direction and binder saturation level. After applying the scale relationships, a binder saturation rate (W) equal to 5% is adopted to simulate a stiff to very stiff naturel intact rock, with low to high UCS.

Table 1. Experimental range for artificial intact rock parameters and their corresponding values at real scale for three scale factors: 10, 25 and 50.

$\gamma_m = 13kN/m^3$ , $20kN/m^3 < \gamma_p < 32kN/m^3 \Rightarrow \gamma^*_{moy} = \frac{\gamma_p}{\gamma_m}$				
Parameters	3D-printing (W=5%)	$L^{*} = 10$	$L^{*} = 25$	L* = 50
E [GPa]	0.20-0.32	4.0-6.5	10.0-16.0	20.0-32.0
UCS [MPa]	1.1-1.8	20.0-35.0	55.0-90.0	110.0-180.0
σt [MPa]	0.1-0.6	2.0-12.0	5.0-30.0	10.0-60.0

#### 3.1 Artificial 3DP joint rock

Before studying the feasibility to produce an artificial fractured rock mass, it is necessary to investigate the behavior of a single artificial joint. Many studies indicates that fractal surfaces with a self –affine replication have great potential to describe surface roughness of a natural rock joint in granite, sandstone, or marble over several orders of magnitude (Candela et al., 2012; Y. Li et al., 2017; Lin et al., 2019; Odling, 1994; Sausse, 1998; Yang et al., 2001, 2010; Zhang et al., 2019). Such surfaces satisfy a scale invariance, and are statistically unchanged by transformation.

$$x \to \lambda x; \ y \to \lambda y; \ z(x,y) \to \lambda^H z(x,y)$$
(1)

Where H is called the Hurst exponent related to the fractal dimensions  $D_f$  of the surface via H=3- $D_f$ .

The Power spectrum Density (PSD) is used as a quantitative description to generate a self-affine rough surface (Nie et al., 2019; Persson, 2014). A set of ideal self-affine rough surfaces similar to a natural rock joint

of dimension 150mm x 150mm are generated by power spectrum density method. It includes six rough surfaces with same roughness shape but different values of the couple (H<sub>i</sub>= 0.5-0.75-0.99;  $\sigma_j$  =0.75-1), where  $\sigma$  is the standard deviation of the surface elevation. By decreasing H and increasing  $\sigma$  the surface gets rougher (Fig. 5).



Fig. 5. Ideal 150×150cm self-affine surface, with  $\delta x=\delta y=1$ mm, a) (H=0.5;  $\sigma=1$ mm) rough surface b) (H=0.99;  $\sigma=0.75$ mm) smooth surface

These surfaces were printed using binder jetting process with an estimated blinder rate (W) between 5.7% and 6.5% in the Z-printing direction, and then scanned using a 3D scanner with an accuracy of 50 $\mu$ m. The scanning results confirm that the printed surfaces are isotropic in the X-Y plan, and highlight the resolution limits of the binder jetting 3DP process, as below the 8mm scale 3DP process is not able to reproduce the required surface.



Fig. 6. Shear test specimens printed using Binder Jetting process

The constructed joints underwent 20 direct shear tests, with constant normal stress equal to 0.4MPa, 0.8MPa and 1.2MPa. Preliminary results revealed three behaviors depending on the applied normal stress (Fig. 7): (i) at low normal stress, about 10% of the UCS value, asperities with the larger wavelength cause

dilation; (ii) at normal stress equal to 35% of the UCS value, tensile and/or slip cracks were observed in and under the longer wavelength asperities, which propagate within the intact matrix. These cracks are developed during the shearing process, and lead to a joint closure in association with asperities crushing, and rock matrix plastic deformation; (iii) at normal intermediate stress equal to 25% of the UCS value, the two mechanisms were conjointly observed. It is noteworthy that the unevenness (i.e. small asperities) tends to be damaged in all cases. Theses mechanisms has already been observed on natural fractures (Bahaaddini et al., 2016; Huang et al., 2002).



Fig. 7. Shear and dilation curves tests for (H=0.5 and  $\sigma$ =0.75) at different normal stresses: 1.2MPa (red), 0.8MPa (green), 0.4MPa (bleu), dilation behavior: when u<sub>n</sub> increases with u<sub>t</sub>, contraction behavior when u<sub>n</sub> decreases with u<sub>t</sub>

Dataset collected from the 20 tests are used to estimate the cohesion and friction angles of the artificial joint hypothesizing that they follow a Coulomb behavior. The friction angle is equal to  $31^{\circ}$  with a stander deviation equal to  $2^{\circ}$  regardless the fractal parameters, while the cohesion is closed to zero. This is compatible with the friction angle of natural joint (Barton & Choubey, 1977; Hauquin, 2016).

#### 3.3 Artificial random fractures rock mass

"The fractured rock mass can be modeled in two different approaches (Hamdi et al., 2017) regarded as: (i) a continuous medium, (ii) a discontinuous medium. This assumption depend on block size formed by the discontinuities intersection compared to the size of the structure, as well as the stress level within the rock mass ( $\sigma_{max}$ ) compared to the rock mass compressive strength (UCS). In the present work, the rock mass is modeled as discontinuities behavior corresponding to the red zone (Fig. 8). The size of the excavation being equal to 10cm×10cm, so the dimension of the block should vary approximately between 1 to 10cm. The blocks will therefore be connected by printed bridges, creating the final volume of the physical model equal to 2.25m<sup>3</sup>.



Fig. 8. GT30F1R1-AFTES- classification of rock mass according to failure behavior and modelling type (discontinuous or continuous model)



Fig. 9. a) 3D numerical random artificial fractured rock mass, b) numerical artificial rough rock joint

#### **4 MONITORING SYSTEM: FIBER OPTIC**

Preliminary tests are carried out on two-pieces printed cylinders with W=6.5% in the Z-direction. The two halfcylinders are assembled with SPEFOL adhesive to get a cylinder specimens, in which we glued a "*monomode low bed loss*" fiber optic (Soga & Luo, 2018). The objective of these tests is to investigate the ability of the fiber optic to measure the deformation inside the printed material

#### Fig. 10).

Fig. 11 displays plots of the stress-strain curves at the center of four longitudinal parts of the fiber optic and the deformation measured by the press. The results show consistency in the fiber optic measurements, which are 2 times higher than that measured by the press sensors. This discrepancy falls into the classical difference between local and global strain measurements in rock engineering. It may also be partially the consequence of the presence of the adhesive. In addition, the UCS value is lower than that of a continuous cylinder possibly because the glued plan disturbs the mechanical properties of the cylinder. Going further, we are developing a procedure to integrate the fiber optic into the material during the printing process.



Fig. 10. Fiber optic (green lines) embedded in 3DP specimens



Fig. 11. Stress-strain curves present the strain measured at the center of the fours longitudinal parts of the fiber optic: S1 (blue), S2 (orange), S3 (gray), S4 (yellow); and the black curve presents the strain measured by the machine sensor

#### **10 CONCLUSIONS**

This study presents a new approach of a 3D reduced scale physical model of explicit stochastic fractured rock mass. 3DP based on sand and liquid binder mixture is adopted to reproduce the artificial rock mass with controllable geometrical and mechanical parameters. The mechanical parameters obtained from shear, compression and tensile tests on our replica are translated to prototype scale by applying scaling relationships. The results show that the binder jetting 3DP with 5% binder saturation rate successfully replicate the behavior of intact rock, and of joints and may be used to create a model of rock mass with a scaling factor up to 50. Further on, a set of experimental tests will be performed on larger 3DP cylinder specimens with explicit fractures before realizing the physical model. As for the monitoring system a new procedure is being conducted to integrate the fiber optic and stress sensor in the 3DP material during printing process.

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