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# Numerical modeling of a conglomeratic rock from Costa Rica, Central America

Danilo A. Jiménez Ugalde
Department of Civil Engineering, Pontifical Catholic University of Rio de Janeiro, Rio de Janeiro, Brazil, danilo.jimenezugalde@gmail.com

Sergio A.B. da Fontoura
Department of Civil Engineering, Pontifical Catholic University of Rio de Janeiro, Rio de Janeiro, Brazil, fontoura@puc-rio.br

SUMMARY: The mechanical properties of conglomeratic rocks are difficult to study by conventional laboratory tests. On the other hand, *in-situ* tests are more representative to establish the mechanical properties of these materials but, in general, take a long time to execute and represent a high cost for projects. This paper presents a methodology to obtain the mechanical properties of a conglomerate, using the results of a numerical modeling study carried out in virtual rock samples. A conglomeratic rock from Costa Rica was used as a study case. To determine the validity of the estimation, the results from the numerical modeling were compared with data from *in-situ* tests performed in the same conglomerate.

KEYWORDS: Conglomerate, Numerical modeling, Bimrock.

## 1 INTRODUCTION

Many engineering works in Costa Rica are developed in conglomerates. The engineering design of these works requires a comprehensive protocol for characterization and for evaluation of the mechanical properties of these materials.

The Costa Rican Electricity Institute (ICE) is currently studying the largest hydroelectric infrastructure work in Central America, El Diquís Hydroelectric Project (PHED). For this project, it is expected to have open cut sections up to 110 m high, underground excavations with a span between 6 m and 32 m, and a foundation for the 170 m high concrete face rockfill dam.

The conglomeratic rocks found in the area of study are classified as unwelded bimrocks (Sonmez et al. 2009). These rocks, in essence, are a mixture of good-quality blocks embedded in a less competent matrix, whose shear strength and deformability are mainly ruled by the volumetric block proportion.

This paper presents the results of numerical experiments that were conducted in synthetic samples to obtain the deformability modulus and the strength parameters of the conglomerate from the Paso Real Formation. Jiménez (2015) provides a full description of the laboratory tests and field works carried out to determine the deformability and the shear strength of the matrix and the blocks of the conglomerate. The numerical experiment results were compared with the field test results.

## 2 MATERIALS AND METHODS

### 2.1 Conglomerate from the Paso Real formation

This investigation studied the medium-coarse conglomerates from the Paso Real formation. The rock is a terrigenous, intraformational, oligomictic, clast-support conglomerate. The blocks are formed by different kinds of lavas with a maximum observable dimension of

60 cm. The morphology of the blocks is sub-rounded with medium sphericity. The grading of the matrix surrounding the blocks varies from clay to pebbles. The conglomerate matrix is well consolidated. The volumetric block proportion is between 50 and 60%. The conglomerate is poorly stratified, and it is slightly fractured to massive.

## 2.2 Geotechnical survey

The geotechnical survey used for this investigation was performed at the dam site of the PHED. It considered not only the results of 13 core drill holes with an NQ diameter (Fig. 1), but also the data collected from 5 investigation tunnels with a total length of 600 m and with excavation diameters from 4 to 14 m (Fig. 2). Moreover, the survey included the geotechnical information obtained from a conglomerate outcrop of approximately 45 $m^2$, located at CRTM coordinates 1005400 N, 580100 E (Fig. 3).

Figure 1. Example of a drill core box.

### 2.2.1 Laboratory tests

The laboratory tests were conducted in matrix and blocks samples from the conglomerate. These rock samples were recovered from the drill holes. The tests were carried out in the following laboratories: Rock-Fluid Interaction Laboratory (LIRF) at PUC-Rio (Brazil), Geotechnics and Environment Laboratory (LGMA) at PUC-Rio (Brazil), and Geotechnics Laboratory of ICE (Costa Rica).

The laboratory tests were performed to obtain, separately, the strength parameters and the deformability of the matrix and the blocks of the conglomerate. All the tests were in accordance with ASTM standards or other methods suggested by the ISRM.

The laboratory tests included the following: seismic wave velocity, point load, diametral load, uniaxial compression, and triaxial compression.

Figure 2. Example of an investigation tunnel.

Figure 3. Outcrop used in this investigation.

### 2.2.2 Field tests

The field test results were used in this investigation as a comparative parameter to measure the validity of the estimations from the numerical tests carried out on virtual samples. All the in-situ tests were performed in the investigation tunnels excavated at the dam site of the PHED.

This investigation used the results of three multistage direct shear tests, according to the method suggested by the ISRM (1974), on 700 mm square samples with normal stresses ($\sigma_n$) ranging between 0.15 MPa and 1.0 MPa. From the interpretation of these tests, the Mohr-Coulomb strength parameters were obtained (Table 1).

Table 1. *In-situ* multistage shear test results.

| Test Number | Cohesion, c (MPa) | Friction angle, $\phi$ (degrees) |
|---|---|---|
| G2-3 | 0.77 | 35.4 |
| G2-4 | 0.62 | 44.1 |
| G3-2 | 0.52 | 48.3 |

Plate load tests were also performed to determine the deformability modulus of the conglomerate. These tests were carried out in accordance with the method suggested by the ISRM (1979), using a circular plate of 45 cm in diameter and load cycles of 0.36 MPa, 0.71 MPa, 1.42 MPa, 2.9 MPa, 4.3 MPa, 5.7 MPa and 7.12 MPa. The value of the deformability modulus reported by the plate load tests varied between 800 MPa and 3500 MPa.

## 2.3 Virtual samples

Virtual samples were generated from images of the conglomerates and later used in the numerical tests. These samples were developed based on images of the outcrop during the field works (Fig. 4). The procedure followed to obtain these virtual samples consisted in digitizing the images by means of a computer-aided design program, separating the sample into two main materials: the blocks and the matrix. The interface between the blocks and the matrix was later included as a third material.

The interface thickness was defined by means of field observations. Thickness ranges were established according to the maximum observable dimension of the blocks ($d_{mod}$). In this way, a thickness of 3 mm to 6 mm was used around the blocks with a $d_{mod}$ up to 10 cm, 9 mm to 12 mm around the blocks with a $d_{mod}$ up to 45 cm, and 15 mm around the blocks with a $d_{mod}$ greater than 45 cm.

The virtual samples used in the numerical biaxial tests were rectangular and had a height-base relation of 3:1. They were generated in three different outcrop representative sizes: 30x90 cm$^2$, 60x180 cm$^2$ and 90x270 cm$^2$. In addition, 70 cm square virtual samples were used for numerical simulation of direct shear tests, and a 270 cm square sample was used for modeling plate load tests.

## 2.4 Numerical modeling

The virtual samples of the conglomerate were used to perform numerical tests, specifically biaxial compression tests, thus obtaining, based on their interpretation, the mechanical parameters of strength and deformability. The finite element method was used to perform the numerical experiments on the virtual samples. For this purpose, the commercial PLAXIS 2D 2014 software package was required, considering a two-dimensional plane strain loading condition.

In all the cases, a graded mesh of six-node triangular elements was adopted. The constitutive model for all the materials in the virtual samples was the linear elastic, perfectly plastic model with Mohr-Coulomb strength parameters and with a dilatancy angle ($\psi$) equal to zero degrees.

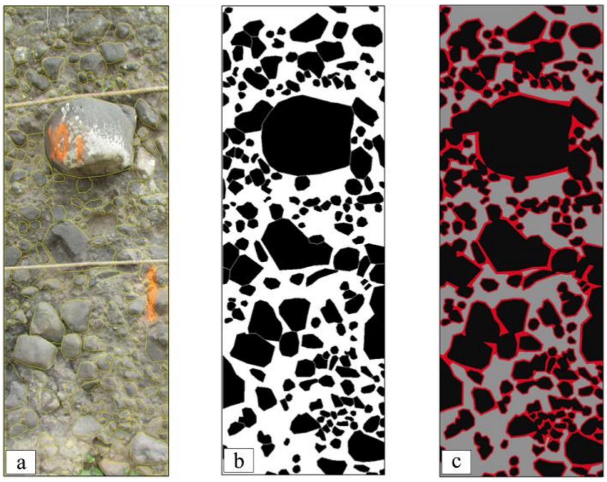


Figure 4. Example of a virtual outcrop sample: (a) Digitization of the image, (b) Sample constituted only by the matrix (white) and the blocks (black), (c) Final sample including the interface material (red) between the blocks (black) and the matrix (gray).

The following boundary conditions were used in the biaxial compression tests: (a) Lower side: restricted movement on the horizontal and vertical axes, (b) Upper side: restricted movement on the horizontal axis, uniform vertical displacement, and (c) Lateral sides: free movement on the horizontal and vertical axes. The procedure for conducting the biaxial tests was as follows: (a) First stage: application of confining pressure ($\sigma_3$), modeled as a uniform pressure imposed on the lateral sides and on the upper side of the virtual sample. The confining pressure remained constant throughout the test. Seven confining pressures were used in the tests: 0 MPa (uniaxial compression), 0.25 MPa, 0.5 MPa, 1 MPa, 2 MPa, 4 MPa and 8 MPa. (b) Second stage: application of a uniform vertical displacement on the upper side of the sample, increasing in a controlled manner until reaching a maximum axial strain $\varepsilon_a$=0.1.

With respect to the numerical direct shear tests, the following boundary conditions were applied: (a) Lower side: restricted movement on the horizontal and vertical axes, (b) Upper side: uniform vertical confining pressure, (c) Lower lateral sides: zero horizontal displacement and free vertical displacement, and (d) Upper lateral sides: constant horizontal displacement and free vertical displacement. The direct shear tests were carried out according to the following procedure: (a) Application of confining pressure, which was constant throughout the test, (b) Increased horizontal displacement on the upper lateral sides with the aim of simulating the shear load on the tested sample.

# 3 RESULTS

## 3.1 Strength parameters

To study the conglomerate strength, numerical tests (biaxial compression and direct shear) were performed on the virtual samples described in the methodology. Three different cases were used in the numerical tests, varying the strength parameters of the matrix (Table 2) and the interface (Table 3). For these analyses, the strength parameters of the blocks (Table 4) and the deformability parameters of all the materials were considered constant.

Table 2. Strength and deformability parameters of the conglomerate matrix as used in the numerical analyses.

| Case | $c$ (MPa) | $\phi$ (deg) | $UCS$ (MPa) | $\sigma_t$ (MPa) | $E$ (MPa) | $\nu$ | $\gamma_d$ (MN/m$^3$) |
|---|---|---|---|---|---|---|---|
| 1 | 2 | 41.5 | 8.9 | 0.9 | 1280 | 0.23 | 0.021 |
| 2 | 0.8 | 45 | 3.9 | 0.4 | 1280 | 0.23 | 0.021 |
| 3 | 0.35 | 49 | 1.9 | 0.2 | 1280 | 0.23 | 0.021 |

The biaxial compression tests showed that, during the loading, the first plastic points within the virtual samples appear in the interface zone between the blocks and the matrix (Fig. 5a). The plastic zone proportionally increases as the axial strain increases. At the end of the tests, tortuous failure surfaces surrounding the blocks (Fig. 5b), a pattern that has been previously described by tests on physical models (Lindquist 1994) and numerical models (Xu et al. 2008; Afifipour & Moarefvand 2014), were identified.

Table 3. Strength and deformability parameters of the conglomerate interface as used in the numerical analyses.

| Case | $c$ (MPa) | $\phi$ (deg) | $UCS$ (MPa) | $\sigma_t$ (MPa) | $E$ (MPa) | $\nu$ | $\gamma_d$ (MN/m$^3$) |
|---|---|---|---|---|---|---|---|
| 1 | 1.5 | 41.5 | 6.7 | 0.6 | 960 | 0.23 | 0.021 |
| 2 | 0.4 | 45 | 1.9 | 0.2 | 960 | 0.23 | 0.021 |
| 3 | 0.12 | 54 | 0.8 | 0.08 | 960 | 0.23 | 0.021 |

Table 4. Strength and deformability parameters of the conglomerate blocks as used in the numerical analyses.

| $c$ (MPa) | $\phi$ (deg) | $UCS$ (MPa) | $\sigma_t$ (MPa) | $E$ (MPa) | $\nu$ | $\gamma_d$ (MN/m$^3$) |
|---|---|---|---|---|---|---|
| 9.5 | 55 | 60 | 6.0 | 5000 | 0.28 | 0.027 |

The numerical tests allowed obtaining the stress-strain curves, by means of which the conglomerate strength was calculated (Fig. 6a). The principal stresses were determined based on the peak strength of each biaxial compression test, and the results were represented in the space $\sigma_1$-$\sigma_3$, where it was possible to observe a non-linear increase of the major principal stress ($\sigma_1$) with an increase of the minor principal stress ($\sigma_3$) (Fig. 6b).

For all the cases under analysis, the uniaxial compressive strength (UCS) obtained from the biaxial tests showed an almost constant behavior (a slight tendency to increase) with the increase of the scale of the samples (Fig. 7). The same behavior was observed in the cohesion interpreted from the biaxial compression tests (Fig. 8), while the friction angle showed a constant to a modest trend to decrease as the scale of the samples increased (Fig. 9).

Based on the numerical direct shear tests and the empirical *Bim Strength Criterion* proposed by Kalender et al. (2014), the strength parameters of the conglomerate were also calculated. All the results were compared with the strength parameters from the in-situ direct shear tests performed in the investigation tunnels of the PHED (Table 5).

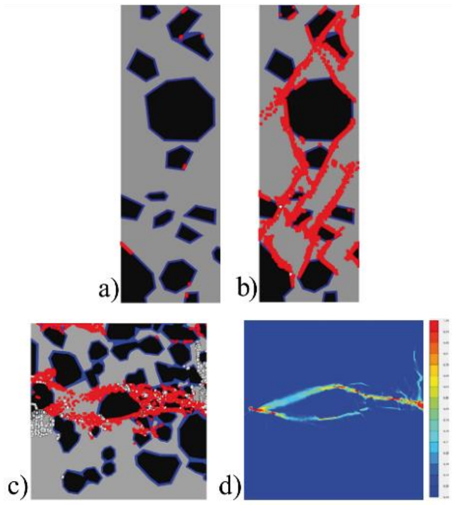


Figure 5. (a) Initial plastic regions in the biaxial compression tests ($\sigma_3$=8 MPa, $\varepsilon_a$=0.01), (b) Plastic regions at the end of the numerical biaxial compression test ($\sigma_3$=8 MPa, $\varepsilon_a$=0.045), (c) Plastic regions at the end of the direct shear test ($\sigma_n$=8 MPa), (d) Deviatoric strain at the end of the direct shear test ($\sigma_n$=8 MPa). Red: Shear failure plastic points. White: Tensile failure plastic points.

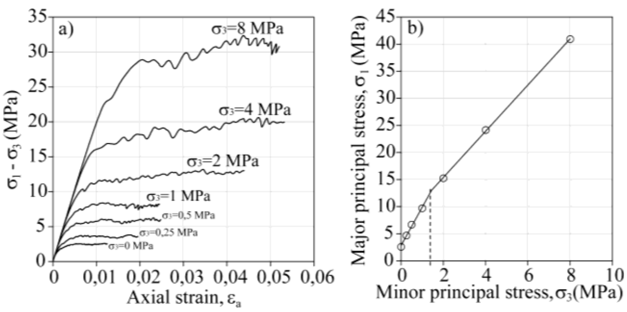


Figure 6. Example of a numerical biaxial compression test performed on the virtual samples of the conglomerate: (a) Stress-strain curve, (b) Bilinear strength envelope in the interval of the confining pressures under analysis.

## 3.2 Deformability parameters

The deformability of the conglomerate was studied by means of numerical biaxial compression tests and numerical plate load tests. A total of four cases were analyzed, varying the deformability properties of the different materials that form the conglomerate (Table 6). All the cases analyzed to determine the deformability used constant strength parameters, corresponding to Case 1 on Tables 2-3. The Poisson parameter used in the testing was considered constant for all the tests (Tables 2-4).

The deformability moduli from the numerical tests are within the variation interval defined by the in-situ plate load tests (Table 7).

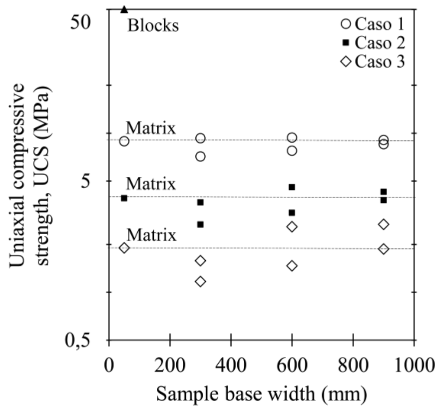


Figure 7. Uniaxial compressive strength of the virtual samples determined through numerical tests. Black: Matrix. White: Horizontal sample. Gray: Vertical sample.

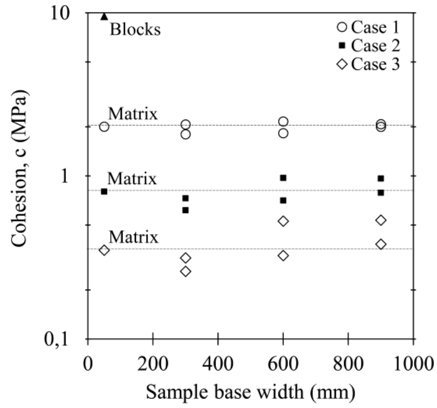


Figure 8. Cohesion estimated based on the numerical biaxial compression tests on virtual samples. Black: Matrix. White: Horizontal sample. Gray: Vertical sample.

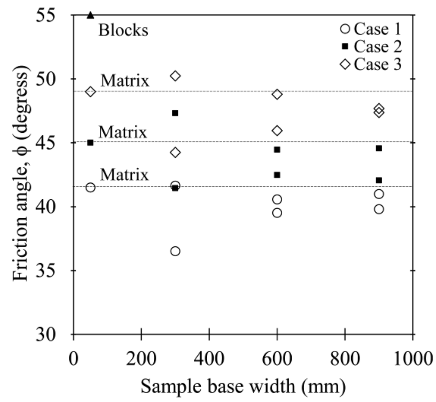


Figure 9. Friction angle estimated by means of the numerical biaxial compression tests on virtual samples. Black: Matrix. White: Horizontal sample. Gray: Vertical sample.

Table 5. Comparison of the strength parameters obtained from the numerical tests, the empirical methods, and the *in-situ* tests.

| Parameter | Test / Criterion | Case 1 | Case 2 | Case 3 |
|---|---|---|---|---|
| *C* (MPa) | Direct shear – *Numerical* | 1.92-2.23 | 0.64-0.88 | 0.4-0.46 |
| | Biaxial Compression – *Numerical* | 1.8-2.16 | 0.62-0.97 | 0.26-0.53 |
| | *Bim strength Criterion* | 1.94-2.09 | 0.84-0.89 | 0.41-0.41 |
| | Direct shear – *In situ* | 0.52-0.77 | 0.52-0.77 | 0.52-0.77 |
| $\phi$ (Degrees) | Direct shear – *Numerical* | 39.1-52.4 | 42.9-57 | 43.1-57.7 |
| | Biaxial Compression – *Numerical* | 36.5-41.6 | 41.4-47.3 | 44.2-50.2 |
| | *Bim strength Criterion* | 34.9-36.1 | 35.1-37.1 | 35.4-38.2 |
| | Direct shear – *In situ* | 35.4-48.3 | 35.4-48.3 | 35.4-48.3 |

Table 6. Deformability of the different materials used in the numerical analyses.

| Case | Matrix | Interface | Blocks |
|---|---|---|---|
| A | 1280 | 960 | 5000 |
| B | 800 | 600 | 5000 |
| C | 2000 | 1500 | 5000 |
| D | 1280 | 960 | 10000 |

Table 7. Comparison between the deformability modulus from the numerical tests (biaxial compression and plate load) and the *in-situ* plate load tests.

| Test | Deformability Modulus, *E* (MPa) | | | |
|---|---|---|---|---|
| | Case A | Case B | Case C | Case D |
| Biaxial Compression – *Numerical* | 1845-2430 | 1510-1760 | 2770-3190 | 2090-2990 |
| Plate load – *Numerical* | 2290 | 1545 | 3260 | 2550 |
| Plate load – *In situ* | 800-3500 | 800-3500 | 800-3500 | 800-3500 |

## 4 CONCLUSIONS

The characterization of the conglomerate was performed through conventional laboratory tests that were separately conducted on the matrix and the blocks.

The results validate how the numerical tests on virtual samples constitute a useful tool to determine the mechanical parameters (strength and deformability) of conglomerates.

The empirical *Bim Strength Criterion* by Kalender et al. (2014) also provided a suitable approximation of the strength parameters of the conglomerate under study.


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