Some new developments on the representation and standardization of rock mechanics data: From the laboratory to the full scale project

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ABSTRACT:. An effort has been made to create a Rock Mechanics Database that may be used in the future as a tool for the design of excavations in rocks. This is the reason it was designed to be web-driven through the UCIS platform of TUNCONSTRUCT (Technology Innovation in Underground Construction, http://www.tunconstruct.org/). Its main feature is that it is hierarchical, that is, it starts from the mineralogical-microstructural characterization and reduced raw lab mechanical testing data, then it goes to the data referring to the behavior of the rock in loading and unloading-reloading, as well as to post-peak behavior, separately, after it goes to the identification of elasticity moduli, then to plasticity and damage properties of the rock according to an appropriate constitutive mechanical model, and so on. In order to achieve this for different tests on the same rock - that may be performed by different laboratories - some kind of standardization of procedures is required although not significant departure from established ISRM Standardization Procedures of basic rock mechanics tests is being made. These procedures are discussed here. The next thing to consider is how to upscale the parameters of the intact rock identified from lab testing to the real life scale of the project.

1 INTRODUCTION

Numerical simulation tools assisting the design and construction of underground excavations in rocks employ appropriate rock constitutive models and model parameters. These models may be elastic, elastoplastic (deformational or flow models), elasto-viscoplastic etc. (i.e. Beer & Exadaktylos, 2007). The parameters of the intact rock used in these models are identified from monotonic or cyclic lab tests such as tension, compression, shear, hollow cylinder and so on. Each laboratory uses its own methodology to analyze, store and retrieve this data. The result is that a vast amount of unharmonized data is dispersed throughout Europe – with some of them to be found from the literature or in website (i.e. Hoek's RocLab (RocLab v1.0) for the elasticity and strength parameters of the Hoek and Brown failure criterion according to lithology). It is not uncommon that only a single value of Young's modulus and Poisson's ratio is used even if the rock displays stress-dependant elasticity and anisotropy. In tensile tests the elasticity of the rock is not evaluated even if it is usually significantly different from the elasticity in compression ('unilateral phenomenon'). Furthermore, this rock testing data, are not accessible to other practitioners not involved in the particular project, even if they are concerned with more or less the same rock types tested before.

The aim of this work is to create a *relational rock mechanics database* directly linked in UCIS platform of TUNCONSTRUCT (http://www.tunconstruct.org) that will be continuously upgraded from underground excavation projects. It might be an essential tool in the future for the design of tunnels and other types of underground excavations (e.g. boreholes, caverns etc.). In addition, it would greatly help the *harmonization* and *standardization* of rock mechanics testing by laboratories. The Rock Mechanics Database (RMDB) was written in SQL, and contains standard element mechanical tests on a range of rocks (sedimentary, igneous and metamorphic). Also, an opportunity is open, namely the creation of various useful micromechanical models of "synthetic rocks" and deduction relationships among the various physical, microstructural and mechanical properties of rocks via Data Mining techniques.

2 STRUCTURE OF THE DATABASE

The structure of the database is shown in Fig. A.1 in Appendix A. The steps followed for filling the RMDB were done in close cooperation with Technical University of Graz – Institute for Rock Mechanics and Tunneling (TUG-IRMT) and are the following: a) filling it with the data (templates for keeping common format and terminology have been used), b) finalizing the excel sheets, as well as collecting external photos and microscope photos, c) testing the database to see that it works properly.

A brief description of the basic features and structure of the RMDB has as follows:

- The Database is relational and is written in SQL.
- The RMDB is comprised from 3 distinct interrelated sections, namely: *Rocks Section:* Contains the tables, which are groups of properties and every row inserted is a record of a group of properties, with all the information about the rocks that have been tested, i.e. their origin, microscopy observations, mineral composition, texture and microstructure or fabric, physical properties and photos. *Experiments Section:* In this Section the geometry of the specimens, boundary conditions, measurement techniques (i.e. LVDT's, strain gages etc), basic deformational and strength parameters estimated through the experimental test-ups considered and the

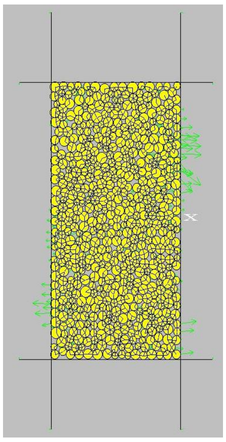
relative data files are contained in respective tables. *Laboratories Section:* This Section contains the tables with all the information for the laboratories that conducted the tests and processed the experimental results. The experiments section is divided into 5 subsections representing the experiment types, i.e. Brazilian Tests (BT), Drilling Tests (DT), Shear Tests (ST), Uniaxial Compression / Triaxial Compression Tests (UCTC) and Uniaxial Tension Tests (UT). The rocks and laboratories sections, as well as each subsection of experiments section, contain several tables from which one table is always the major table (parent table) containing basic information while the others are minor tables containing additional information (children tables). Every row of data inserted into the tables is a record and the rows of the children tables are strictly depended on the rows of their major table. Thus, the database will refuse to store a data row in a child table if there is no major record that is related with this data.

- It relates any rock stored in the database (19 different rock types from Technical University of Crete (TUC) and 10 from TUG-IRMT have been already stored) with all the tests performed by several labs on intact specimens of this rock in tensile, compressive, shear and drilling test conditions.
- It is able to store the local coordinates X,Y,Z of the location of a specimen of a given lithology sampled in a given tunnel project, hence it communicates with other tasks dedicated for the creation of the 'Ground Model'.
- It relates one Lab with many tests etc.
- It may lead to correlations among the rock microstructure with its various mechanical properties.
- Up-to-now the main test types are petrographic observations in optical microscope for assessment of grain size, porosity, mineralogical set-up etc., simple weighting tests, as well as standard tests such as UC, TC, UT, BT, ST and one new non-standard test namely the DT. With regards to the classification of rock types we follow simply the standard petrography, mineralogy and rock mechanics terms respected by the Rock Mechanics Community.

At this stage the data reduction is performed in two levels and stored in the Excel sheets, namely Level-0 and Level-A. In Level-0 where the code number of the test, geometry of the specimen are indicated, the maximum strain, failure strain and failure stress are also shown, as well as the time, force, confining stress, axial and lateral strains are displayed in columns. In Level-A the experimental curve is decomposed into loading and unloading-reloading branches and the elasticity of the rock is evaluated. In a next level, the plasticity of the rock may be subsequently evaluated according to an appropriate yield criterion (e.g. hyperbolic Mohr-Coulomb or other) and Level-A data.

The merits of such a database are the following:

1. The basic feature of this database is that each experiment has been previously properly evaluated and the nonlinear relations of stresses with strains are represented with mathematical functions (polynomials, exponential etc) (*data reduction procedure*). This leads to easy reproduction and retrieval of each test and moreover to generalization to any stress conditions by recourse to TC model (i.e. nonlinear elastoplastic constitutive model).
2. Moreover the RMDB may be exploited for calibration of the micromechanical parameters of discrete element codes such as PFC2D or PFC3D (Itasca a and b) (Fig's 1a, b).
3. Data mining may be performed in a second stage in order to extract useful rules or relationships between the various rock microstructural and physicomechanical parameters, for example relation between Young's modulus with uniaxial compressive strength, porosity, grain size or density etc.
4. Based on item (3) above, preliminary evaluation of basic elasticity and strength parameters in the design phase of an underground excavation project with RMDB may be achieved.
5. One idea is that the RMDB may provide advice on what model/parameters to use depending on the rock type and geological conditions (Beer, pers. Comm.). From the geological model (that specifies rock types, joint networks, major discontinuities etc.) a suggested material model and parameters are automatically determined for each geological region using reduced parameters from the lab test data base (or from lab tests done for the specific project).



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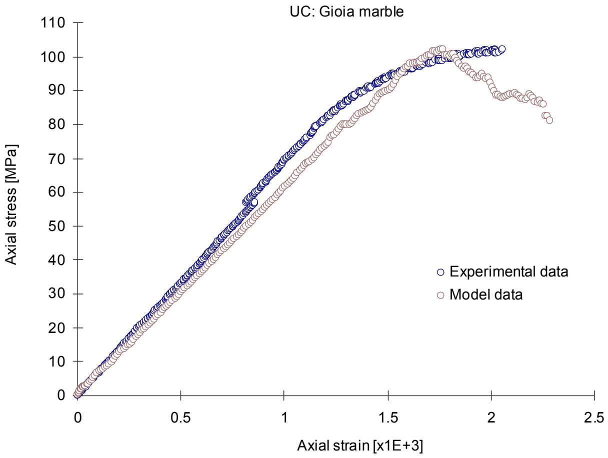


(b)

Figure 1. Calibration of micromechanical parameters of discrete element model for Gioia marble; (a) Particle model of axisymmetric test. Its micromechanical parameters should be identified on experimental data. (b) Example of particle model calibration on experimental data.

3 TEST DATA REDUCTION METHODOLOGY

The databank of TUNCONSTRUCT contains the experimental results of tests in the form of Excel worksheets for each test on each rock type.

In such a worksheet there are two levels of data analysis, namely Level-0 and Level–A. In Level-0 where the code number of the test, geometry of the specimen are indicated, the maximum strain, failure strain and failure stress are also shown, as well as the raw data i.e. time, force, confining stress, axial and lateral strains are displayed in columns. In Level-A the experimental curve is decomposed into loading and unloading-reloading branches and the elasticity of the rock is evaluated. The plasticity of the rock may be subsequently evaluated according to an appropriate yield criterion (i.e. Mohr-Coulomb, nonlinear Mohr-Coulomb, Drucker-Prager etc). The first two levels of data reduction-model calibration of the Uniaxial/Triaxial Compression, Uniaxial Tension and Brazilian tests are explained below.

3.1 *Level 0 and Level A data analysis of UC and TC tests*

For the demonstration of the analysis of UC and TC tests we will use as an example triaxial tests on Gioia mable. The specimens were cylindrical with diameter 38mm and height 78 mm approximately. During the tests the axial force (F), the engineering axial strain (ε_a), and the engineering radial (or lateral) strain (ε_r) were recorded by LVDT's and stored on computer. The axial stress (σ_a) was computed from the formula

$$\sigma_a = \frac{F}{\pi D^2 / 4} \tag{1}$$

Fig. 2 illustrates the primary experimental data obtained from a UC test (the same types of diagrams are also obtained from TC experiments).

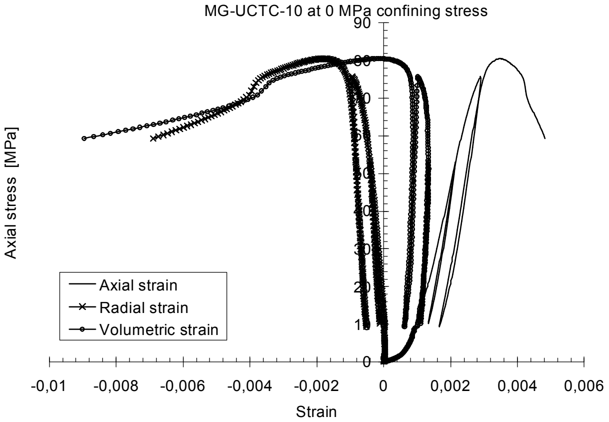


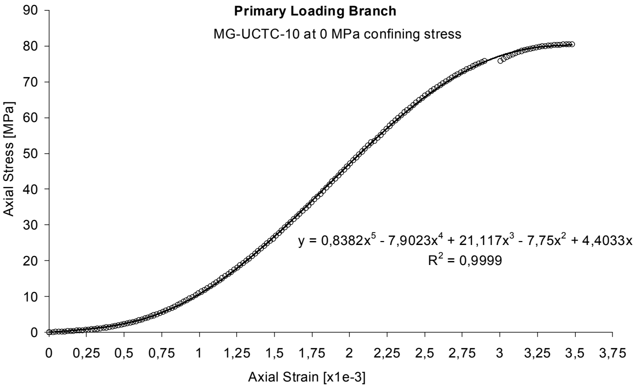
Figure 2. Axial stress vs. axial, radial and volumetric strains for Gioia Marble specimen MG-UCTC-0 at zero confining stress.

In the sequel, the observed mechanical behavior of the marble in Uniaxial Compression (UC) and Triaxial Compression (TC) is described with simple mathematical relations. Note that in this paragraph we deviate momentarily from the assumed stress sign convention and we assume compressive stresses as positive. First, by considering only the loading branch of the UC data, the path of a rock sample to failure can be followed by plotting the measured axial and radial strains versus the applied axial stress. For example the graphs of axial stress vs. axial strain and radial strain vs. axial strain for the uniaxial compression test MG-UCTC-0 are displayed in Figs. 3a and b. The data taken from primary loading loops are fitted by polynomials of the form

$$\begin{aligned} &\sigma_a = a_1 x + a_2 x^2 + a_3 x^3 + \ldots, \\ &1000 \cdot \varepsilon_r = b_1 x + b_2 x^2 + b_3 x^3 + \ldots, \\ &x = 1000 \cdot \varepsilon_a \end{aligned} \tag{2}$$

The nonlinearity of marble is manifested by the dependence of the tangent modulus of deformability and lateral strain factor on the applied stress. In fact, differentiating formulae (2) with respect to x or ε_a we obtain the following expression for the tangent moduli

$$\begin{aligned} &E_t = \frac{\partial \sigma_a}{\partial \varepsilon_a} = a_1 + 2a_2 x + 3a_3 x^2 + \ldots, \\ &\nu_t = -\frac{\partial \varepsilon_r}{\partial \varepsilon_a} = -b_1 - 2b_2 x - 3b_3 x^2 + \ldots \end{aligned} \tag{3}$$



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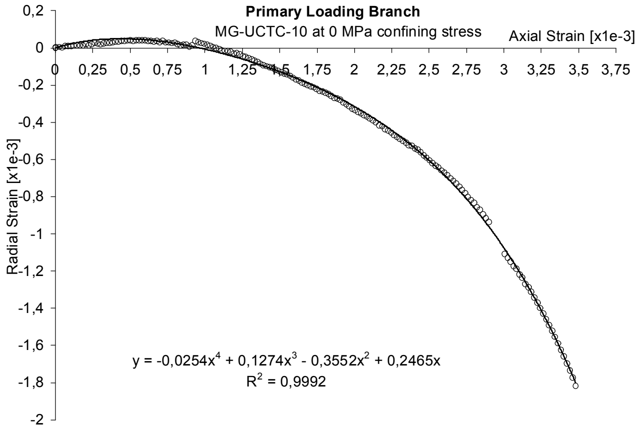
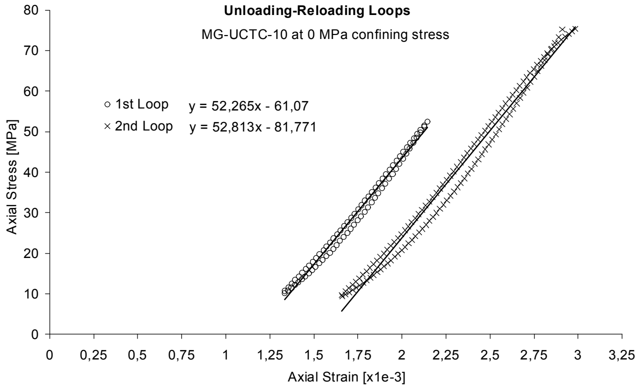


(b)

Figure 3. Loading branches of (a) axial stress- axial strain and (b) radial strain-axial strain curves of Gioia marble specimen MG-UCTC-0 in UC and fitted polynomial curves.

In the case of test MG-UCTC-0 two unloading-reloading cycles were performed before the peak stress at failure in order to infer its elastic properties. From the graphs displayed in Figs. 4 a, b it may be observed that the unloading-reloading curves corresponding to $\sigma_a - \varepsilon_a^{(el)}$ and to $\varepsilon_r^{(el)} - \varepsilon_a^{(el)}$ display hysteresis. Neglecting hysteresis for the sake of simplicity, each of these loops is best-fitted by straight lines.



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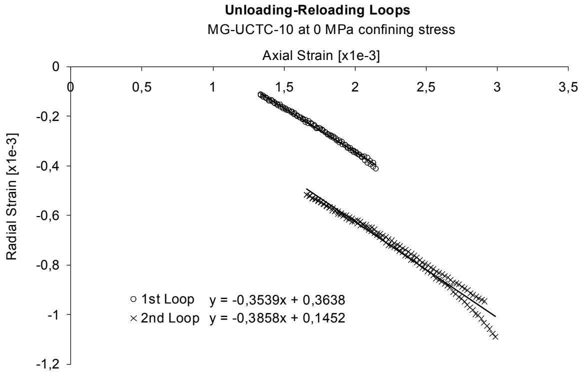


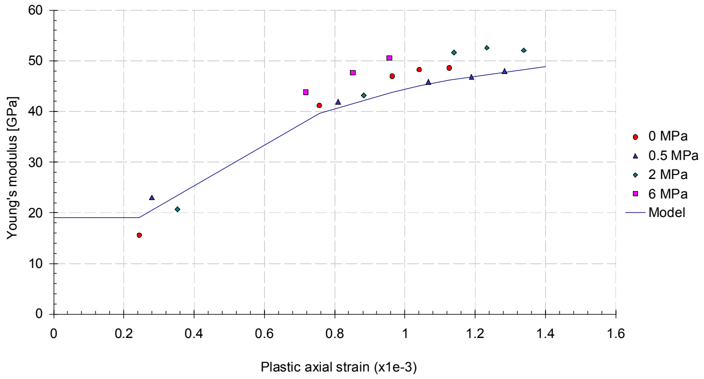
(b)

Figure 4. Unloading-reloading loops for Gioia marble in UC (a) $\sigma_a - \varepsilon_a^{(el)}$, (b) $\varepsilon_r^{(el)} - \varepsilon_a^{(el)}$.

The elasticity moduli are then plotted against plastic axial strain. It should be noticed that in the case of Gioia marble: a) both elasticity moduli seems to be constant relatively to the plastic strain and b) only two unloading-reloading curves are available thus it is not a good example to capture possible non-linear behaviour. In general, in order to plot the elastic parameters against the plastic strain in the pre-peak regime, at least three loops are required at small, intermediate and close to the crack damage stress (Martin & Chandler, 1994). Therefore we will use as an example triaxial tests conducted on Serena sandstone. For this sandstone the dependence of Young's modulus and Poisson's ratio on the plastic axial strain may be easily quantitatively described through simple mathematical models (e.g. Fig's 5a and b):

$$E_t = \begin{cases} 16 & 0 \le 1000\cdot\varepsilon_a^{(pl)} < 0.25 \\ 53\left(1 - e^{-\frac{1000\cdot\varepsilon_a^{(pl)}}{0.75}}\right) & 1000\cdot\varepsilon_a^{(pl)} \ge 0.25 \end{cases},$$

$$\nu_t = \begin{cases} 0.07 & 0 \le 1000\cdot\varepsilon_a^{(pl)} < 0.25 \\ 0.2193\left(1 - e^{-\frac{1000\cdot\varepsilon_a^{(pl)}}{0.4046}}\right), & 1000\cdot\varepsilon_a^{(pl)} \ge 0.25 \end{cases} \qquad (4)$$



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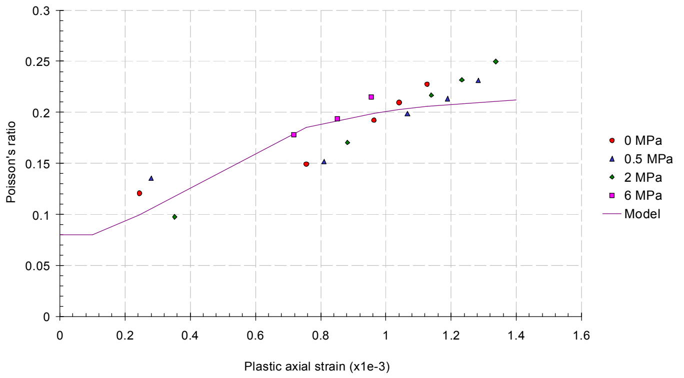


(b)

Figure 5. Dependence of (a) Young's modulus and (b) Poisson's ratio on the plastic axial strain.

3.2 *Level 0 and Level A analysis of UT tests*

We follow the same procedure of the first level of analysis followed for UC and TC tests for the estimation of best fit parameters. For illustration purposed we employ the results from a series of direct tension experiments on cylindrical Lorano marble specimens of height H= 140 mm and diameter of D= 30 mm. Both axial and lateral strains were measured by taking the mean values recorded from four strain-gages attached at specimen mid-height. The input for this analysis is given in terms of stress-strain curves which contain a number of unloading-reloading loops, as shown below in Fig. 6. The axial stress is computed by virtue of relationship (1).

Fig. 7 displays the primary loading curves of Lorano marble in UT. The elastic behaviour of the marble in tension is studied on the unloading-reloading curves for each loop presented in Fig. 8. By fitting straight lines through each loop the variation of Young's modulus and Poisson's ratio may be derived and plotted as a function of the axial plastic strain as it is illustrated in Fig. 9. The following simple two-parameter empirical equations have been found to describe the elastic behaviour of this marble in UT

$$E_t = \frac{1}{1/30.55 + 0.054\sqrt{\left(1000\cdot\varepsilon_{\mathrm{a}}^{(\mathrm{pl})}\right)}}, \qquad (5)$$

$$\nu_t = \frac{1}{1/0.26 + 6.23\sqrt{\left(1000\cdot\varepsilon_{\mathrm{a}}^{(\mathrm{pl})}\right)}}$$

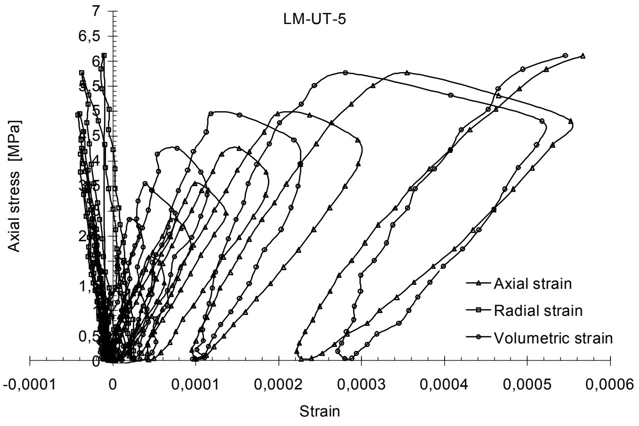
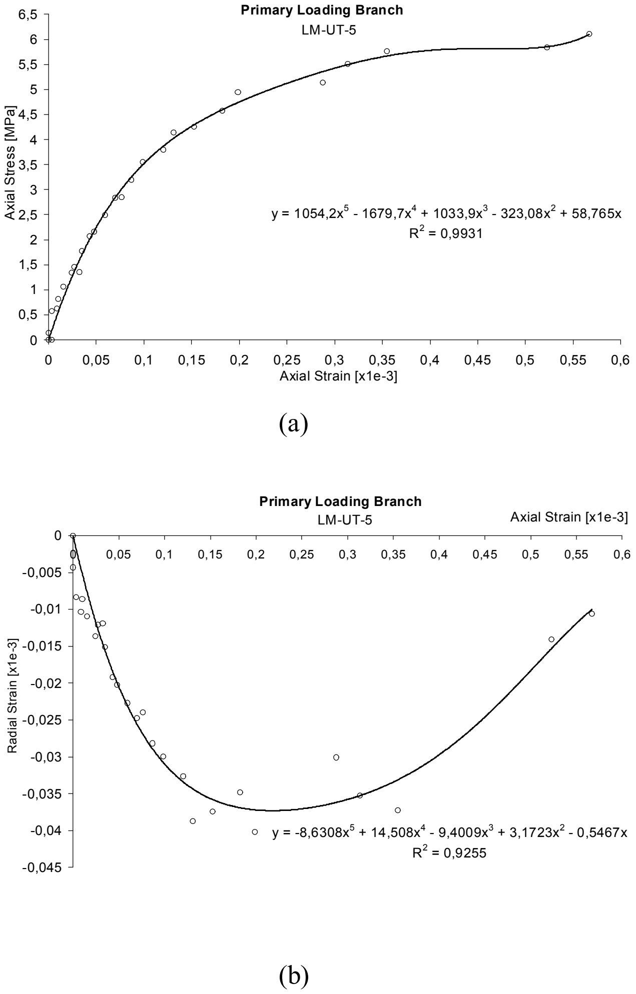


Figure 6. stress vs. axial and radial strains for Lorano Carrara marble specimen LM-UT-5 in UT.



(a)

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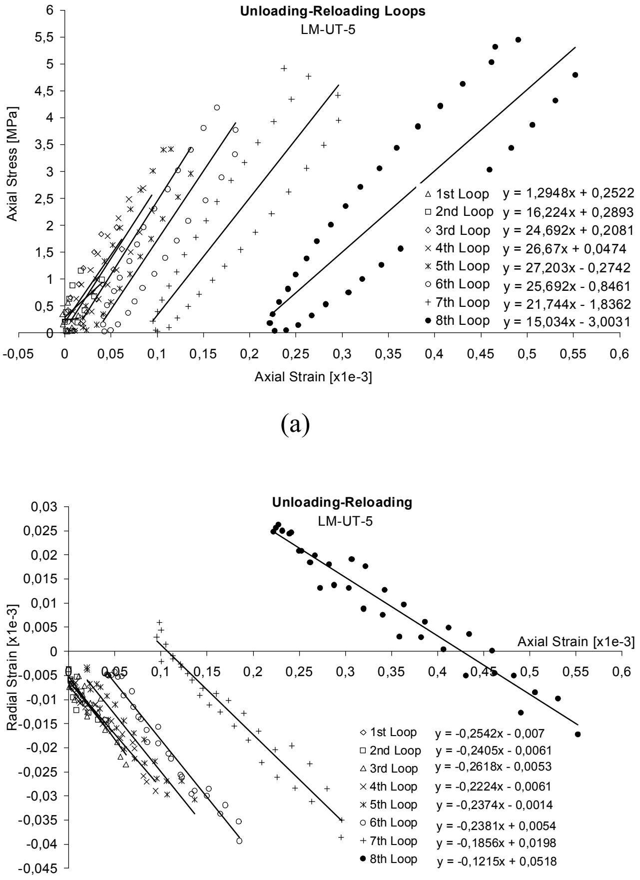
Figure 7: Loading branches of (a) axial stress- axial strain and (b) radial strain-axial strain curves of Lorano marble specimen LM-UT-5 in UT and fitted polynomial curves.



(a)

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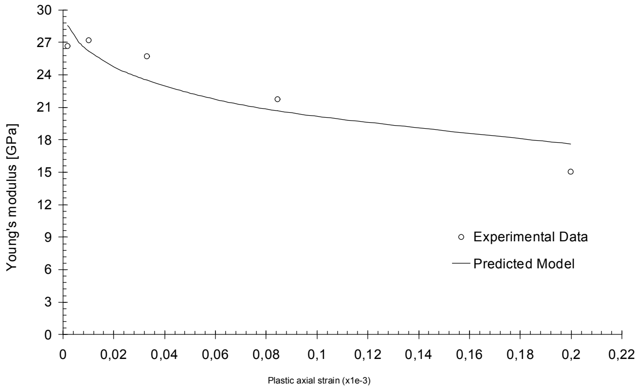
Figure 8: Unloading-reloading loops for Lorano marble in UT (a) $\sigma_a - \varepsilon_a^{(el)}$, (b) $\varepsilon_r^{(el)} - \varepsilon_a^{(el)}$.



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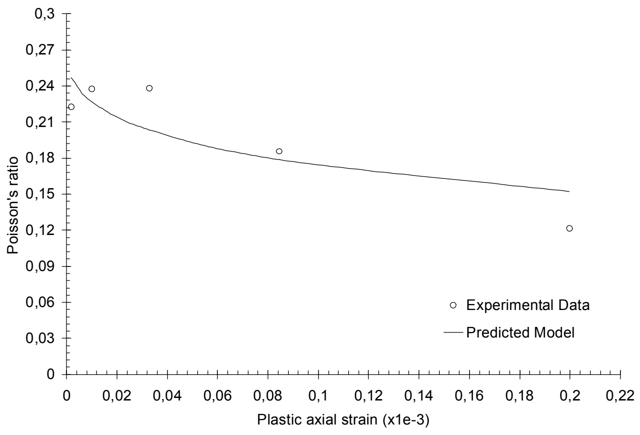


(b)

Figure 9. Degradation of (a) Young's modulus and (b) Poisson's ratio with the evolution of plastic axial strain.

3.3 *Level 0 and Level A analysis of BT tests*

For the analysis of the BT tests we will use as example an experiment that was conducted on Gioia marble. Again as in previous sections we firstly plot the horizontal stress against the axial and lateral strains. The horizontal stress at the centre of the disc is estimated from the isotropic Brazilian formula:

$$\sigma_x = \frac{2F}{\pi D t} \tag{6}$$

where F is the measured axial force and D, t the diameter and thickness of the test specimen. Next, we separate the primary loading branches from the loops and we apply exponential best fit curves on the data as follows (Fig. 10a and b):

$$\begin{aligned} \sigma_x &= \sigma_{tx}\left(1-\exp\left(-m_{tx}\varepsilon_x\right)\right) \\ \sigma_x &= \sigma_{ty}\left(1-\exp\left(-m_{ty}\varepsilon_y\right)\right) \end{aligned} \tag{7}$$

where $\sigma_{tx}, m_{tx}, \sigma_{ty}, m_{ty}$ are best-fitted parameters.

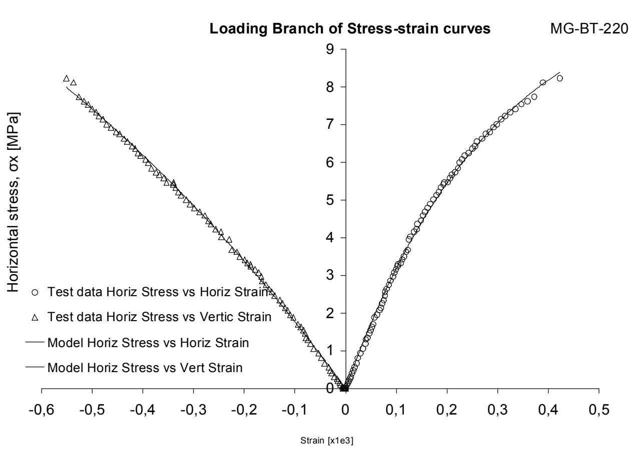
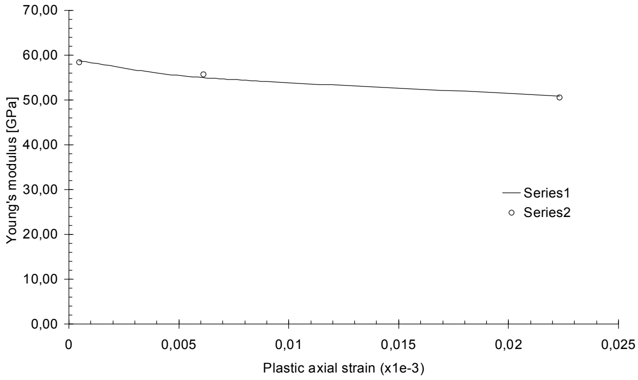


Figure 10. Primary loading branches of horizontal stress-axial strain and horizontal stress - radial strain curves of Gioia marble specimen in BT and fitted exponential curves.

Assuming that the marble is isotropic the tangent deformation modulus and lateral strain factor of the primary loading branch may be calculated by the formulae:

$$E_t = -8\frac{(d\sigma_x / d\varepsilon_x)(d\sigma_x / d\varepsilon_y)}{(d\sigma_x / d\varepsilon_y)+3(d\sigma_x / d\varepsilon_x)} \qquad (8)$$
$$\nu_t = -\frac{(d\sigma_x / d\varepsilon_x)+3(d\sigma_x / d\varepsilon_y)}{(d\sigma_x / d\varepsilon_y)+3(d\sigma_x / d\varepsilon_x)}$$

where the derivatives are calculated easily from formulae (7). It should be noted here that similar formulae for anisotropic rocks are not difficult to be derived. For the unloading-reloading loops the derivatives are simply the slopes of the curves. Then the dependence of the elastic moduli on the lateral plastic strain is described by either formulae (4) or (5) for monotonically increasing or descreasing functions, respectively (i.e. Fig. 11a and b).



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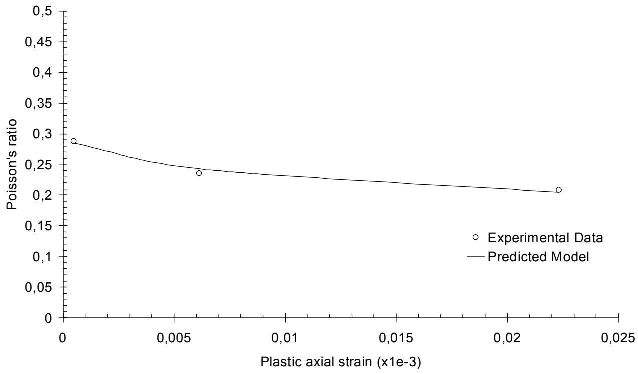

(b)

Figure 11. Deterioration of (a) Young's modulus and (b) Poisson's ratio on the plastic horizontal (lateral) strain of Gioia marble.

4 CONCLUSIONS

In this work we have presented the basic properties of a rock mechanics database and only the basic features of Levels 0 and A of analysis. This database is a first attempt to harmonize rock mechanics data before trying to collect additional data from several laboratories. At this point the database supports only the most commonly used rock mechanics tests; however, in the future it can be enriched with more types of tests. Although not presented here, the database has a web interface through which the data can be easily accessed by any user worldwide.

Apart from the database, a test data reduction methodology was presented regarding the UC, TC, UT and BT tests. The methodology puts on the table a large number of parameters that have to be measured during a typical rock mechanics test, as well as the basic analysis of the data that have been gathered. The manner of the execution of the tests is not insignificant issue. For example, strain measurements during Brazilian or direct tension tests are very important for the understanding of tensile properties of rocks; also, the number of unloading-reloading loops, the type of boundary conditions and post-peak measurements are very important issues that have to be revisited. The benefit of the processed data stored is that they are ready to be used for design of excavations in rocks, for further development at higher levels of analysis, for rock mechanical modelling, as an educational tool etc.

The next issue to be considered is how to upscale the parameters of the intact rock identified from lab testing to the real life scale of the project, by taking into account the size effect exhibited by the intact brittle or quasi-brittle rocks and the effect of joints. This work is under preparation and it will be presented shortly.

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APPENDIX A

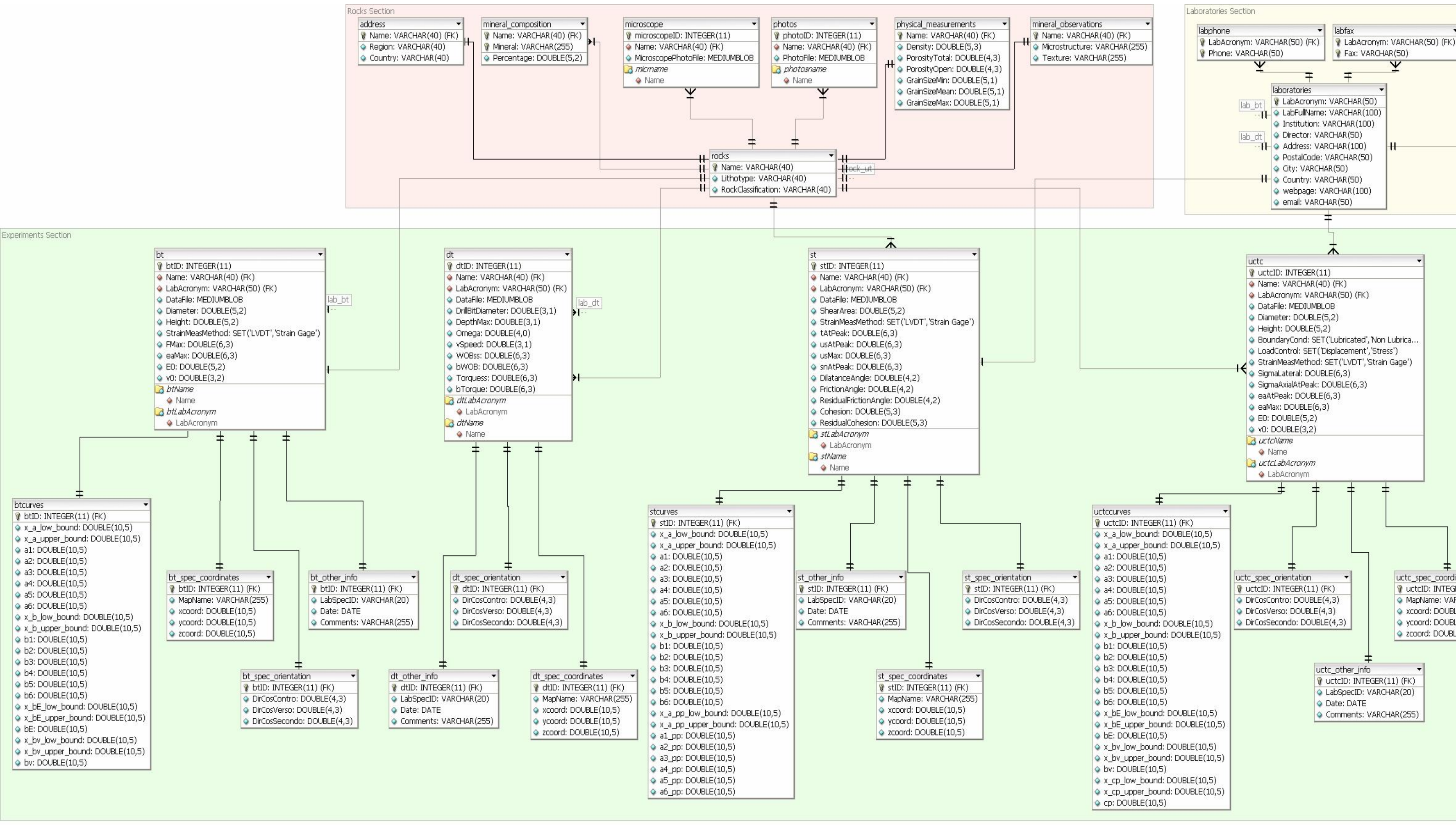

Figure A.1. Relational diagram of the rock mechanics database.