Determination of deformation characteristics of natural rock using methods of close-range photogrammetry

Martin Brček, Marek Frašťia, Martin Ondrášik, Miloslav Kopecký

Department of Surveying, Faculty of Civil Engineering STU in Bratislava, Radlinského 11, 810 05 Bratislava, Slovakia

martin.brcek@stuba.sk

Abstract. In the field of civil engineering, traditional deformation sensors are used (measurements of changes of length and widths in the stressed material), such as an electrical resistance strain gauge, deviation meters (mechanical dial gauge, electronic digital indicator, LVDT). These sensors work quite well, but the sample surface preparation and fixing the sensors on the sample surface can be timely and work skill demanding. On the other hand, conventional non-destructive testing methods, such as rebound hammers or ultrasonic pulse propagation have a disadvantage in large data scatterness and low reliability. This paper focuses on a practical, more reliable and cost-effective method for determining deformation characteristics, calculated from digital images using the principle of close-range photogrammetry. To verify the effectiveness of this method, a test was performed on a sample of natural stone from the tunnel Višňové. The data were obtained by these methods and correlated with the used load. After plotting the stress-strain curve, the static modulus of elasticity and the modulus of deformation were determined. These modules were compared with those determined from resistance strain gauge measurements.

1. Introduction

The modulus of elasticity, as well as the modulus of deformation, is used to express the deformation properties of various building materials, including natural materials such as rocks. Either field or laboratory test methods can be used to determine the above parameters. In this study, a laboratory static uniaxial compression test was used, where the deformation modulus is determined from the ratio between the compressive stress and the strain.

As standardly used methods for measuring small deformations, tensometric measurements of electrical resistance, mechanical deviation meters with analog or digital gauge and LVDT (linear variable differential transformer) sensors can be considered. More modern but more expensive electro-optical sensors are used to. Among the mentioned methods, the sensitive tensometric measurements of electrical resistance are the most often used for the measurement of deformations. They are based on the principle of transformation of the measured deformation into the electrical quantity. When using this method, the strain gauges are attached by various means, but most often by means of strain gauge glues. However, gluing the strain gauge requires experienced workers, the work itself is technically demanding and time consuming. On the other hand, dial indicators are relatively simple and easy to handle, but these may not reach the required sensitivity, and accuracy. LVDT sensors are more suitable for use due to their higher sensitivity, which transforms a change of length into a change of the magnetic field, which causes a change of the impedance of the coil through which the electric current flows. Due to the higher weight, inertia and dimensions compared to other sensors, the LVDT application is smaller. Finally, although the LVDT sensors provide high-precision of online measurements, it is only a point and one-dimensional measurement, which is generally not suitable for measuring a large number of points, the number depending on the dimensions of the tested sample.
At present, new methods are developed, such as acoustic emission [1], [2], digital image correlation [3-6], and close-range photogrammetry [7-10] and their use in determining mechanical parameters, including the deformation modules is increasing. Among these techniques, the method of close-range photogrammetry gained credit, especially for its high accuracy (in the case of a large scale the accuracy is in µm), contact lessness, dynamism and the ability of quick analyze of the recorded data and low operating costs - a digital camera, powerful computer and specialized photogrammetric software are sufficient. This method also enables automatic measurement of 1D, 2D or even 3D spatial model of objects, surfaces and their changes, e.i. displacement, deformations and defects.

The motion information keeper is either natural objects (crystals, grains, fragments, stains) or artificially created markers on the surface of the rock. By comparing the markers captured in the images before deformation and after it, information about the vector and the size of the deformation can be obtained using the correlation function.

The aim of this paper is to evaluate the ability to use the method of close-range photogrammetry in order to determine geotechnical parameters such as modulus of elasticity and modulus of deformation. A rock sample of granite from the tunnel Višňové, which is currently under construction process, was used to determine the static modulus of elasticity in compression. The modulus of elasticity as well as the modulus of deformation were determined both, by means of measuring the strain by the method of close-range photogrammetry, and by means of conventionally used methods of electrical resistance strain gauges.

One Sony RX100 IV CCD camera with a digital shutter was used in this study to eliminate shake (frame rate 1s) with the application of continuous photography.

2. Elasticity modulus and deformation modulus

The resistance of the material against deformation is characterized by the modulus describing the dependence between the deformation of the solid body due to the applied load (applied external force). The modulus of elasticity, also called the Young's modulus of elasticity (E, equation 1), is given by Hooke's law for homogeneous isotropic masses, where this dependence is linear and the deformation is directly proportional to the stress in the material. The validity of Hooke's law is limited, i.e. applies only to certain materials and only under certain loading conditions. In the case of many building materials, including rocks, the dependence of stress on strain is generally non-linear, when the material behaves both, elastically and plasticly. For this reason, in practice, the modulus of deformation (E_{def}, equation 2) is used instead of the modulus of elasticity. The amount of deformation of a material is expressed by the relative deformation - strain (ε), which represents the ratio of the change in dimension (increase or decrease) to the original dimension (equation 3). Because the rock transmits mainly compressive stresses coming from the load created by building structures, it is important to examine its elastic, respectively elastic-plastic behavior under compressive stresses. With such a stress, the dimensions in the direction of the applied load are reduced, i.e. the material is compressed.

The modulus of elasticity as well as the modulus of deformation is an important factor in this respect, which cannot be neglected when designing geotechnical structures. In general, their value increases with increasing value of rock strength, but this dependence is not linear. The modulus of elasticity is usually determined at stress (σ) not exceeding 1/3 of the rock strength. It is determined from the releasing branch of the stress-strain curve according to equation 1. To calculate the modulus of deformation (equation 2) the value of the total deformation (ε_{total}) is to be determined for the corresponding stress. It usually does not exceed 1/2 of the rock strength, but must be greater than 1/3 of its strength. Unlike the modulus of elasticity, the modulus of deformation is determined from the load branch of the stress-strain curve and not from its relaxing part (figure 1).
\[ E = \frac{\sigma}{\varepsilon_{\text{elastic}}} \]  
\[ E_{\text{def}} = \frac{\sigma}{\varepsilon_{\text{total}}} \]  
\[ \varepsilon = \frac{\Delta l}{l} \]

Figure 1. Stress-strain curve of rocks under compressive stress; adjusted after [11]

3. Tested rock material
The tested samples were prepared from rock blocks from the tunnel Višňové (the tunnel is a part of the section of the D1 highway Lietavská Lúčka - Dubná skala) during the construction of the southern tunnel tube using the ADECCO-RS method. It should be mentioned that the rock blocks were detached from the massif by blasting, which to some extent disrupts the original structural bonds of the material. Based on the classification of rocks according to [12], it is a coarse-grained granite of a massive structure composed of quartz, K-feldspar and biotite. No significant physical or mechanical anisotropy was observed during macroscopic identification.

4. Experimental methods
All preparatory works and laboratory tests were performed in the laboratory of rock mechanics at the Department of Geotechnics, Faculty of Civil Engineering STU in Bratislava in accordance with applicable technical standards and recommendations.

4.1. Sample preparation
Uniaxial compression stress tests are usually performed on dimensional test specimens (cylinders, cubes). In our study, cylinders with a diameter of 50 mm and axial length 100 mm, i.e. the ratio \( l/d \cong 2 \) (figure 2) were used. The diameter of the test samples was based on the dimensions of the largest grains in the rock, the ratio of at least 10:1 was respected, which corresponds to the methodological recommendation of the ISRM (International Society for Rock Mechanics and Rock Engineering, [13]).
Figure 2. Preparation of the rock samples; ELE International Core power tools CX20C3 (top left), detail view at the rock block and drill bit attachment (top in the middle), granite block after drilling (top right); SIRI Multidisco table saw for cutting rocks (bottom left) and ready to test rock cylinders (bottom right).

4.2. Determination of static elasticity modulus
The static modulus of elasticity $E$ (MPa) was determined using resistance strain gauges of universal type (HBM 1-LY41-20 / 120, electrical resistance 120 Ω, k-factor 2.08, temperature compensation coefficient 10.8 E-06 / ºC), which was attached to the surface of the test specimen using the two-component adhesive HBM X60 used for cold curing. The test specimen (rock cylinder) with axially symmetrically mounted strain gauges (Tenz1 and Tenz2) in its central part was placed between the contact surfaces of the test press (figure 3). The press (ELE Compression / Tension Machine 36-1410 / 01) met the requirements according to [14] for continuous load increase in a time of 0.5 ± 0.2 MPa/s. Subsequently, a basic axial stress $\sigma_0$ (MPa) of approximately 2% of the value of the tested compressive strength $\sigma_e = 139.59$ (MPa) was applied. The determination of compressive strength was performed on an identical rock sample, which was prepared and tested according to the methodological procedure [15]. In the next phase, the stress increased evenly up to the value $\sigma_u = 1/3$ of the expected value of compressive strength ($\sigma_e$). This level is called the upper load stress. The test continued by reducing the load to the value of the basic stress. Subsequently, two further identical loading and unloading cycles were performed. In the third cycle, a constant stress $\sigma_0$ was maintained for at least 30 seconds. The working diagram of the cycling process is shown in Figure 4. The measured values of stress and strain were continuously recorded by means of the universal measuring amplifier Spider8 (module for system data collection). The sampling frequency of the data collection was set to 10 Hz. The static modulus of elasticity in compression $E$ was determined from the relation

$$E = \frac{\Delta\sigma}{\Delta\varepsilon} = \frac{(\sigma_u - \sigma_0)}{(\varepsilon_u - \varepsilon_0)}.$$
Figure 3. Experimental equipment; a hydraulic device for compression/thrust ELE 36-1410 / 01, camera Sony DSC-RX100M4 with a tripod, DAQ Module Spider8, notebook, stopwatch, granite rock sample equipped with electric resistance strain gauges.

Figure 4. Work diagram scheme; t - time interval (in seconds) of the complete load cycle including the load and relaxing branch of the stress; A – point at which the strain $\varepsilon_0$ is calculated at the basic axial stress $\sigma_0$; B – point at which the strain $\varepsilon_u$ is calculated at the upper load stress $\sigma_u$.

4.3. Close-range photogrammetry, time-baseline method

The field of close-range photogrammetry includes several methods that can be used to measure displacements and deformations of various objects. The choice (but also the complexity) of a particular method depends on the required outputs - e.g. change in length, plane or space, discrete point measurements or non-selective area measurements, etc. In this case, it was necessary to determine the relative length changes (gradient of 1D) during sample loading test, and therefore the time-baseline method was chosen, where the observation position (of the camera) is fixed and changes on selected points (figure 5) on individual images (epochs) are evaluated. The choice of camera for shooting was influenced by the need of the interval shooting function (at least 1 s), small lens distortion, the possibility of manual focusing, and we also wanted to prevent camera shake caused by tilting the mirror. A camera with the stated requirements of the SONY DSC-RX100M4 was available.

The technical parameters of the camera and its settings during shooting are in table 1:

| Table 1 Camera SONY DSC-RX100M4
| Camera parameters | camera settings |
|-------------------|-----------------|
| sensor            | 1.0"- type Exmor CMOS |
| lens              | ZEISS® Vario-Sonnar T |
| resolution        | 5472 x 3648 (20.1 MP) |
| sensor size       | 13.142 mm x 8.762 mm |
| pixel size        | 0.0024 mm |
| focal length      | 20.810 mm |
| distortion        | under 5 pixels |
| shutter speed     | 1/10 s |
| ISO               | 100 |
| format            | JPEG fine |
| shooting          | interval 1 s |
| focusing          | manual |
| flash             | off |
To determine the real length changes, it is necessary to ensure several conditions:

a) high spatial geometric resolution of the image,

b) ensuring high image quality,

c) elimination of projective distortion,

d) ensuring high stability of the camera in terms of constant elements of exterior and interior orientation,

e) determining the size of the pixel in the reference space in a plane parallel to the image plane and passing through the observed point,

f) elimination of the effect of lens distortion in the event of an effect on the results,

g) measurement of the image coordinates of observed points with an accuracy of more than 0.1 pixel.

In order to determine only the relative deformations and due to the small expected deformations, it is sufficient in this case to consider only conditions a), b), d), g).

**Figure 5.** Position of the test sample in the field of view of the camera with the location of the measured points (left) and an example of the measured point (right). The stopwatch located on the left ensured the synchronization of the images with other sensors for comparison of measurements.

**High spatial geometric resolution.** This is the size of the projected pixel on the observed object (GSD - Ground Sampling Distance). The smaller this size, the higher the spatial resolution achieved and the higher the theoretical accuracy of determining the change. In our case, the value GSD = 0.038 mm was calculated. We can influence the spatial resolution by the resolution of the sensor, the distance of the camera from the observed object (in our case approx. 0.33 m) and by the size of the focal length.

**Image quality assurance.** High accuracy of image coordinate measurement requires high-quality image material in order to use the full accuracy capacity of image operators to measure point elements. Here, the parameters of the camera settings and the conditions in the object space, including the signaling of the observed points, enter into the process. The camera settings ensure low noise by setting the appropriate ISO sensitivity, the appropriate depth of field (aperture value), low image compression (data format). Conditions in the object space mainly affect the illumination of the object and the size and contrast of the observed points.

**Ensuring camera (image) stability.** The time-baseline method requires a fixed position and orientation of the camera as well as fixed elements of the interior orientation (principal distance, principal point coordinates, lens distortion). The stability of the camera position was ensured by
attaching it to a high-quality photo tripod and the stability of the interior orientation parameters, in turn, by switching off the autofocus and turning off any optical stabilization.

Measurement of image coordinates. This factor has the greatest impact on the quality of the results. PhotoModeler © software with the Least Square Method (LSM) algorithm was used to measure image coordinates. This algorithm can measure (compare/match) image parts bounded by image window including circular features. PhotoModeler uses this function for searching circular coded targets but the target should be of at least approximately circular shape (Figure 5 on the right). The points were measured semi-automatically, thus after manual placing the fence, the point was measured. However, the problem here is that we cannot always ensure the same size of the fence, which causes different pixels to interfere with the calculation in each epoch, and the position of the specified point may then differ slightly. If we assume the practical accuracy of the LSM image operator under given conditions at the level of 0.1 pixels, then we calculate the theoretical accuracy of determining the position of a point on an object as 0.1 x GSD (in our case 3.8 µm). The accuracy (mean error) of determining the length between two points on the sample is then $m_D = \sqrt{2} \times 3.8 = 5.4 \, \mu m$ and the mean error of determining the change in length is $m_{\Delta D} = \sqrt{2} \times 5.4 = 7.6 \, \mu m$.

5. Results and discussions
This section discusses the data collected during and after the laboratory test when the data were analyzed and comprehensively compared.

Figure 6 shows the gradually evolving deformation in time, based on data obtained from strain gauges. The loading and unloading process was repeated four times. The resulting curves are very similar to each other, but differ in the size of deformation recorded. The rate of mutual deviation increases with increasing load, reaching 18% at the highest load level. The measured data from both strain gauges were subsequently processed by the averaging method and thus adjusted for the following calculations. The static modulus of elasticity was determined from the third load cycle (figure 7) and reached the value $E = 8.08$ GPa.

![Figure 6. Curve deformation versus time for granite sample; the blue and red curves show the deformation measured by strain gauges and the black curve represents their mean value](image-url)
Figure 7. Stress and strain diagram showing four load cycles

The deformation recorded by the method of close-range photogrammetry in comparison with the strain gauge method (figure 8) acquired a higher rate in each load cycle. It is clear from Figure 8 that the photogrammetric data show significant noise. In most cases (more than 60%) the values of measured deformation differed from each other by 32 to 81 mm/m (in percentage by about 5 to 11%) in extreme cases by up to 200 mm/m (almost 30%). The moving average method with a period of n = 3 was applied to retrieve the data, which increased clarity and at the same time gained a clearer picture of the trend.

Figure 8. Comparison of recorded deformations measured by two different methods; the black curve represents the average values from the strain gauges, the purple curve shows the data from the close-range photogrammetry (the figure on the right shows the adjusted photogrammetric data by the moving average method).

The maximum changes in the direction of the pressure on the sample were measured in the images up to 6 pixels, but the maximum change of the distance up to 1 pixel. This means that the whole press device moved downwards by approximately 0.22 mm during the test and the maximum length change between measured points (approx. 40 mm) was only up to 0.03 mm. The large noise of the data from the photogrammetry (figure 7) was very probably caused by the insufficient accuracy of the
measurement of image coordinates, caused by the texture of the material in combination with the selected measuring image operator.

It should not be forgotten that the natural textural-structural features of the rock (i.e. rock components such as mineral grains of various shapes) used for motion observation were not ideal observation points providing a sufficient contrast image for photogrammetric processing. Artificially created high-contrast dots or marks (using a combination of white and black) that are sprayed (sprayed, hand-dotted or roller-printed) on the surface of the rock sample could provide some improvement in this area [9].

From the data obtained by the photogrammetric method, the modulus of elasticity \( E = 6.01 \) GPa was determined. The difference between the values of the modulus of elasticity determined by digital photogrammetry and the conventional strain gauge method was relatively large, up to 25%.

The modulus of deformation \( E_{def} \) was also determined, which reached the value \( E_{def} = 5.98 \) GPa in the case of digital photogrammetry and in the case of the strain gauge method \( E_{def} = 7.35 \) GPa. A comparison of the two results shows an almost 20% difference.

The results of both methods document the fact that the values of the specified modules are too low. According to the Atlas of Rocks in Slovakia [16], healthy rocks of the same lithological type reach the value \( E_{def} = 41.5 \) GPa. However, it should be mentioned that the tested rock sample was prepared from the rock material originated from the tunnel Višňové, where the ADECO-RS method (blasting work on the full profile of the tunnel tube) was used. This material could be in large extend broken by a system of microcracks, which disrupted the natural integrity and strength of the rock, which also adversely affected the determined values of the modulus of elasticity of both methods used. Deformation modulus determined by field tests in comparable rock type [17] for different rock quality designation (RQD) were in the range from 0.42 GPa to 29 GPa.

6. Conclusions
This paper describes a new method of measuring a natural rock sample deformation for the purpose of determining the modulus of elasticity in compression. The method is based on digital photogrammetry and the determined modulus of elasticity differed from the modulus determined by the conventional strain gauge method by almost 25%.

However, we believe that the determination of the elasticity modulus of a rock material by digital photogrammetry can be much more accurate using further improvements. We are planning to test another image operator, artificial signaling of circular targets on the sample, artificially applied surface object texture and increase of camera resolution.

In addition, another innovative recording device will be installed - a digital USB microscope, in order to identify the deformation of the rock sample in the longitudinal and transverse planes.

Acknowledgment
This work has been supported by the Grants Agency of the Slovak republic VEGA under the Grant No. 1/0530/19.

References
[1] M. Huang, L. Jiang, P.K. Liaw, C.R. Brooks, R. Seeley, and D.L. Klarstrom, “Using Acoustic Emission in Fatigue and Fracture Materials Research,” JOM - The Minerals, Metals & Materials Society, 50 (11), p.1-12, 1998.
[2] M. Korenska, L. Padzera, and M. Manychova, “Effects of Material Structure of Concrete on
Acoustic Emission Signal Parameters,” European Working Group on Acoustic Emission (EWGAE), Vienna, 8th to 10th September 2010.

[3] A.H.A. Santos, R.L.S. Pitangueira, G.O. Ribeiro, and R.B. Caldas, “Study of size effect using digital image correlation,” Revista Ibracon de Estruturas e Materiais, 8 (3), p. 323-340, 2015.

[4] A.H.A. Santos, R.L.S. Pitangueira, G.O. Ribeiro, and E.V.M. Carrasco, “Concrete modulus of elasticity assessment using digital image correlation,” Revista Ibracon de Estruturas e Materiais, 9 (4), p.587-594, 2016.

[5] H. Huang, L. Liu, F.C. Sham, Y.S. Chan, and S.P. Ng, “Optical Strain Gauge vs. Traditional Strain Gauges for Concrete Elasticity Modulus Determination,” Optik - International Journal for Light and Electron Optics, 121 (18), p. 1635-1641, 2010.

[6] J. Lee, E.J. Kim, S. Gwon, S. Cho, and S.H. Sim, “Uniaxial static stress estimation for concrete structures using digital image correlation,” Sensors, 19 (2), 319, 2019.

[7] U. Hampel, and H.G. Maas, “Application of digital photogrammetry for measuring deformation and cracks during load tests in civil engineering material testing;“ In: A. Grün, and H. Kahmen (eds.), Optical 3-D Measurement Techniques VI, Volume II, pp. 80–88, 2003.

[8] U. Hampel, and H.G. Maas, "Photogrammetric techniques incivil engineering material testing and structure monitoring,” Photogrammetric Engineering and Remote Sensing, 72 (1), pp. 39–45, 2006.

[9] A. Al-Mosawe, H. Agha, L. Al-Hadeethi, and R. Al-Mahaidi, “Efficiency of image correlation photogrammetry technique in measuring strain,” Australian Journal of Structural Engineering, 19 (3), 207-213, 2018.

[10] M. Fraštia, M. Marčiš, M. Bajtala, Š. Sokol, M. Plakinger, P. Blišťan, M. Gergeľová, and J. Ižvoltová, Možnosti metódy časovej základnice v digitálnej fotogrametrii. In Geodesy, Cartography and Geographic Information Systems 2016. Košice: Technická univerzita v Košiciach, CD-ROM, [10], 2016 ISBN 978-80-553-2603-0 (in Slovak).

[11] J. Pauli, and T. Holoušová, “Mechanika hornin. Laboratori zkoušky hornin,” ČVUT Praha, s. 123, 1991.

[12] STN 72 1001, “Classification of soil and rock;“ 2010.

[13] Z.T. Bieniawski, and M.J. Bernede, ”Suggested methods for determining the uniaxial compressive strength and deformability of rock materials: Part 1. Suggested method for determining deformability of rock materials in uniaxial compression,” International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, 16 (2), p. 138-140, 1979.

[14] STN EN 14580, “Natural stone test methods - Determination of static elastic modulus,“ 2005.

[15] STN EN 1926, “Natural stone test methods – Determination of compressive strength,” 2007.

[16] R. Holzer, M. Laho, P. Wagner, and M. Bednárik, "Inžinierskogeologický atlas hornín Slovenska," ŠGÚDS Bratislava, pp. 532, 2009 (in Slovak).

[17] M. Kuvik, and J. Frankovská, Determination of deformation modulus from in-situ pressuremeter and dilatometer tests. In Proceedings of the XVII ECSMGE-2019. Reykjavik: The Icelandic Geotechnical Society, 2019.