JOURNAL OF SUSTAINABLE UNDERGROUND EXPLORATION VOL. 2 NO. 1 (2022) 55-68

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J-SUE

http://publisher.uthm.edu.my/ojs/index.php/j-sue

e-ISSN : 2821-2851

Journal of Sustainable Underground Exploration

A Numerical Investigation for In-Situ Measurement of Rock Mass Mechanical Properties with a CCBO Probe and Evaluation of the Method's Error in Estimating the In-Situ Stresses with the Overcoring Technique

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DOI: https://doi.org/10.30880/jsue.2022.02.01.008
Received 26 November 2022; Accepted 28 November 2022; Available online 30 November 2022

Abstract: Accurate determination of rock stress in great depths has become one of the most critical issues in civil and mining affairs along with the expansion of underground excavation spaces' scale and deepening of under-excavation areas. The hydraulic fracturing method and coring-based laboratory methods including ASR, DSCA, and AE are main techniques in rock stress measurement in the earth's depth. Thus far, previous studies have reported repeated samples from the values obtained from the above mentioned techniques. Nonetheless, the "Compact Conical Borehole Overcoring" (CCBO) technique is an example of the stress-relief method and this technique, is one of the most cost-effective and accurate methods for measuring the in-situ stresses simply by digging one borehole either in the tunnels' wall or in the deep wells' depth. The current study aims at analyzing the overcoring technique with the CCBO probe to identify errors regarding the number of sensors installed, as well as checking its ability to estimate mechanical parameters of mass rock in-situ. In this study, we have utilized the analytical method based on numerical simulations to determine the accuracy of the method's dependence on the number of sensors installed on the probe. We performed numerical analysis using COMSOL finite element software, as well as MATLAB software. In addition, we attempted to propose possible relations for estimating mechanical parameters of mass rock using the probe, a method determined by the inventors.

Keywords: In-situ stresses, overcoring, measurement accuracy, numerical methods, CCBO method, COMSOL

1. Introduction

The in-situ measurement of stress is crucial for the construction of underground structures, as it influences the mechanical behavior of rocks. In addition, the stability of rock structures is highly dependent on the initial state of stress. Numerous tools and techniques are available today for calculating in-situ stress for all rock conditions. Kim and Franklin, for instance, proposed several methods proposed by the International Society for Rock Mechanics, such as flat jack, hydraulic fracturing, and overcoring methods such as USBM and CSIRO. Finding the three axes condition of stresses from a single borehole is desirable, which cannot be achieved in all methods; however, this can be achieved through the Compact Conical Borehole Overcoring (CCBO) method. Furthermore, the stress release for the overcoring process occurs in smaller dimensions, which is a significant advantage. The CCBO method was coined by a Japanese researcher named S. Kobayashi in 1985. In this method, the pilot well at the end of the borehole is drilled in a conical shape, and an epoxy-bonded probe containing 12 to 24 strain gauges is connected to the inside of the pilot well. Then, during the overcoring procedure, these strains are continuously recorded by a data logger and ultimately converted into the intensity and direction of the existing stresses by a relationship involving coefficients for calculating the stress

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concentration. Notably, due to the unique conical shape at the end of the pilot well, the existing coefficients in this relation have no analytical basis and can only be calculated using existing numerical methods, including boundary and finite elements.

Eventually, in 1990, this method was completed by Katsuhiko Sugawara and Yuzo Obara and accepted as one of the ISRM standard methods. In this method, three axes of stress and a complete field can be obtained with single drilling, and probe installation in the pilot well is straightforward and accurate. The CCBO method described in this article extends Sugawara and Obara's Hemispherical-ended cell method. In the proposed method, the stress conditions can be computed by measuring the strains on the surface of a hemisphere at the end of a borehole, and its error can also be determined. Calculations of stress from strain by these equations are related to isotropic and homogeneous rocks, and stress relief can be done in this technique with the same dimensions as the initial borehole drilling [1]. In addition, Compact Conical Borehole Monitoring (CCBM) is also available [2].

Notably, the average duration of each CCBO test is less than two hours, and the maximum borehole depth for the tunnel wall in this test is 40 meters. The cell's outer wall typically contains twelve, sixteen, or twenty-four strain gauges. Connecting the conical-shaped strain gauge probes, as shown in Fig. 1 and 2, to a conical socket at the end of the borehole enables a complete three-dimensional evaluation of the stress field using the CCBO method. Like other methods, the CCBO assumes linear elastic conditions and identical and homogeneous rock. First, a 76 mm-diameter drill (i.e., NX borehole) is used to drill a borehole to the specified length (the maximum drilling length is 40 meters). A conical shape is drilled at the end of the drilling borehole using a diamond drill bit to create a socket for installing the cell. In order to complete shaping the end of the borehole, a downhole camera is sent to the end of the borehole to assess the quality of the drilling, as shown in Fig. 3. The conical socket should be completely smooth and conical, with an isotropic geometry. The conical cavity (socket) should then be inspected for cracks and water. The socket's surface is then polished and prepared for adhesion using a soft cloth and acetone. After rechecking the end of the borehole with the camera for the final evaluation of the socket's surface quality, all relevant electrical devices are evaluated before the actual installation of the cell. The probe is then inserted into the installation tool, and its head is completely coated with adhesive. At this point, we can rotate the installation tool to position the cell in the desired direction. The glue is then strengthened by compressing the cell to the end of the borehole under high pressure for 30 minutes. When the adhesive has hardened, the installation tool is removed from the borehole, and the exact distance between the cell installation and the tunnel wall is calculated, as this distance is essential for sending the overcoring drill and carrying out the process. Then, the electrical tools and data loggers undergo a second evaluation. The overcoring procedure is carried out with a 3 mm thick, 76 mm in diameter hollow drill inserted to the cell installation's length. Then, it drills an additional 100 to 300 millimeters and relieves the cell of stress (Fig. 4). It should be noted that the cell is irretrievable and remains at the bottom of the borehole. During the over coring process, the data measured by the strain gauges on the cell are recorded every 5 mm of the drill's advancement or every 2 mm if a higher degree of sensitivity is required. The data is saved in the computer, and one of the cell outputs is used to validate the overcoring process by examining the relationship between changes in strain and drill length advancement [3].

In the following sections, practical and theoretical features and details, as well as data interpretation, will be thoroughly examined. It should be noted that this article suggests the number of strain gauges required to increase accuracy and introduces relationships obtained from numerical simulations using the COMSOL Multiphysics finite element software and MATLAB software for the in-situ estimation of the mechanical parameter of rock using the probe, as determined by the inventors.

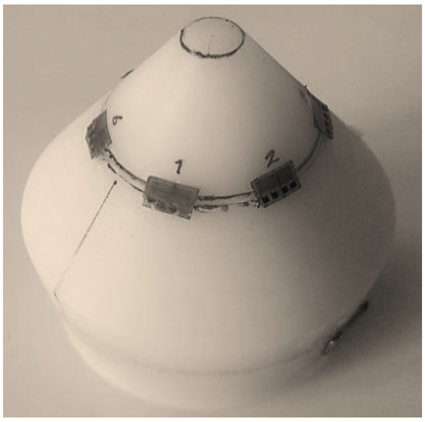

Fig. 1 - The conical part of the probe that contains the strain gauges

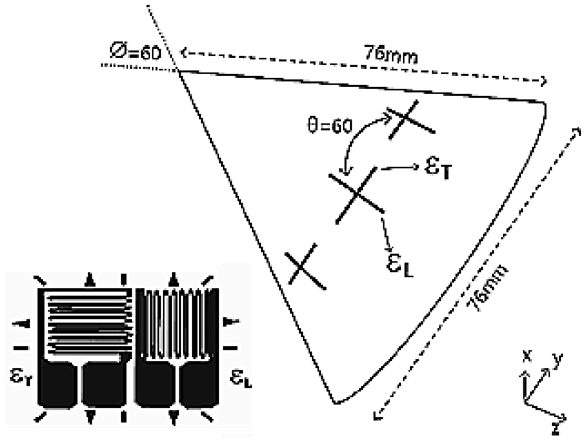

Fig. 2 - The position of the strain gauges on the probe's conical head

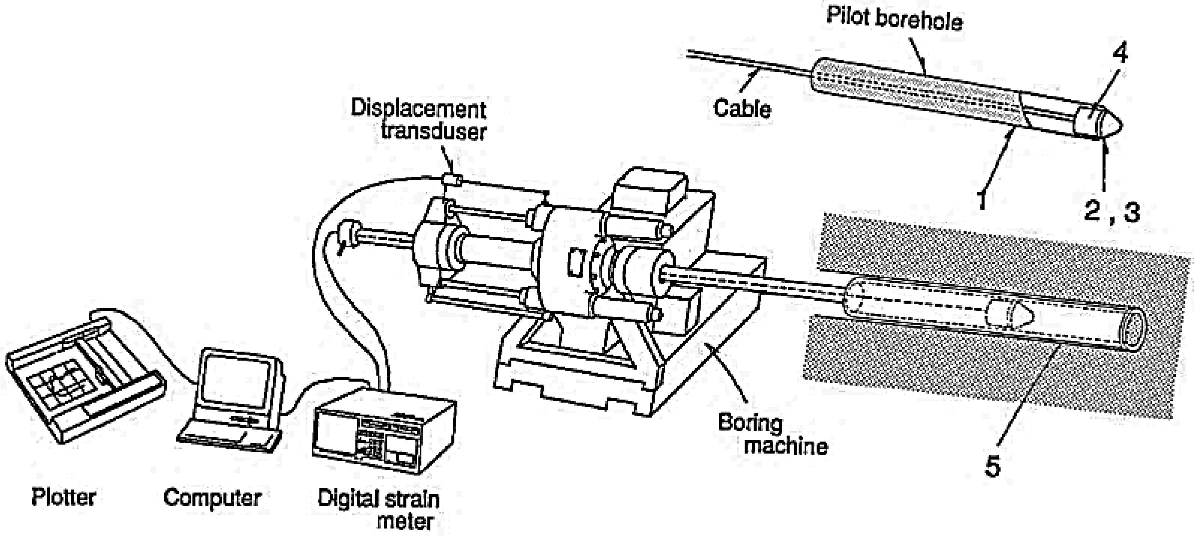

Fig. 3 - Schematic image of the CCBO tool for measuring in-situ stresses, 1) Borehole with 76 mm diameter, 2) Forming a conical end, 3) Cleaning the borehole's end, 4) Attaching the cell to the borehole's end and 5) Overcoring [3]

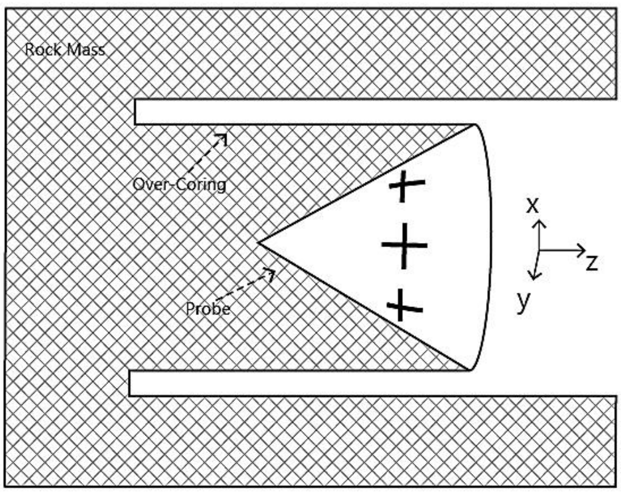

Fig. 4 - The probe's placement in the rock at the completed overcoring procedure

2. Methodology

The data obtained from the overcoring procedure and the separation of the conical socket from the rock mass, which results in a change in shape, are measured by strain gauges and read and stored by the data logger. The amounts of strains on strain gauges in the specified directions are analyzed as raw data. The initial assumption is that the in-situ stresses surrounding the space of the drilled borehole are uniform, and their component sizes are calculated by transforming the strains recorded by the cell and the numerical analysis relations.

In this method, as depicted in Fig. 5, cylindrical coordinates with (r,θ,z) components, spherical coordinates with $(\theta,\emptyset,\rho)$ components, and Cartesian coordinates with (x,y,z) components are considered for calculating the rock's in-situ stress tensor using strains obtained from the overcoring process. As illustrated in the figure, the **z** direction is regarded as a longitudinal direction of the drilled borehole, and the stress tensor $\{\boldsymbol{\sigma}\}$ is defined as per Equation (1):

$$\{\sigma\} = \{\sigma_x, \sigma_y, \sigma_z, \tau_{xy}, \tau_{xz}, \tau_{yz}\} \qquad (1)$$

Where $\sigma_x, \sigma_y, \sigma_z, \tau_{xy}, \tau_{xz}, \tau_{yz}$ denote the six components of the symmetric stress matrix in the Cartesian coordinates [1].

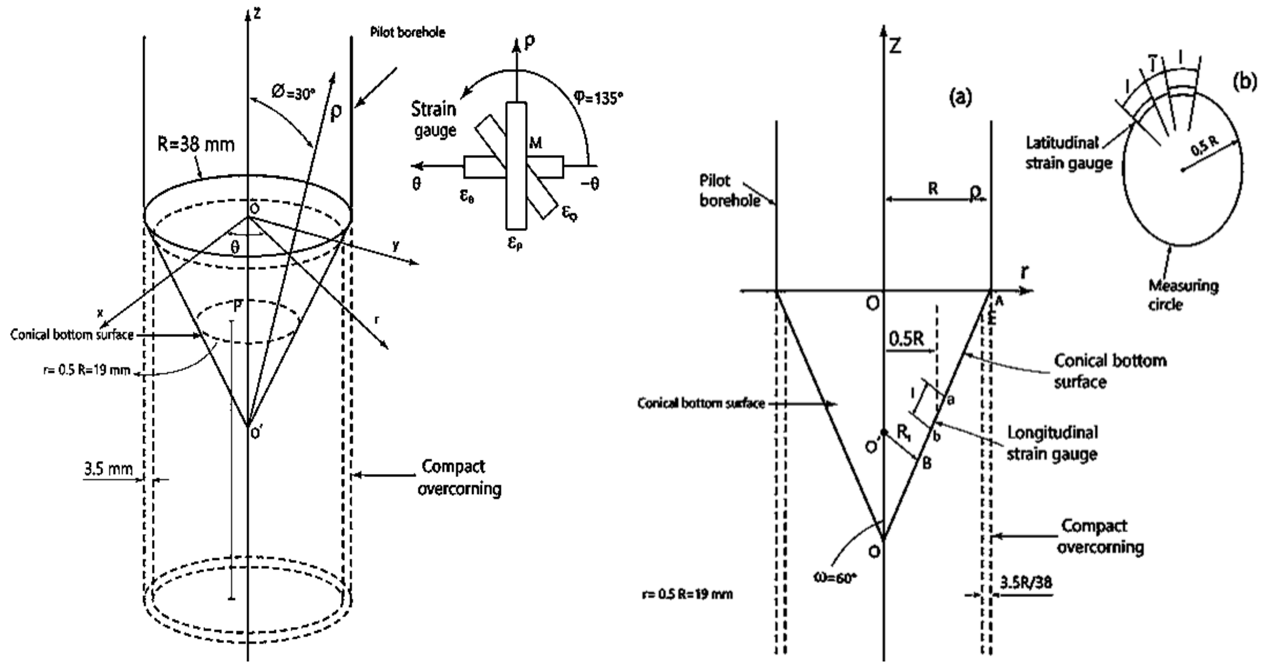

Fig. 5 - Cylindrical coordinate system and the Cartesian corresponding to the cell [4], [5]

Strain gauges measure strains at six or eight distinct cell points in two or three different directions. These points are positioned axially symmetrically on a circular surface with a radius of 19 mm, in the center of the probe's lateral side, and at 45- or 60-degrees angles from one another. Notably, the angle between strain gauges cannot be 90 degrees [6]. It is important to note that the measuring points were positioned based on theoretical calculations and practical tests conducted by the method's founders.

The authors of this article conducted a MATLAB-based analysis of the relationships between their position and stress measurement error in the following section. At each strain gauge installation point, the sixteen-method of strain gauge measures the tangential strain (ε_θ) and radial strain (ε_ρ). In contrast, the twenty-fourth method of the strain gauge adds a diagonal strain to each measurement point, denoted by (ε_r). This quantity improves the precision and reduces the measurement error. As demonstrated in Fig. 5, the angle between (ε_r) and (ε_θ) is 45 degrees, and the angle between (ε_r) and (ε_ρ) is also 45 degrees. The calculated strains of the conical socket are given by Equation (2) [1].

$$\{\beta\} = \{\beta_1, \beta_2, \ldots\ldots \beta_n\}^T \qquad (2)$$

"n" is the number of strain gauges on the probe; for instance, ($n = 16$) is the sixteen-method of the strain gauge; in this case, the strains are measured in two directions at eight measurement points, and ($n = 24$) is the twenty-four-method of the strain gauge, in which the number of measurement points is still eight, but the number of measurement directions, by strain gauges, reaches three, with the addition of diagonal strain. The matrix-like Equation (3) is used to calculate in-situ stresses, where $[\boldsymbol{A}]$ is a matrix of elasticity coefficients obtained from numerical analysis in the form

($nx6$) and is normalized by the amount of Young's modulus [1]. It should be noted that the measurement error of the in-situ stresses decreases as n, the number of strains measured in different directions, increases. This issue was also investigated by the authors of this article using a program written in MATLAB.

$$[A]\{\sigma\} = E.\{\beta\} \tag{3}$$

After measuring the strains $\{\varepsilon_\theta, \varepsilon_\rho, \varepsilon_\emptyset\}$ at the location of the strain gauges with the tangent installation angle, which exhibit values such as $(\theta = 0, 60, 120, \ldots., 300)$ in the case of six measurement points and $(\theta = 0, 45, 90, \ldots., 315)$ in the case of eight measurement points, it is possible to calculate the stresses in the isotropic state, and also possible to calculate the stresses in the isotropic state by forming a system of equations and unknowns through Equation (4). In this equation, E denotes Young's modulus of rock, and $A11, A13, \ldots$, and $D32$ represent the constant strain calculation coefficients presented in Table 1 of the values calculated using the boundary element method in the source [1]. The values of strain coefficients depend on the values of Poisson's ratio for rock, and since there is no analytical solution to calculate them, they are derived through numerical calculations. Moreover, in Fig. 6 and 7, the amounts calculated by the authors using the COMSOL finite element software are presented in various Poisson's ratios of rock and according to the changes in the position of the strain gauges or ρ.

$$\begin{Bmatrix}\varepsilon_\theta\\ \varepsilon_\rho\\ \varepsilon_\emptyset\end{Bmatrix} = \begin{bmatrix} A_{11} + A_{13}\cos 2\theta, & A_{11} - A_{13}\cos 2\theta, & C_1, & D_{11}\sin\theta, & D_{11}\cos\theta, & 2A_{13}\sin 2\theta \\ A_{21} + A_{23}\cos 2\theta, & A_{21} - A_{23}\cos 2\theta, & C_2, & D_{21}\sin\theta, & D_{21}\cos\theta, & 2A_{23}\sin 2\theta \\ A_{31} + A_{33}\cos 2\theta + A_{32}\sin 2\theta, & A_{31} - A_{33}\cos 2\theta - A_{32}\sin 2\theta, & C_3, & D_{31}\sin\theta - D_{32}\cos\theta, & D_{31}\cos\theta + D_{32}\sin\theta, & 2A_{33}\sin 2\theta - 2A_{32}\cos 2 \end{bmatrix} \times \frac{\{\sigma\}}{E} \tag{4}$$

Table 1 - Strain coefficients in the isotropic state [1]

Poisson's ratio	A_{11}	A_{13}	A_{21}	A_{23}	A_{31}	A_{32}	A_{33}
0.1	1.002	-1.726	0.109	0.343	0.562	-0.802	-0.724
0.2	1.000	-1.752	0.022	0.365	0.519	-0.818	-0.707
0.25	0.999	-1.733	-0.021	0.373	0.496	-0.821	-0.693
0.3	0.997	-1.704	-0.065	0.380	0.474	-0.822	-0.679
0.4	0.989	-1.611	-0.154	0.386	0.426	-0.823	-0.625
Poisson's ratio	**C_1**	**C_2**	**C_3**	**D_{11}**	**D_{21}**	**D_{31}**	**D_{32}**
0.1	-0.155	0.655	0.246	0.082	1.542	0.802	-1.725
0.2	-0.263	0.641	0.185	0.095	1.627	0.860	-1.860
0.25	-0.3.17	0.636	0.155	0.101	1.673	0.886	-1.923
0.3	-0.371	0.632	0.126	0.108	1.716	0.911	-1.983
0.4	-0.481	0.630	0.071	0.123	1.787	0.953	-2.091

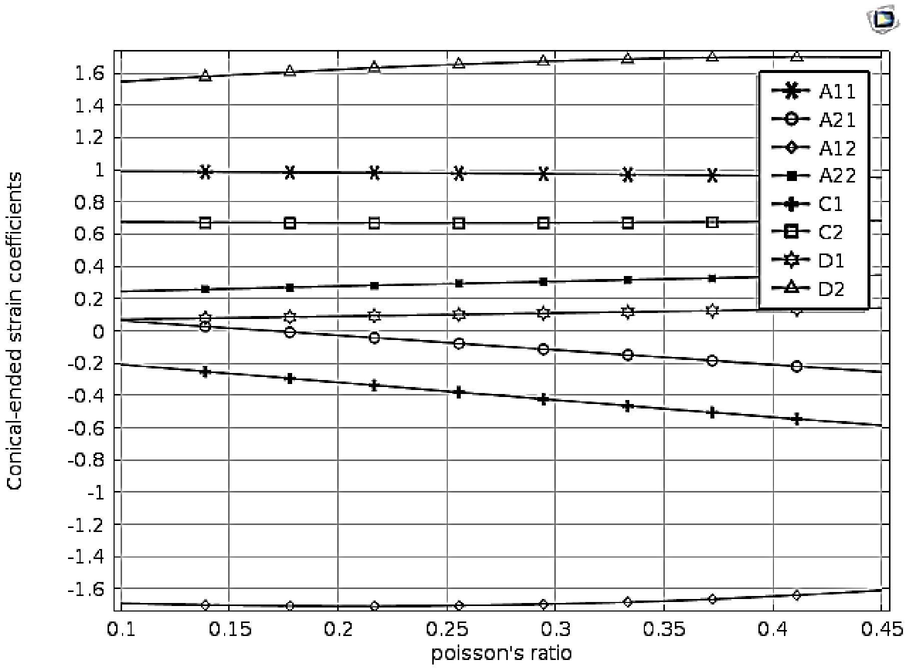

Fig. 6 - Variations of strain coefficients concerning variations of the Poisson's ratio for a conical-ended borehole using the finite element method

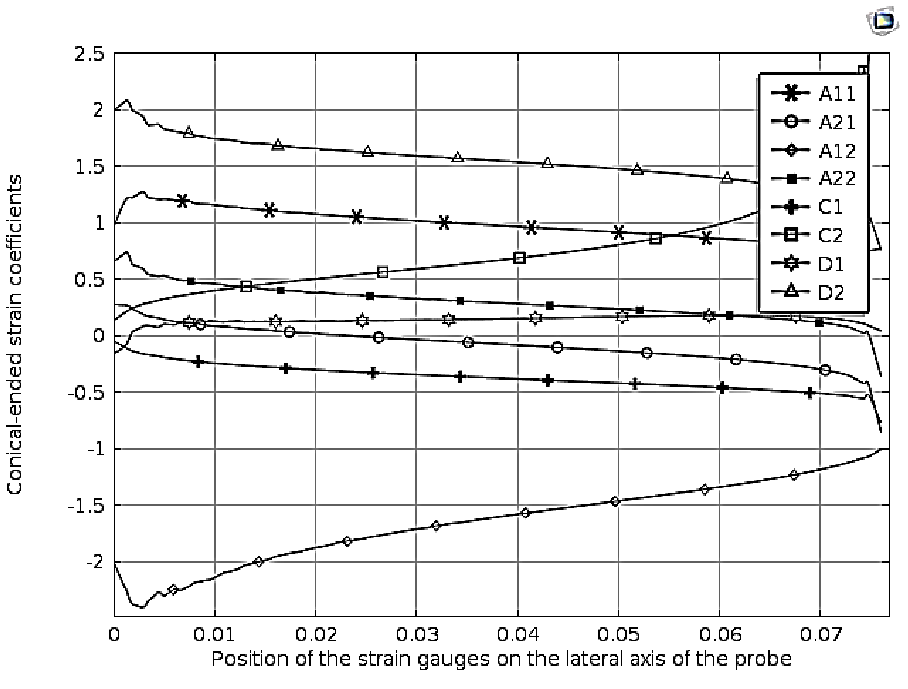

Fig. 7 - Variations of strain coefficients concerning variations of ρ for a conical-ended borehole using the finite element method

3. Least Squares Method

The least squares method is a mathematical method for analyzing multiple linear regressions related to the mathematical science of statistics. This method for analyzing overcoring measurements is summarized below. As stated previously, the inventors employed this method to reduce the stress error calculated by the CCBO method. In this method, the number of measurements taken during overcoring equals the sum of the strains or displacements of $\boldsymbol{n}$. Therefore, according to the linear elastic theory, the following equation relates these n observations linearly to the six stress components in place (in an arbitrary global coordinate system) [7]:

$$[Y] = [X][b] + [\varepsilon] \quad (5)$$

Where $[\boldsymbol{Y}]$ is an $(N \times 1)$ matrix of observations or measured strain values, $[\boldsymbol{X}]$ is an $(N \times 6)$ matrix of coefficients, which, as previously mentioned, was obtained and designated as $[\boldsymbol{A}]$ via numerical methods in the CCBO method. In addition, $[\boldsymbol{b}] = [\boldsymbol{\sigma_o}]\ \boldsymbol{XYZ}$ is a (1×6) matrix containing six stress components at the measurement location, whereas $[\boldsymbol{\varepsilon}]$ is an $(N \times 1)$ matrix of residual errors associated with measurements. In the least squares analysis, it is generally assumed that the components of the $[\boldsymbol{\varepsilon}]$ matrix are uncorrelated (independent) variables with zero mean and identical variance. It can be demonstrated that the calculation of the least squares of the stress matrix minimizes the value of $[\boldsymbol{\varepsilon}]\boldsymbol{t}[\boldsymbol{\varepsilon}]$, and the result of the system in the form of six equations and six unknowns is given by the following equation:

$$[X]^t[X][b] = [X]^t[Y] \qquad (6)$$

Solving Equation (6) yields the normal and shear stresses in the test area that most closely corresponds to the displacement or strain data observed at the test site. These six components can be used to determine the most probable principal stresses and their direction in the global coordinate system [7]. The CCBO method determines the most probable amount for the stresses' size using the least squares method. Equation (3) will be normalized as Equation (7), where $[\boldsymbol{B}] = [\boldsymbol{A}]^{\boldsymbol{T}}\ [\boldsymbol{A}]$ and $\{\boldsymbol{\beta}^*\} = [\boldsymbol{A}]^{\boldsymbol{T}}\ \{\boldsymbol{\beta}\}$. Consequently, the most probable values for the rock's stress or $\{\boldsymbol{\sigma}^*\}$ are obtained in the form of Equation (8), where $[\boldsymbol{C}]$ is the inverse matrix of $[\boldsymbol{B}]$.

$$[B]\{\sigma\} = E.\{\beta^*\} \qquad (7)$$

$$\{\sigma^*\} = E.[C].[\beta^*] \qquad (8)$$

In general, the standard deviation (Σ_i) of each stress component is calculated by factoring in the amount of measurement error according to the normal distribution of Equation (9), where (Σ_β^2) is the variance of the measured strains, and (C_{ii}) is the size of the recorded strains concerning the diameter of the matrix's diagonal $[\boldsymbol{C}]$ [1].

$$\Sigma_i^2 = C_{ii}E^2\Sigma_\beta^2, \text{ i=1, 2 ,...6} \qquad (9)$$

The analysis of the least squares method described in the preceding section is valuable for determining the mean estimate of in-situ stress fields that best correspond to the measured strains. For a considerable time, the least squares method was the only method utilized in the statistical analysis of multiple sampling tests. Nonetheless, statistical methods have recently become a viable alternative. For instance, a more promising method is proposed that employs Monte Carlo analysis to determine confidence intervals for the magnitude and direction of the mean of the principal stresses from a set of stress measurements. This technique utilizes a sample of the normal probability distribution function (or pdf) estimated from several borehole measurements [7].

4. Checking Error in CCBO Method

As the existing coefficients for the conversion of strains to stresses lack an analytical solution and are based on the accuracy of numerical methods, reducing errors in this method is entirely dependent on the accuracy with which rock strains are measured at the desired points. In other words, factors such as the geometry of the borehole and conical socket, the placement of the strain gauges as well as their number and quality, the type of resin used in the probe's manufacturing, the adhesive used to connect to the rock, and the matrix conditions of the rock, such as orientation and heterogeneity, have a significant impact on the calculations.

The variance of each stress component is directly proportional to the number of measurement points, the magnitude of the $[\boldsymbol{C}]$ matrix value, as well as (Σ_β^2) variance error among the measured values of strain by strain gauges. In the CCBO method, the (C_{ii}) size or diagonal components of the $[\boldsymbol{C}]$ matrix depend on the radius of the circle of strain gauges, their number, and the rock Poisson's ratio values. In this method, the value of (C_{max}) decreases as the number of strain gauges increases. Thus, where the Poisson's ratio value for rock is equal to 0.25, the (C_{max}) value in the CCBO method is equal to the case where the strain is measured by a rosette of strain gauges in the cylindrical borehole's wall [1]. In order to increase the accuracy of the method, it is necessary to minimize the maximum (C_{max}) value from (C_{ii}) to optimize the placement order and the number of strain gauges [1].

Assuming that Σ_β^2 is fixed, we can conclude that minimizing the diagonal diameter of the $[\boldsymbol{C}]$ matrix yields the highest stress determination accuracy. In its transposition, this matrix equals the inverse of the coefficient multiplication of the $[\boldsymbol{A}]$ matrix. The $[\boldsymbol{A}]$ matrix, on the other hand, is in the $(N \times 6)$ state, which means it has six columns (corresponding to the six stress components) and N rows (Equivalent to twice the number of measurement points in the case of using strain gauges capable of measuring in two directions and equivalent to three times the number of measurement points in strain gauges capable of measuring strain in three directions).

For instance, if there are six measurement stations in two axial and tangential directions, N equals 12. Thus, the number of columns in this matrix of coefficients is always fixed, while the number of rows is variable. As an illustration, the coefficients matrix depicted in Equation (10) shows a hypothetical situation of the stations' measurement number to the extent of 360 numbers (per one degree), with six columns and 720 rows (with the assumption of two tangential and axial strains measurement at each station). The $[\boldsymbol{C}]$ matrix derived from a large coefficient matrix in this manner will have the lowest (C_{ii}) values.

For this evaluation, the authors created a program in the MATLAB software environment. This program enables the formation of the $[\boldsymbol{C}]$ matrix in various sizes, as well as the investigation and evaluation of the (C_{ii}) values for any measurement station number between 3 and 360 or more, utilizing the graphs in Fig. 6 and 7 and extracting the data related to the coefficients of Equation (10) from them. As shown in Fig. 8 and 9, as the number of measurement stations increases, supposedly from 3 to 360 stations, the (C_{ii}) values decrease from approximately, 10^{-1} order to approximately $10^{-3}$and 10^{-4}order, the measurement accuracy improves. In addition, according to Fig. 10, where the program's input is based on the coefficients' changes along the coordinates as in Fig. 7 of the ρ axis, the optimal location for measuring stations and strain gauge installation is in the middle of the lateral side of the cone, or $\rho = 0.038$.

$$A=\begin{bmatrix} A_{11}+A_{12}\cos 0\,. & A_{11}-A_{12}\cos 0\,. & C_1. & D_1\sin 0\,. & D_1\cos 0\,. & 2A_{12}\cos 0 \\ A_{21}+A_{22}\cos 0\,. & A_{21}-A_{22}\cos 0\,. & C_2. & D_2\sin 0\,. & D_2\cos 0\,. & 2A_{22}\cos 0 \\ A_{11}+A_{12}\cos 2\,. & A_{11}-A_{12}\cos 2\,. & C_1. & D_1\sin 1\,. & D_1\cos 1\,. & 2A_{12}\cos 2 \\ A_{21}+A_{22}\cos 2\,. & A_{21}-A_{22}\cos 2\,. & C_2. & D_2\sin 1\,. & D_2\cos 1\,. & 2A_{22}\cos 2 \\ A_{11}+A_{12}\cos 4\,. & A_{11}-A_{12}\cos 4\,. & C_1. & D_1\sin 2\,. & D_1\cos 2\,. & 2A_{12}\cos 4 \\ A_{21}+A_{22}\cos 4\,. & A_{21}-A_{22}\cos 4\,. & C_2. & D_2\sin 2\,. & D_2\cos 2\,. & 2A_{22}\cos 4 \\ & & \vdots & & & \\ A_{11}+A_{12}\cos 720\,. & A_{11}-A_{12}\cos 720\,. & C_1. & D_1\sin 360\,. & D_1\cos 360\,. & 2A_{12}\cos 720 \\ A_{21}+A_{22}\cos 720\,. & A_{21}-A_{22}\cos 720\,. & C_2. & D_2\sin 360\,. & D_2\cos 360\,. & 2A_{22}\cos 720 \end{bmatrix} \quad (10)$$

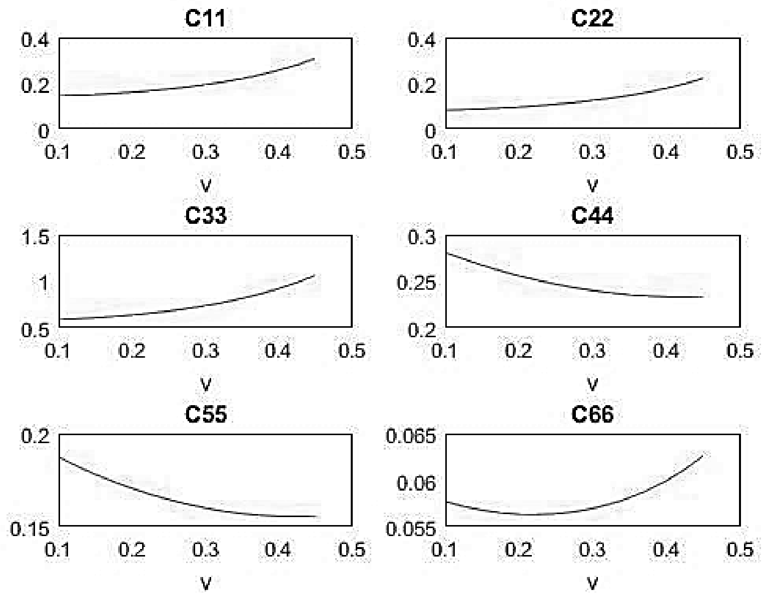

Fig. 8 - C_{ii} values for conical-ended borehole and three measuring stations for different amount of Poisson's ratio

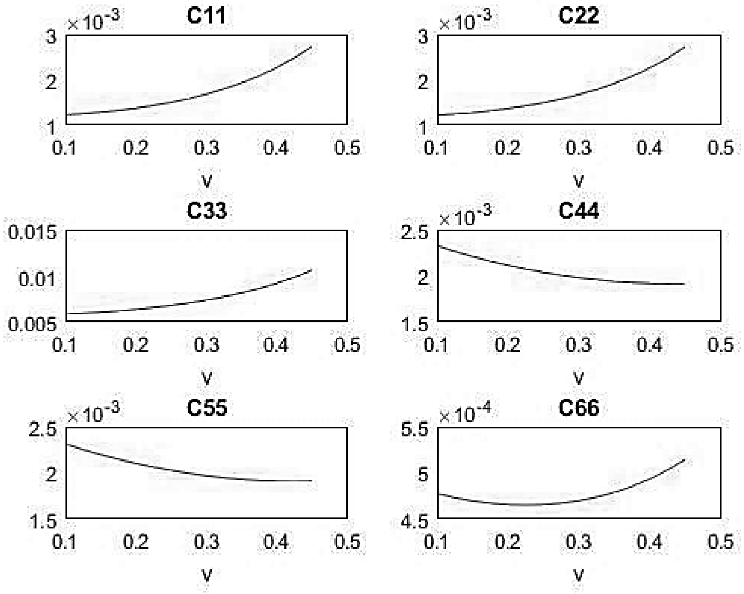

Fig. 9 - C_{ii} values for conical-ended borehole and 360 measuring stations for different amount of Poisson's ratio

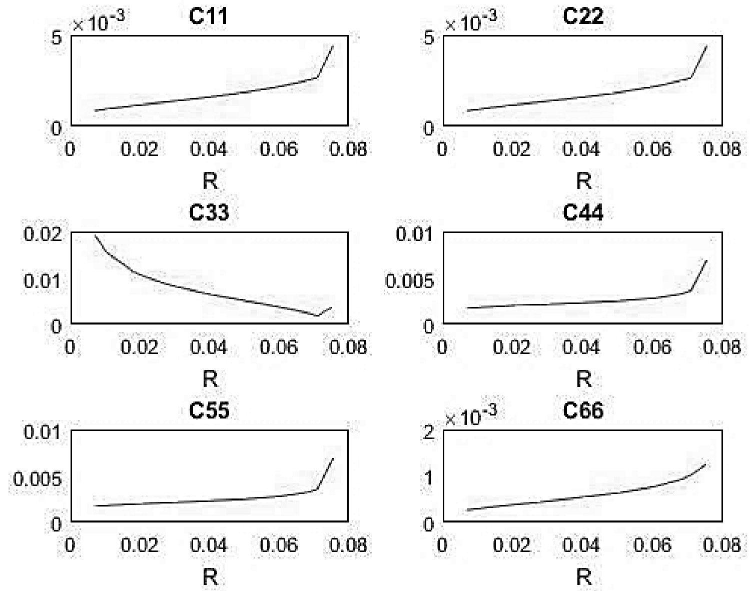

Fig. 10 - C_{ii} values for a conical-ended borehole according to the changes in the value of ρ from zero to 0.076 meters

5. Determination of the Rock's Matrix Mechanical Parameters, Using the In-Situ Method

Young's modulus and Poisson's ratio are also required to calculate the strain stress tensor components, as mentioned in the CCBO method review. There are two ways to calculate these values. The first involves conducting laboratory tests on the drilling core, and the second involves loading the rock in situ using a metal ring and measuring the resulting strains with a probe. Typically, the laboratory procedure is utilized, and the second procedure is only used to verify the laboratory values' accuracy.

The laboratory experiment involves multistage uniaxial loading, and it is necessary to calculate the rock's elasticity, nonlinear behavior, and anisotropy [1]. In the laboratory method, as illustrated in Fig. 11, three cylindrical pieces with dimensions of 25×50 mm are extracted from the drilling core using a drill. Then, by installing four strain gauges along their length and performing a multistage uniaxial test, the maximum strain measured by the in-situ cell is attempted to be reached. The samples are then computed based on the applied stress, the measured strain, and the linear relationship between Young's modulus and Poisson's ratio [8].

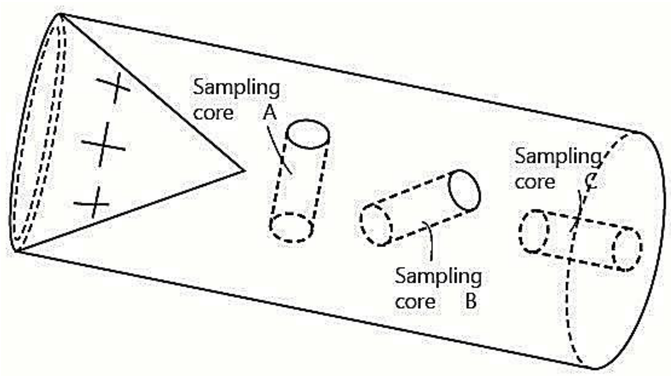

Fig. 11 - Overcoring examples used for laboratory uniaxial compression testing [8]

During in-situ loading, a metal ring similar to fig. 12, a flat ring with a width of 6 mm, is placed in the borehole while the cell and strain gauges are fully engaged with the rock via an adhesive. By applying P axial pressure to it, the relationship between pressure changes and resulting strains is studied, and Young's modulus and Poisson's ratio values of rock can then be calculated using special charts derived from BEM analysis [1].

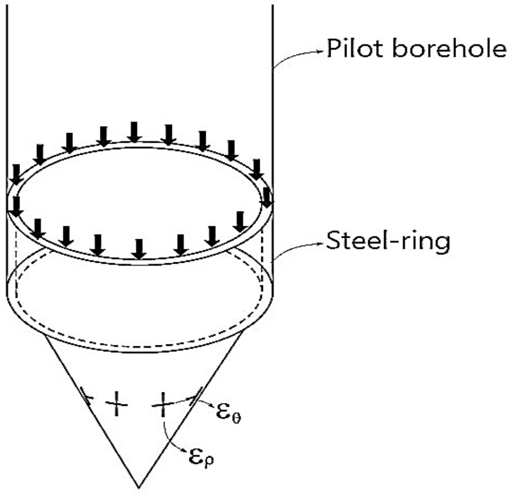

Fig. 12 - Schematic representation of in-situ axial loading for estimating rock mechanical parameters

5.1 Numerical Analysis for In-Situ Estimation of Poisson's Ratio

According to the innovators of the CCBO method, it is possible to evaluate the elasticity modulus of rock in situ using this probe and a specific metal ring by applying force, as mentioned in the introduction. However, the article's authors attempted to conduct research based on this concept by numerically simulating the force application process using COMSOL finite element software to determine Poisson's rock ratio. With the assumption that the rock's matrix is homogeneous and isotropic concerning various mechanical parameters, a software model resembling Fig. 13 was developed. The loading process was then simulated, as depicted in Fig. 14, and the radial and axial strain values on the conical surface of the probe were recorded at six measuring stations.

According to the findings of these studies, for each value of the modulus of elasticity of rock and each value of the applied force P, there is always a constant relationship between the value of $\varepsilon_\theta/\varepsilon_\rho$ ratio and Poisson's ratio of rock, ranging from 0.1 to 0.4, as depicted in Fig. 15's diagram. Notably, In the homogeneous and isotropic state of the rock and when applying a homogeneous and uniform force by the metal ring, the value of the $\varepsilon_\theta/\varepsilon_\rho$ ratio is always a fixed number in all strain measurement stations; therefore, only one station's data can be used to estimate the value of the rock matrix Poisson's ratio. In addition, it is evident from this evaluation that if $\varepsilon_\theta/\varepsilon_\rho$ ratio values are unequal in different stations, it can be predicted that the sampled rock demonstrates conditions such as anisotropy and heterogeneity.

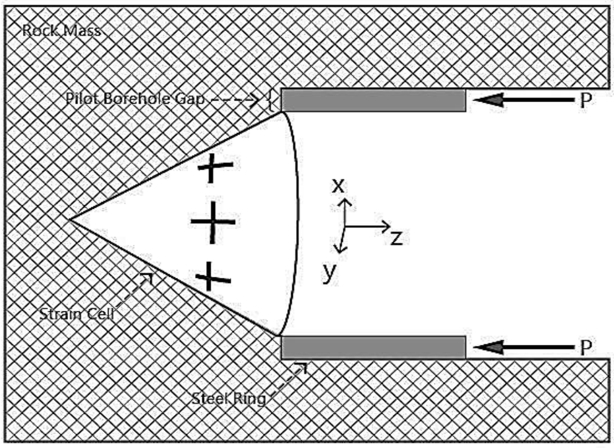

Fig. 13 - Schematic illustration of in-situ axial loading for estimating rock mechanical parameters

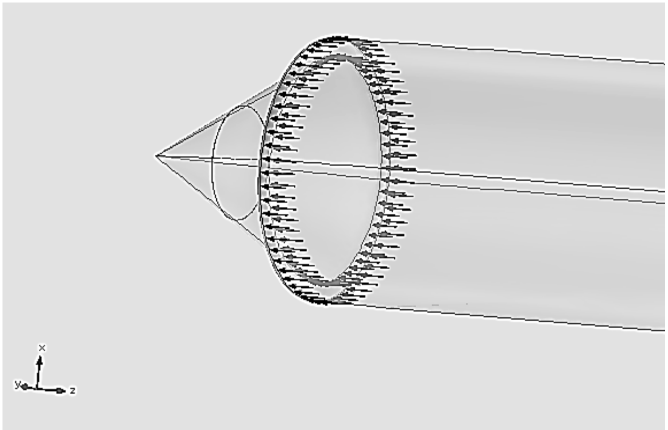

Fig. 14 - Metal ring loading and numerical evaluation of mechanical parameters using COMSOL finite element software

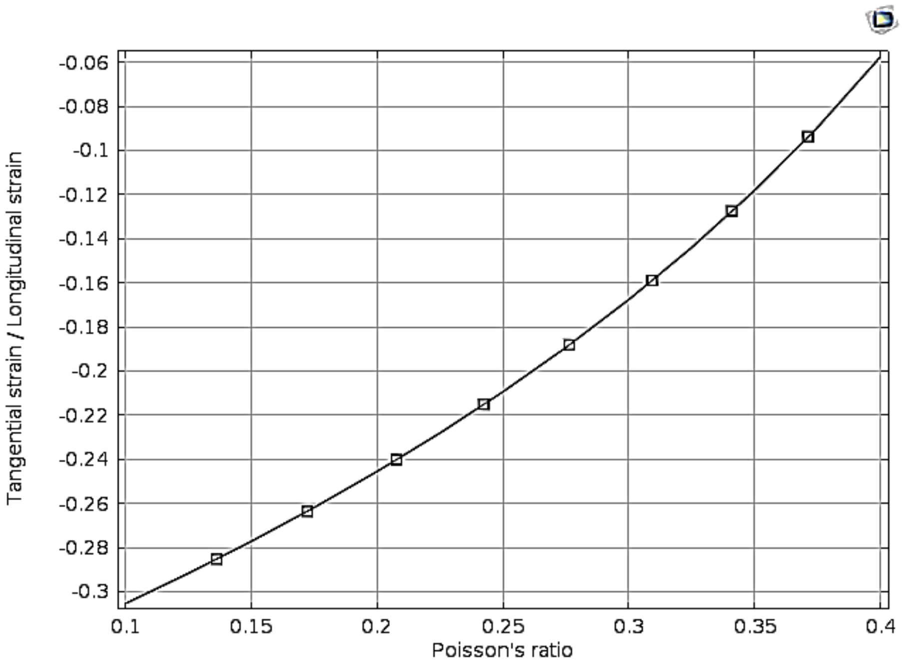

Fig. 15 - The relationship between $\varepsilon_\theta/\varepsilon_\rho$ and Poisson's rock ratio in any value of rock's elastic modulus and *P* applied force

5.2 Numerical Analysis for In-Situ Estimation of Elasticity Modulus

Using COMSOL finite element software, the authors of this article attempted to estimate the modulus of elasticity of rock through numerical simulation of the force application process. As shown in Fig. 13, the software created a model based on the assumptions of rock matrix homogeneity and isotropy for various types of mechanical parameters. Then, the loading process, as depicted in Fig. 14, was simulated, and the strain values on the conical surface of the probe were recorded at six radial and axial measuring stations. Because the amount of recorded strain in these simulations varied with all three variables of applied force, Poisson's ratio, and the rock's elasticity modulus, as shown in Fig. 16, attempts were made to draw 3D diagrams of the strain's simultaneous changes in radial and tangential stations, in different Poisson's ratios of rock, along with changes in the modulus of the rock's elasticity ranging from 10 to 210 Gpa and changes in the applied force ranging from 5 KN to 55 KN.

Then, using curve fitting in MATLAB software's Polynomial method, as depicted in Fig. 17, a polynomial relationship of the fourth degree, identical to Equation (11), was extracted with exactitude. To this end, the coefficients $P00, P10, P01$, and... $P04$ can be derived from Table 2 based on the axial or radial strain type and different values of Poisson's ratio. Notable in Equation (11) is that the term $f(x, y)$ corresponds to the amount of compressive force applied by the metal ring, y is the measured strain in radial or tangential strain gauges after applying the force, and x corresponds to the elasticity modulus of rock and is the unknown criterion. According to the assumption of isotropy and homogeneity of the rock in this analysis, all tangential and axial strains have identical results and can be used at all measurement stations.

$$\begin{aligned} f(x,y) = P00 + P10 \times x + P01 \times y + P20 \times x^2 + P11 \times x \times y \\ +P02 \times y^2 + P30 \times x^3 + P21 \times x^2 \times y \\ +P12 \times x \times y^2 + P03 \times y^3 + P40 \times x^4 \\ +P31 \times x^3 \times y + P22 \times x^2 \times y^2 \\ +P13 \times x \times y^3 + P04 \times y^4 \end{aligned} \tag{11}$$

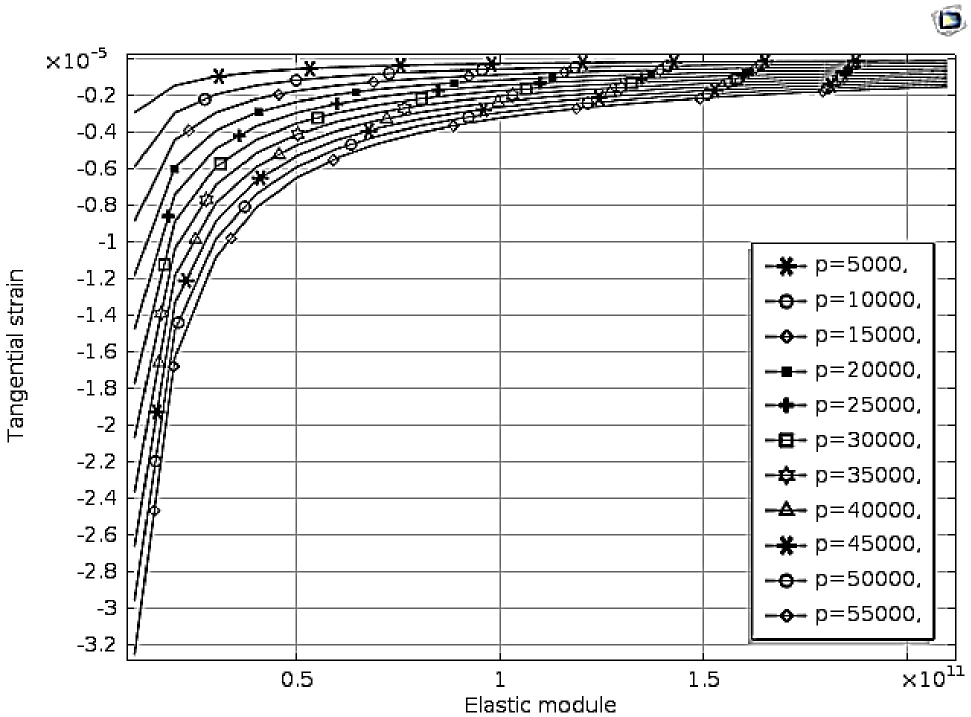

Fig. 16 - Output diagram of numerical analysis in COMSOL software for estimating the in-situ elasticity modulus by applying pressure by a metal ring and measuring tangential strains in the $\theta = 0$ measuring station of the CCBO probe with the Poisson's ratio of rock equal to 0.3

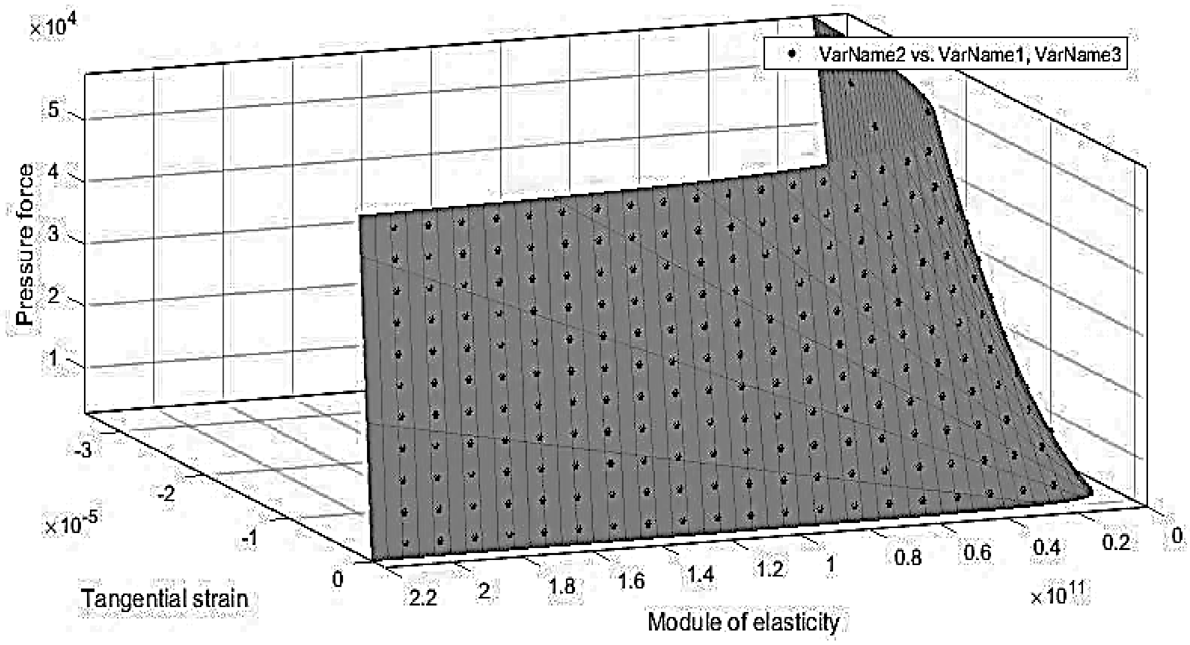

Fig. 17 - Curve fitted to numerical analysis results in MATLAB software for estimating in-situ elasticity modulus by applying pressure by a metal ring and collecting tangential strains in $\theta = 0$ measuring station of the CCBO probe with rock's Poisson's ratio equal to 0.3

Table 2- Rock's in-situ elasticity modulus coefficients at various Poisson's ratio values

coefficients	ϑ=0.1		ϑ=0.2		ϑ=0.3		ϑ=0.4	
	T	L	T	L	T	L	T	L
P00	5.728e+04	5.728e+04	5.728e+04	5.728e+04	5.728e+04	5.728e+04	5.728e+04	5.728e+04
P10	3.16e+04	3.16e+04	3.16e+04	3.16e+04	3.16e+04	3.16e+04	3.16e+04	3.16e+04
P01	-8.568e+04	8.568e+04	-8.568e+04	8.568e+04	-8.568e+04	8.568e+04	-8.568e+04	8.568e+04
P20	-5.779e-10	8.003e-09	3.084e-09	-5.809e-10	-1.083e-08	-1.416e-08	-2.521e-08	1.814e-08
P11	-4.727e+04	4.727e+04	-4.727e+04	4.727e+04	-4.727e+04	4.727e+04	-4.727e+04	4.727e+04
P02	1.195e-08	1.315e-08	1.624e-09	-1.725e-09	1.288e-09	-5.633e-09	1.533e-08	1.225e-08
P30	-2.161e-09	1.775e-09	-2.522e-10	4.36e-09	-9.125e-09	-4.472e-09	2.184e-08	3.929e-09
P21	-7.101e-09	1.869e-08	4.984e-09	8.319e-09	2.8e-08	-1.518e-08	-2.685e-08	1.457e-08
P12	2.168e-08	3.998e-08	-1.891e-08	1.114e-09	-4.197e-09	-1.3e-08	-9.866e-09	6.14e-09
P03	-7.979e-09	1.252e-08	1.67e-08	-1.532e-08	4.719e-09	-3.178e-09	6.323e-08	-9.848e-09
P40	7.061e-10	-1.739e-09	-7.287e-10	2.172e-09	-2.698e-09	2.817e-09	1.763e-08	-4.107e-09
P31	3.046e-09	2.116e-09	1.885e-10	1.286e-08	1.305e-08	-1.136e-09	-2.464e-08	5.994e-10
P22	8.681e-09	2.001e-08	-1.203e-08	6.609e-09	-9.578e-10	-3.431e-09	-1.127e-08	-3.134e-09
P13	-4.841e-09	8.019e-09	1.021e-08	-7.129e-09	1.752e-09	-1.081e-09	3.83e-08	-6.829e-09
P04	2.071e-12	6.108e-11	-1.639e-11	2.799e-10	1.661e-10	9.629e-11	1.102e-11	-1.03e-10
SSE	1.001e-14	1.112e-14	1.527e-14	1.478e-14	4.049e-14	1.061e-14	8.08e-13	2.73e-14
RMSE	6.806e-09	7.174e-09	8.409e-09	8.272e-09	1.369e-08	7.01e-09	6.116e-08	1.124e-08
R-square	1	1	1	1	1	1	1	1

T = tangential strain from strain gauges on probe
L = longitudinal strain from strain gauges on probe
SSE = The sum of squares due to error
RMSE = Root mean squared error
R-square = the square of the multiple correlation coefficient

6. Conclusion

An overcoring technique based on the continuous conical end borehole method, or CCBO is an accurate, efficient, and dependable method for measuring the three-axis state of in situ stresses in jointed or faulted rock masses. Because the maximum advancement of the drill bit in this method for over coring is 10 cm, it can also be used in highly jointed rocks, which is one of its advantages. This method can also be used for monitoring. The probe's conical shape makes it simple to use and install and measures strain in multiple directions.

The small size of the measuring cone makes it easy to relieve stress on the probe, and if an optical data transmission system is used, the placement of the data transmission cable during drilling for overcoring is facilitated, and the measurement socket is not moved due to the weight of the equipment. This method is quick to install and does not necessitate using a drill with a larger diameter than the probe's diameter for overcoring. Its production is low-cost, and the small probe makes it simple to remove it from the rock mass stress.

Clearly, this method has some drawbacks, including 1. The coefficients used in the final formula for calculating in-situ stresses can only be evaluated numerically and have no analytical solution; 2. This method exhibits a small error; in its theory, additional computational tools such as the least squares method are used to reduce this error; 3. Using glue to connect the strain gauges to the rock requires specific conditions (absence of water and joints in the installation site's conical socket) and can result in large measurement errors; 4. This method is appropriate for shallow depths and tunnel walls, and its application in deep depths is being researched.

This article introduced and evaluated this tool, and the accuracy of this method was evaluated using numerical methods, including COMSOL Multiphysics software. The results show that the device's accuracy is directly related to the number of measuring stations (strain gauge) installed on it, and increasing them from 3 to 15 increases measurement accuracy by approximately 75%. In addition, an examination of the sensor installation coordinates revealed that the optimal location for installing the strain gauges is in the middle of the conical probe's lateral length ($\rho = 0.036$) meters. Furthermore, because this probe can measure the in-situ rock modulus, the possibility of measuring the mechanical parameters of the rock matrix in-situ using numerical analysis was investigated.

According to the results of the analysis, several diagrams were created for the in-situ calculation of the Poisson's ratio of rock in order to develop the concept of loading rock in-situ, as well as to evaluate and calculate the elasticity modulus of rock in different conditions of ring loading and Poisson's ratio of rock; a formula was introduced with great accuracy, which can be used as a tool for checking the anisotropy or heterogeneity of the rock. Finally, the authors hope that by presenting the findings of this research, other researchers will conduct future field studies on the development of the CCBO method. While this method is still in development, it can always be used as an accurate and inexpensive tool in geotechnical projects.

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