

Oleksandr Krukovskyi¹, <https://orcid.org/0000-0002-2659-5095>**Dmytro Vasyliiev**¹, <https://orcid.org/0000-0001-6864-357X>**Viktor Serhiienko**^{1,*}, <https://orcid.org/0000-0002-7374-0654>**Denys Kress**¹, <https://orcid.org/0009-0001-9504-5695>¹M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine, Dnipro, Ukraine*Corresponding author e-mail: viictorms@ukr.net

OBTAINING COMPLETE STRESS-STRAIN CURVES DURING TESTING OF ROCK SPECIMENS UNDER INDUSTRIAL CONDITIONS

Abstract. Long-term operation of underground structures under conditions of high rock pressure necessitates prediction of the state of rocks as they approach the strength limit and after this limit has been reached. Such prediction can be performed by analyzing complete stress-strain curves, which characterize pre-peak deformation, post-peak behavior, the post-peak failure modulus, and residual strength. These characteristics are important for assessing the stability of underground excavations, selecting support parameters, and predicting brittle or gradual rock failure. Standard methods for obtaining complete stress-strain curves usually require specialized laboratories and stationary testing equipment, which increases the duration and cost of testing and limits the possibility of promptly adjusting the testing program at an industrial site.

A method is proposed for obtaining complete stress-strain curves during testing of rock specimens under industrial conditions. The method involves the use of press equipment available at the enterprise, a mobile strain-gauge compressive force measuring device, a longitudinal deformation indicator, and synchronous video recording of the measuring instrument readings. This approach makes it possible to perform tests without equipping the press with a standard automated system for recording load and deformation. Frame-by-frame processing of the video recording is used to form a data array of "longitudinal deformation - compressive force" pairs and to calculate the corresponding values of relative deformation and compressive stress. The obtained data are used to construct the complete stress-strain curve and determine the main mechanical and deformation characteristics of the specimen. The applicability of the method is illustrated by tests of cylindrical gypsum specimens with different height-to-diameter ratios. It is shown that a decrease in this ratio increases the influence of contact friction between the specimen and the press plates, whereas an increase in the ratio changes the failure pattern from gradual failure with a smooth post-peak decline to pronounced brittle failure with an intense post-peak loss of bearing capacity. To reduce the influence of specimen geometry and contact friction, it is recommended to use specimens with a height-to-diameter ratio of not less than 2.

Keywords: rock specimen, destructive testing, uniaxial compression, stress-strain curve.

1. Introduction

For calculating the parameters of underground structures, the characteristics of rocks obtained over a wide range of loads are of considerable importance. The most effective way to determine them is to analyze complete stress-strain curves [1–4]. Obtaining these curves requires a rigid testing machine with control of the specimen loading rate and devices for measuring the compressive force applied to the specimen and its deformation. Various types of testing equipment are described in [5]. To determine the force, rigid elastic structures of special shape with strain gauges attached to them, together with the corresponding set of electronic equipment, are traditionally used. The most accurate method for determining specimen deformation involves bonding strain gauges directly to its surface and measuring changes in their resistance under compressive loading [6]. The advantage of this method is the possibility of measuring deformation only in the central part of the specimen, where the stress distribution approaches a uniform state. This approach is effective for determining Young's modulus, but it does not allow the development of specimen deformation after reaching the strength limit to be tracked because of strain gauge failure. More



widely used are schemes in which strain-gauge extensometers are arranged parallel to the specimen to determine vertical deformation [7]. Their main advantage is the possibility of repeated use, while their disadvantage is the need to correct deformation values caused by the rotation of one of the press plates during the failure of high-strength specimens.

In modern testing machines, the current values of the compressive force acting on the specimen, as well as its deformation, are recorded automatically, with the obtained data stored in digital form [8]. Taking into account the geometric dimensions of the specimen, the obtained digital array is converted into an array of paired values of stress and relative deformation. A stress-strain curve is then constructed. The static Young's modulus is determined from the rising branch of the stress curve. Approaches to its calculation are presented in [9, 10]. An analysis of errors in determining Young's modulus based on stress-strain curves is given in [11]. The ability of a rock to undergo plastic or brittle failure is determined by the shape of the curve after the strength limit has been reached [12–14]. A quantitative characteristic of the risk of rapid specimen failure is the value of the post-peak failure modulus [15]. In some cases, the residual strength of the rock is also of significant importance [16]. Experimental studies of the post-peak deformation of strong rocks presented in [17] show that the post-peak failure modulus, residual strength, and scale effect are of considerable importance when assessing the stability of excavations at great depths.

In modern studies, complete stress-strain curves are considered not only as a source of strength and elastic modulus values, but also as a basis for analyzing post-peak behavior, brittleness, energy characteristics of failure, and the ability of rock to retain residual bearing capacity. In particular, studies [1–4, 12–14] show that the shape of the post-peak branch depends significantly on the lithological type of rock, specimen structure, loading conditions, and the stiffness of the testing machine. Studies of gypsum and gypsum-like materials [18, 19] are of particular interest, since these materials are characterized by a pronounced dependence of the deformation curve shape on the structural state of the specimen, moisture content, the presence of weaknesses, and loading conditions. This makes such materials convenient for demonstrating methodological approaches to obtaining complete stress-strain curves and analyzing post-peak failure.

The simplest case is obtaining a stress-strain curve under uniaxial compressive loading. However, even in this case, stationary equipment is used. Conducting tests in specialized institutions significantly increases the time required to perform them and also raises the cost. In addition, prompt adjustment of the research plan for studying rock properties becomes impossible.

The aim of this work is to develop a method for obtaining stress-strain curves directly under industrial conditions.

2. Methods

The method involves the integrated use of press equipment available at the enterprise and a mobile measuring system that can be delivered to the test site. A prerequisite for applying the method is the availability of press equipment at the enterprise.

Continuous monitoring of the compressive force is not mandatory. However, the upper limit of the operating load range of the press should exceed the expected maximum compressive force applied to the specimen by a factor of three or more. Increasing this ratio makes the testing system more rigid. An increase in the stiffness of the testing system reduces the uncontrolled release of elastic energy accumulated in the press elements and improves the stability of recording the post-peak branch of the stress-strain curve. As a result, the loss of bearing capacity, the post-peak failure modulus, and the transition from gradual to brittle failure of the specimen can be recorded more accurately.

The method is primarily intended for cylindrical specimens prepared from core material, since this shape is the most common in the practice of uniaxial compression testing of rocks and allows the cross-sectional area to be determined directly. Provided that the loading surfaces are plane-parallel and the cross-sectional area can be correctly determined, the methodological approach can also be adapted for specimens of other geometries; however, the obtained results will require separate consideration of the influence of specimen shape.

Preparation of cylindrical specimens is the simplest option. It requires only dividing the core into separate sections by parallel cuts, followed by grinding of the end faces. Within the proposed method, a specimen height-to-diameter ratio of $H/D = 2$ is adopted as the basic value. This ratio is not considered universally optimal for all rocks; however, it represents a compromise for industrial conditions, since it reduces the influence of contact friction compared with low-height specimens and, at the same time, does not create excessive difficulties in specimen preparation, centering, and loading. For more accurate determination of deformation characteristics, it is advisable to use the range $H/D = 2-3$, which is consistent with international recommendations [20–22].

For cutting the core, a cut-off machine intended for metal workpieces can be used. The standard cutting wheel is replaced with a diamond blade. A surface grinding machine is used for grinding the end faces.

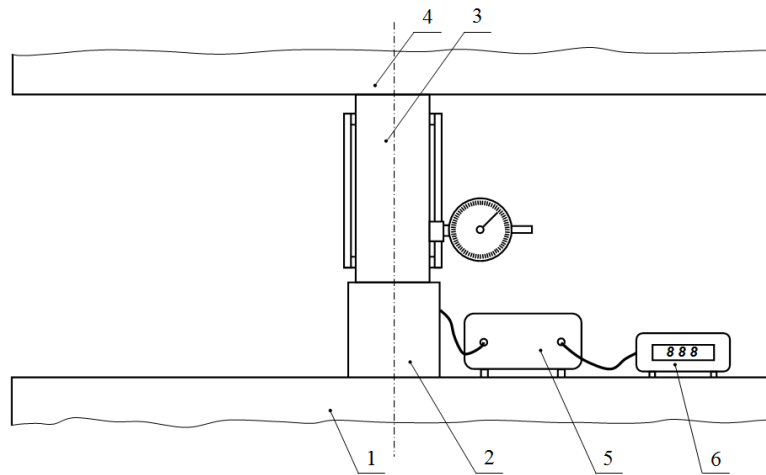
After the prepared specimens are obtained, their height H and diameter D are measured. The geometric dimensions of the specimens are determined using linear measuring instruments with an accuracy of 0.1 mm. The cross-sectional area of the specimen, S , is then calculated.

The basic element of the mobile system is an electronic compressive force measuring device. The force is transmitted to a cylindrical steel elastic element made of structural steel with high stiffness and elastic behavior within the range of applied loads. Strain gauges are bonded to the middle part of the cylindrical surface of the element and connected in a bridge circuit. The bridge is powered by an electronic unit, which also amplifies the bridge unbalance signal that occurs when the element is loaded. A digital voltmeter is used to display the measurement result.

A mechanical reference dynamometer is used to calibrate the compressive force measuring device. The calibration scheme is shown in Fig. 1.

In the simplest version, the longitudinal deformation of the specimen is measured using a dial indicator. The choice of this instrument is explained by the linearity of its

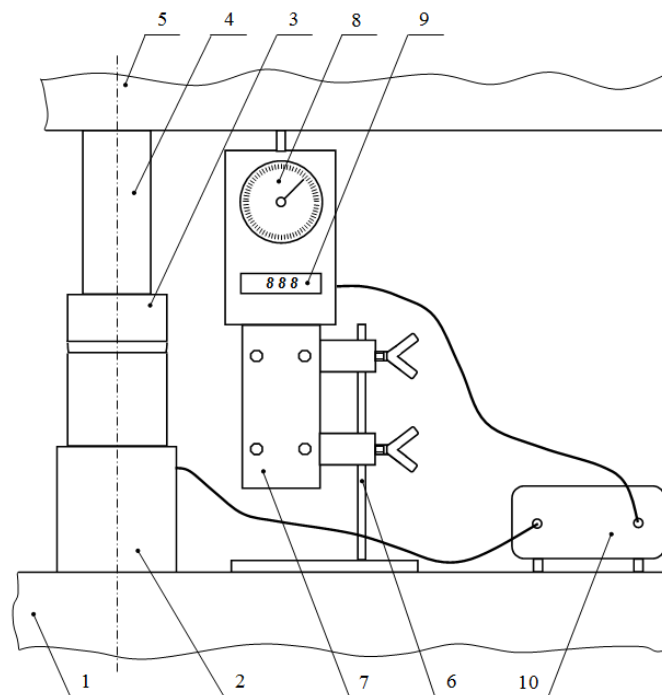
scale over a wide range, its availability and low cost, and its readiness for operation without preliminary warm-up. To improve data recording conditions, it is placed on a movable platform together with a digital voltmeter displaying the compressive force value.



1 – lower press plate; 2 – steel elastic element with strain gauges; 3 – reference dynamometer; 4 – upper press plate; 5 – electronic unit; 6 – digital voltmeter

Figure 1 – Arrangement of equipment for calibrating the compressive force measuring device

Installation of the mobile system between the plates of the stationary press is illustrated in Fig. 2.



1 – lower press plate; 2 – steel elastic element with strain gauges; 3 – spherical support; 4 – rock specimen; 5 – upper press plate; 6 – stand; 7 – movable platform; 8 – dial indicator; 9 – digital voltmeter; 10 – electronic unit

Figure 2 – Layout of the equipment for specimen testing

The individual equipment components are installed as follows. The steel elastic element 2 with strain gauges is placed at the center of the lower press plate 1. Along its vertical axis, the spherical support 3 and the rock specimen under investigation 4 are installed in sequence. The upper press plate 5 is brought into tight contact with the upper end face of the rock specimen, but without applying compressive force. A stand 6 with a movable platform 7 is placed next to the specimen; a dial indicator 8 and a digital voltmeter 9 are mounted on the platform. The connector on the steel elastic element 2 is connected to the electronic unit 10 to supply a stable voltage to the strain-gauge bridge circuit and to amplify the bridge unbalance signal. The platform 7 is positioned so that it lies in the same plane as the center of the plates or, if this is not possible, is shifted slightly toward the front. During adjustment, it is moved vertically until the contact rod of the indicator touches the upper plate. The achieved position is fixed with two side screws. The initial position of the indicator pointer is taken as the zero value of longitudinal displacement. The output of the electronic unit is connected to the input of the digital voltmeter.

A 4K video camera is mounted on a tripod at a distance of 1.5–2.0 m from the specimen. The field of view should include the rock specimen, the dial indicator, and the digital voltmeter. For the tests presented, a recording rate of 5 frames per second was sufficient. For brittle high-strength rocks or rapid post-peak failure, the recording rate should be increased. The dial indicator is the critical element during video recording. To achieve high image clarity, it is illuminated by an LED system. During a trial camera run, the uniformity of illumination of the circular scale of the dial indicator and the image sharpness are checked to ensure clear visualization of the indicator divisions. The appearance of the image at the initial stage of testing, before loading is applied to the specimen, is shown in Fig. 3.

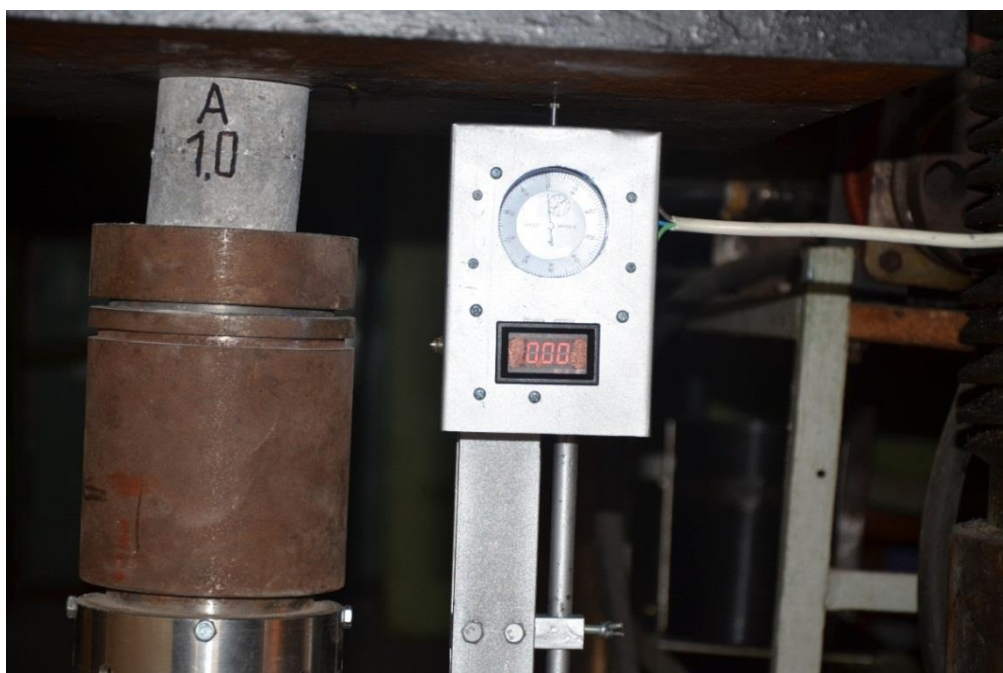


Figure 3 – Image of the rock specimen and measuring instruments before starting the press

To compensate for residual non-parallelism of the specimen end faces, an initial load of approximately 10% of the expected failure load is applied to the specimen. Owing to the presence of the spherical support, both end faces of the specimen come into full-area contact with the compressive elements. At the same time, the spherical support of the press itself, having much higher stiffness, does not respond to this load by changing the relative position of the plates. Due to the adaptive action of the additional spherical support, this position remains unchanged during subsequent loading. The pressure on the specimen is reduced until the voltmeter reading reaches zero, while preventing a gap from forming between the specimen and the upper press plate. After this procedure, the zero reference value of longitudinal displacement is reset if necessary.

The video camera is switched on, and loading of the specimen is started. The recommended load increase per second is 2–5% of the expected failure load. After the failure load is reached, the deformation value is monitored. If the vertical deformation exceeds half of the working range of the indicator, further loading of the specimen is stopped to prevent damage to the indicator. The specimen is then smoothly unloaded until a zero reading appears on the digital voltmeter. The video camera is switched off. The remains of the failed specimen are removed, and the surfaces of the upper plate and the spherical support with which it was in contact are thoroughly cleaned. The next specimen is then prepared for testing.

Data processing involves constructing a stress-strain curve and determining the basic mechanical and deformation characteristics of the rock on its basis. Assessment of the appearance of the failed specimen makes it possible to classify it as a certain type of failure.

Construction of the stress-strain curve is carried out in several stages. At the first stage, the range of the maximum achieved deformation is divided into 20–30 equal intervals. A larger number of intervals adds practically no additional information but significantly increases the duration of data processing. Frames corresponding to the interval boundaries are selected. The values of absolute longitudinal deformation and the corresponding compressive force are recorded. Taking into account the specimen dimensions, the relative longitudinal deformation ε and the corresponding compressive stress σ are calculated.

The first version of the graphical relationship between the current compressive stress σ and the current relative longitudinal deformation of the specimen ε is then constructed. Due to the different inclinations of the curve segments relative to the horizontal axis, their lengths may differ significantly. To construct the next version of the curve, the deformation interval is reduced for sections with a rapid change in compressive stress. By successive approximations during curve construction, approximately equal lengths of curve segments between adjacent points are achieved.

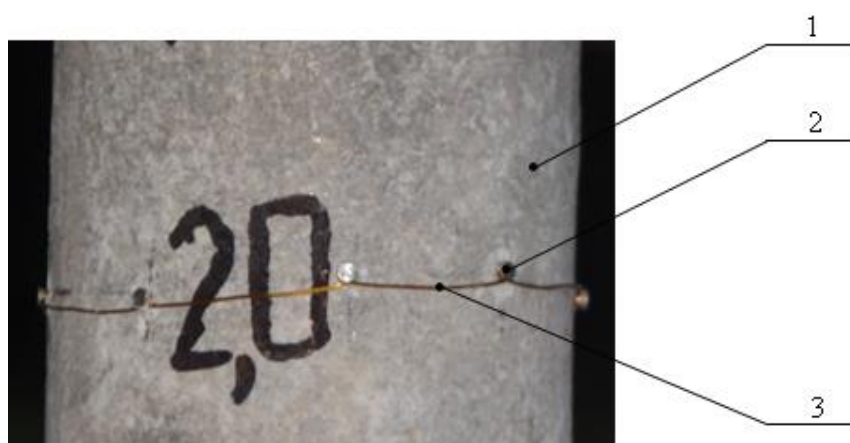
The video file is viewed in slow motion, and the maximum value of the compressive force and the corresponding value of longitudinal deformation are recorded. The recalculated values of compressive stress and relative deformation are added to the data array to construct the final version of the stress-strain curve. The corresponding point of the curve determines the uniaxial compressive strength σ_c and the critical

strain ε_{cr} . The ratio of the increase in rising stress to the corresponding increase in relative deformation on the linear section of the curve determines the static Young's modulus E_{st} . The ratio of the stress drop to the increase in relative deformation on the linear section of the curve after the strength limit has been reached determines the post-peak failure modulus M . If $M > E_{st}$, this indicates the possibility of unstable post-peak failure with a sharp loss of bearing capacity, rapid crack development, and specimen fragmentation. If the compressive stress stabilizes with increasing deformation, the residual strength of the rock σ_{res} can be determined.

The method is most suitable for rocks and model materials with a relatively smooth deformation behavior, as well as for testing machines whose stiffness allows the post-peak branch of the curve to be controlled. For brittle high-strength rocks, the accuracy of recording the post-peak decline depends on the stiffness of the press, the loading rate, the video recording frequency, and the inertia of the measuring instruments.

3. Results and discussion

The described method was used to determine the mechanical and deformation characteristics of gypsum specimens taken from a deposit in the Donetsk region of Ukraine. To demonstrate the capabilities of the method, the results of destructive tests of model gypsum specimens in the form of a circular pillar with a height-to-diameter ratio of 2:1 are presented. The first model was a monolithic gypsum cylinder. In the central part of the second model, reinforcement was installed in the form of eight anchors, the length of which was 15% of the specimen diameter. The anchors were uniformly arranged in a circle and connected into a system by means of a circular tie. The structure of the reinforced model is illustrated in Fig. 4.



1 – gypsum cylinder; 2 – anchors; 3 – circular tie

Figure 4 – View of the central part of the model gypsum pillar with rock-bolt reinforcement and a circular tie

The stress-strain curves for the models are shown in Figs. 5.

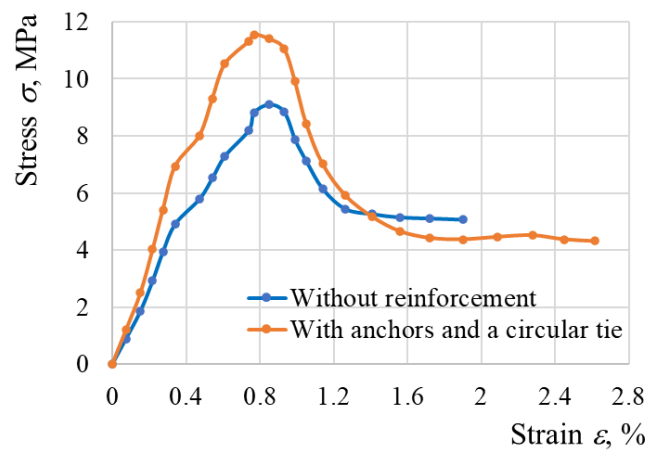


Figure 5 – Stress-strain curves for cylindrical gypsum pillar models with and without reinforcement

The comparative mechanical and deformation characteristics for both models are given in Table 1.

Table 1 – Mechanical and deformation characteristics of the gypsum pillar models

Characteristic	Model without reinforcement	Model with reinforcement
Uniaxial compressive strength σ_c , MPa	9.1	11.6
Residual strength σ_{res} , MPa	5.1	4.2
Critical strain ϵ_{cr} , %	0.84	0.77
Static Young's modulus E_{st} , GPa	1.37	2.40
Post-peak failure modulus M , GPa	0.95	2.25

The experimental results show that the presence of reinforcement increases the stiffness of the model. In addition, the uniaxial compressive strength also increases.

As the specimen height-to-diameter ratio changes, the failure pattern also changes. For specimens with height-to-diameter ratios of 0.5 and 1.0, fragmentation of the specimen into small pieces with a chaotic crack orientation is typical. At ratios of 2.0 and higher, division of the specimen into several separate parts oriented along its axis is clearly observed. Different failure patterns are shown in Fig. 6.

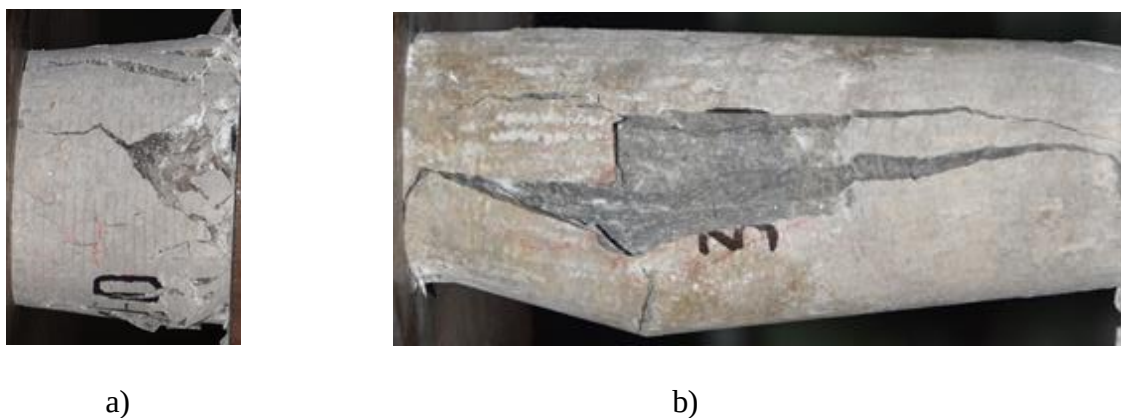


Figure 6 – Change in the failure pattern with increasing specimen height-to-diameter ratio:
a) at a ratio of 1.0; b) at a ratio of 3.0

A tendency toward acceleration of specimen failure after reaching the strength limit was established as the height-to-diameter ratio increased. The failure process of low-height specimens with a height-to-diameter ratio of 1.0 or less is slowed down due to the significant influence of friction between the specimen surfaces and the press plates. The post-peak branch of the stress-strain curve is gentle, with a smooth transition to residual strength. The post-peak failure modulus M has a low value, and its ratio to the static Young's modulus E_{st} is significantly less than unity. The specimen fails gradually, without dynamic effects. In this work, dynamic manifestations of failure are understood as an unstable loss of specimen bearing capacity after reaching the strength limit, accompanied by a sharp load drop, rapid crack development, and specimen fragmentation. With a significant increase in specimen height, the process of transverse deformation in the central part of the specimen is no longer restrained by friction between the specimen and the press plates, which causes the rapid development of vertical cracks dividing the specimen into separate blocks. The rapid loss of bearing capacity leads to a formal increase in the post-peak failure modulus, and its ratio to Young's modulus also increases. This increases the probability of unstable post-peak specimen failure. This probability increases significantly for high-strength specimens due to the large amount of elastic energy accumulated during compression. In addition, when the stiffness of the testing machine is low, the elastic energy accumulated in the testing machine itself is also consumed in specimen failure.

The described tendency is illustrated in Fig. 7.

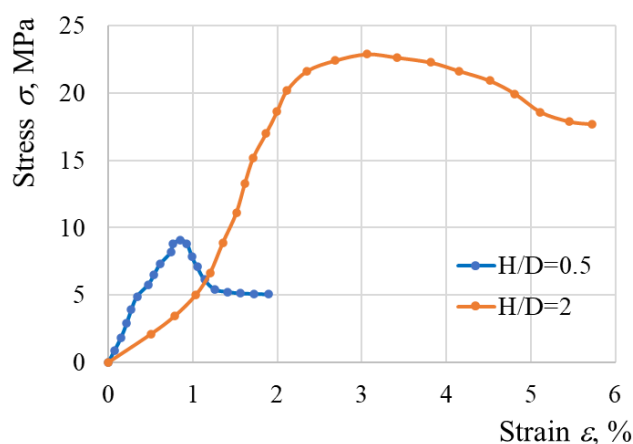


Figure 7 – Comparison of stress-strain curves for cylindrical gypsum specimens with different height-to-diameter ratios

The experimental results show that, when the same testing machine is used, the plastic or brittle nature of failure upon reaching the strength limit depends not only on the rock type but also on the specimen shape. The dynamics of changes in the post-peak failure modulus for gypsum specimens with an increasing height-to-diameter ratio are illustrated by the data given in Table 2.

The research results presented in Table 2 indicate a general tendency for the post-peak failure modulus to increase with an increase in the specimen height-to-diameter ratio (Fig. 8).

Table 2 – Values of the post-peak failure modulus for cylindrical gypsum specimens with different height-to-diameter ratios

Height-to-diameter ratio H/D	0.5	1.0	1.5	2.0	2.5	3.0
Post-peak failure modulus M , GPa	0.2	0.2	1.1	0.7	2.9	9.7

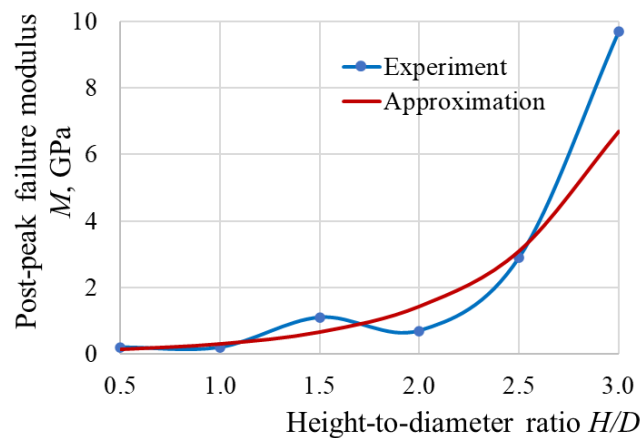


Figure 8 – Experimentally obtained relationship between the post-peak failure modulus of gypsum specimens and their height-to-diameter ratio, and its approximation by an exponential relationship

It should be noted that the dependence of the post-peak failure modulus on the H/D ratio is not strictly monotonic. In particular, the value of M for $H/D = 2.0$ is lower than that for $H/D = 1.5$. This deviation may be related to the natural heterogeneity of the gypsum material, local defects in the specimens, differences in the actual condition of the end faces, contact conditions with the press plates, and the specific features of crack development in a particular specimen. Therefore, the obtained data should be regarded as experimental confirmation of a general tendency rather than as a strictly monotonic functional relationship. To establish a quantitative relationship between M and H/D , it is necessary to increase the number of tests for each height-to-diameter ratio and to perform statistical processing of the results.

The analytical expression for approximating the experimental relationship, with a coefficient of determination $R^2 = 0.90$, has the form:

$$M = 0.066e^{1.54 \cdot H/D}, \quad (1)$$

where M – post-peak failure modulus, GPa; H/D – dimensionless ratio of specimen height to specimen diameter.

Variation in the shape and dimensions of the specimen causes not only a change in the nature of its post-peak failure, but also affects parameters that are usually considered constants for a given rock, such as Young's modulus and uniaxial compressive strength (see Fig. 7). This conclusion is consistent with studies by other authors on the influence of geometry and scale effect on rock strength and deformation [14, 23, 24]. As noted above, friction at the contacts between the specimens and the press has a significant influence on the determination of the mechanical and deformation characteristics of rock specimens. As the specimen height-to-diameter ratio increases, the influence of friction decreases. Deformation along the specimen length in the di-

rection of compressive stress becomes more uniform. Accordingly, the determined physical and mechanical properties of rocks become less dependent on contact friction and the geometric effect of the specimen. In addition, increasing the specimen height makes it possible to determine its absolute and relative deformation more accurately. However, an excessive increase in the specimen height-to-diameter ratio leads to rapid post-peak failure. In accordance with the recommendations given in [20–22], the optimal height-to-diameter ratio of the specimen is in the range from 2 to 3. Accordingly, in further studies aimed at determining the physical and mechanical properties of rocks, the authors of this work will focus on the above-mentioned values.

4. Conclusions

A method has been developed for obtaining stress-strain curves under industrial conditions using press equipment available at the enterprise and a mobile measuring system.

The proposed synchronous video recording scheme makes it possible to form an array of experimental “deformation - load” data without a standard automated press recording system.

Using gypsum specimens as an example, it is shown that the H/D ratio significantly affects the failure pattern and the post-peak branch of the curve.

To reduce the influence of contact friction and the geometric effect, it is advisable to use cylindrical specimens with a height-to-diameter ratio in the range of 2–3, which is consistent with international recommendations.

Conflict of interest

The authors declare no conflict of interest.

REFERENCES

1. Bogusz, A. and Bukowska, M. (2015), “Stress-strain characteristics as a source of information on the destruction of rocks under the influence of load”, *Journal of Sustainable Mining*, vol. 14, issue 1, pp. 46–54. <https://doi.org/10.1016/j.jsm.2015.08.007>
2. Akinbinu, V.A., (2019), “Determination of class I and class II rocks from conventional method based on the mechanism of rock deformation process”, *Insights in Mining Science & Technology*, vol. 1, 555567.
3. Tutluoglu, L., Öge, I. and Karpuz, C. (2014), “Relationship between pre-failure and post-failure mechanical properties of rock material in different origin”, *Rock Mechanics and Rock Engineering*, vol. 48, pp. 121–141. <https://doi.org/10.1007/s00603-014-0549-1>
4. Basu, A., Celestino, T. and Bortolucci, A. (2009), “Evaluation of rock mechanical behaviors under uniaxial compression with reference to assessed weathering grades”, *Rock Mechanics and Rock Engineering*, vol. 42, pp. 73–93. <https://doi.org/10.1007/s00603-008-0170-2>
5. Xie, W.-Q., Liu, X.-L., Zhang, X.-P., Liu, Q.-S. and Wang, E.-Z. (2025), “A review of test methods for uniaxial compressive strength of rocks: Theory, apparatus and data processing”, *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 17, issue 3, pp. 1889–1905. <https://doi.org/10.1016/j.jrmge.2024.05.003>
6. He, Z., Wu, G. and Zhu, J. (2024), “Mechanical properties of rock under uniaxial compression tests of different control modes and loading rates”, *Scientific Reports*, vol. 14, 2164 <https://doi.org/10.1038/s41598-024-52631-1>
7. Vračević, D., Dugonjić J. S., Peranić, J. and Hodanić, M. (2019), Determination of uniaxial compressive strength of limestone, *Zbornik radova*, no. 12, pp. 123–140. <https://doi.org/10.32762/zr.22.1.8>
8. CONTROLS Spa (2026), “Automatic uniaxial and triaxial test system”, available at: <https://controls-group.com/product/automatic-uniaxial-and-triaxial-test-system/> (Accessed 01 March 2026)
9. Malkowski, P. and Ostrowski, L. (2017), “The methodology for the Young modulus derivation for rocks and its value”, *Procedia Engineering*, vol. 191, pp. 134–141. <https://doi.org/10.1016/J.PROENG.2017.05.164>
10. Hsieh, A., Dyskin, A.V. and Dight, P. (2014), “The increase in Young's modulus of rocks under uniaxial compression”, *International Journal of Rock Mechanics and Mining Sciences*, vol. 70, pp. 425–434. <https://doi.org/10.1016/j.ijrmms.2014.05.009>

11. Kuhinek, D., Zorić, I. and Hrženjak P. (2011), "Measurement Uncertainty in Testing of Uniaxial Compressive Strength and Deformability of Rock Samples", *Measurement Science Review*, vol. 11, no. 4, pp. 112–117. <https://doi.org/10.2478/v10048-011-0021-2>
12. Chen, G., Jiang, W., Sun, X., Zhao, C. and Chang'an, Q. (2019) "Quantitative evaluation of rock brittleness based on crack initiation stress and complete stress–strain curves", *Bulletin of Engineering Geology and the Environment*, vol. 78, pp. 5919–5936. <https://doi.org/10.1007/s10064-019-01486-2>
13. Xu, L., Xu, X., Sun, Y. and Lu, T. (2022), "Evaluation of rock brittleness based on complete stress–strain curve", *Mathematics*, vol. 10, 4470. <https://doi.org/10.3390/math10234470>
14. Chen, T., Liu, X., Liu, J., Hu, N., Ma, Q., Cheng, Z., Shi, L. and Dai, W. (2025), "Size effect on damage evolution and failure characteristics of cyan sandstone under uniaxial compression", *Scientific Reports*, vol. 15, 35628. <https://doi.org/10.1038/s41598-025-19512-7>
15. Bukowska, M. (2013), "Post-peak failure modulus in problems of mining geo-mechanics", *Journal of Mining Science*, vol. 49, pp.731–740. <https://doi.org/10.1134/S1062739149050067>
16. Huang, D., Wen, T. Chen, N. and Yang, Yu. (2026), "Energy evolution-based method for determining residual strength of rock", *Rock Mechanics and Rock Engineering*, vol. 59, pp. 381–399. <https://doi.org/10.1007/s00603-025-04854-5>
17. Skopochka, S.I., Krukovskiy, O.P., Serhiienko, V.M. and Bulich, Yu.Yu. (2023), "Research of strength and features of deformations of rocks in uranium deposits", *Geo-Technical Mechanics*, no. 167, pp. 66–76. <https://doi.org/10.15407/geotm2023.167.066>
18. Ma, H., Song, Y., Chen, S., Yin, D., Zheng, J., Shen, F., Li, X. and Ma, Q. (2021), "Experimental investigation on the mechanical behavior and damage evolution mechanism of water-immersed gypsum rock", *Rock Mechanics and Rock Engineering*, vol. 54, pp. 4929–4948. <https://doi.org/10.1007/s00603-021-02548-2>
19. Wang, S., Liu, Z., Zhang, K., Zhu, G. and Zheng, H. (2022), "Experimental study on strength weakening of gypsum rock with effect of long-term overlying strata pressure", *Sustainability*, vol. 14, 11442. <https://doi.org/10.3390/su141811442>
20. ASTM Committee on Soil and Rock (2023), *ASTM D7012-23 Compressive strength and elastic moduli of intact rock core specimens under varying states of stress and temperatures*, ASTM International, West Conshohocken, United States.
21. Ministry of land and resources (2015), *DZ/T 0276.18-2015 Regulation for testing the physical and mechanical properties of rock. Part 18: Test for determining the uniaxial compressive strength of rock*, China Standards Press, Beijing, China.
22. Ulusay, R. (2015), *The ISRM suggested methods for rock characterization, testing and monitoring: 2007–2014*, Springer, Cham, Switzerland. <https://doi.org/10.1007/978-3-319-07713-0>
23. Li, G., Xiaofeng, C., Hu, L., Tao, Z. and Tang, C. (2022), "Rock failure and instability from a structural perspective: insights from the shape effect", *Rock Mechanics and Rock Engineering*, vol. 55, pp. 937–952. <https://doi.org/10.1007/s00603-021-02703-9>
24. Skopochka, S., Krukovskiy, O., Palamarchuk, T. and Prokhorets, L. (2020), "On the methodology for considering scale effect of rock strength", *Mining of Mineral Deposits*, vol. 14, no. 4, pp. 24–30. <https://doi.org/10.33271/mining14.04.024>

ОТРИМАННЯ ПОВНИХ КРИВИХ «НАПРУЖЕННЯ-ДЕФОРМАЦІЯ» ПРИ ВИПРОБУВАННІ ЗРАЗКІВ ГІРСЬКИХ ПОРІД У ВИРОБНИЧИХ УМОВАХ

Круковський О.П., Васильєв Д.Л., Сергєєнко В.М., Кресс Д.В.

Анотація. Довготривала експлуатація підземних споруд в умовах високого гірського тиску зумовлює необхідність прогнозування стану гірських порід при наближенні до межі міцності, а також після її досягнення. Такий прогноз може бути виконаний на основі аналізу повних кривих «напруження-деформація», які характеризують domeжове деформування, післяпикову поведінку матеріалу, модуль спаду та залишкову міцність. Стандартні методики отримання таких кривих зазвичай потребують спеціалізованих лабораторій і стаціонарного випробувального обладнання, що збільшує тривалість і вартість досліджень та обмежує можливість оперативного коригування програми випробувань безпосередньо на підприємстві.

Запропоновано методику отримання повних кривих «напруження-деформація» при випробуванні зразків гірських порід у виробничих умовах. Методика передбачає використання наявного пресового обладнання підприємства, мобільного тензометричного вимірювача стискального зусилля, індикатора поздовжньої деформації та синхронної відеофіксації показань вимірювальних приладів. Покадрова обробка відеозапису дає змогу сформувати масив даних «поздовжня деформація - стискальне зусилля» та розрахувати відповідні значення відносної деформації і стискального напруження. Отримані дані використовуються для побудови повної кривої «напруження-деформація» та визначення основних механічних і деформаційних характеристик зразка. Працездатність методики проілюстровано на прикладі випробувань циліндричних гіпсових зразків із різними співвідношеннями висоти до діаметра. Показано, що зменшення цього співвідношення посилює вплив контактного тертя між зразком і плитами преса, тоді як його збільшення змінює характер руйнування від поступового руйнування з плавним післяпиковим спадом до вираженого крихкого руйнування з інтенсивним післяпиковим спадом несучої здатності. Для зменшення впливу геометрії зразка та контактного тертя рекомендовано використовувати зразки зі співвідношенням висоти до діаметра не менше 2.

Ключові слова: породний зразок, руйнівний контроль, одновісний стиск, крива «напруження-деформація».