STRENGTH AND DEFORMATION PROPERTIES OF THE INTACT GNEISS ROCK FROM ZHELEZNITSA TUNNEL OF STRUMA HIGHWAY (BULGARIA)

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ABSTRACT. The article presents the laboratory test results from the intact gneiss rock from Zheleznitsa Tunnel of Struma Highway (Bulgaria). The following parameters were determined: uniaxial compression strength from direct loading and Point load test, the tensile strength from Brazilian test, as well as the elastic modulus and the Poisson's ratio. Correlation analyses between the parameters were carried out and the relevant equations and their correlation strength were determined. Cross-calculation were performed to complete the populations with correlated values. The statistical distributions of the parameters populations were estimated and the characteristic values were determined.

Keywords: intact rock, strength parameters, elastic modulus, cross-correlations, characteristic values

ЯКОСТНО-ДЕФОРМАЦИОННИ СВОЙСТВА НА НЕНАРУШЕНАТА СКАЛА ОТ ТУНЕЛ „ЖЕЛЕЗНИЦА“ НА АМ „СТРУМА“

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РЕЗЮМЕ. В настоящата статия са обобщени резултатите от лабораторните изследвания на ненарушената скала (гнайси), изграждащи масива, през който преминава Тунел „Железница“ на АМ „Струма“. Определени са якостта на едносов натиск чрез преки изпитвания и чрез точково (поасоново) натоварване, якостта на опън по Бразилския метод, както и модулът на еластичност и коефициентът на Поасон. Изследвани са корелационните зависимости между тях и са определени съответните зависимости и тяхната значимост. Извършено е допълване на пряко определените съвкупности от данни със са изчисления по тях стойности. Направени са оценки на статистическото разпределение на стойностите за отделните показатели на ненарушената скала, като са определени съответните характеристични стойности.

Ключови думи: ненарушена скала, якостни свойства, еластичен модул, корелационни връзки, характеристични стойности

Introduction

Zheleznitsa Tunnel is a part of a newly constructed section from Struma Highway between Blagoevgrad and Simitli towns (South-west Bulgaria). It is with total length of 2,280m, comprises two parallel tubes with maximum top cover of about 110m.

The tunnel passes through a rock-mass of amphibolites and amphibolitic gneisses with Neo-Proterozoic age, from the Troskovski Metamorphic Complex. The region is characterized by intensive contemporary tectonic and seismic activity (Dobrev et al., 2000; 2015). The various tectonic and seismic stages had superimposed each other to produce numerous adjacent blocks in the rock-mass with quick transitions to extreme degrees and spatial orientation of fracturing, jointing and foliation (Fig. 1).

An extensive drilling campaign was carried out including 16 boreholes up to 135m deep. More than 150 nos. of HQ and NQ rock-core samples with were collected for laboratory testing.

As the project approach for evaluating the rock-mass properties was based on Hoek-Bray strength and deformation models the following major mechanical parameters of the intact rock were determined: uniaxial compression strength (UCS - ASTM D7012-14) from direct loading, tensile strength from Brazilian test (BTS-ISRM, 2007), as well as the elastic modulus E_{el} and the Poisson's ratio μ (ASTM D7012-14), determined as average from the central linear portion of the stress-strain curves. To evaluate the compression strength of rock from the disturbed and crushed intervals point load tests (PLT - ASTM D5731) were carried out by loading in axial (vertical) and diametral (horizontal) directions of dry core specimens.

Fig. 1. Typical sequence of intact and crushed core intervals (depth interval 37m-47m).

The UCS's and the BTS's were tested out on air dry specimens and water saturated to constant weight specimens. Complete degradation during saturation from about one third to half of the tested specimens was observed.

The scope of the current study is to present the applied correlation analysis and cross-calculations between the parameters in order to enrich the direct testing data matrix, as well as the calculation of their characteristic values, based on the estimated statistical distributions. All calculations were carried out with MS EXCEL.

Relationships between parameters

A vast quantity of studies dealing with empirical correlations between the rock physical and mechanical parameters can be enlisted, but none of them, no matter of their simplicity or complexity none are universally verified. If they are recommended for common engineering practice, important applicability cautions and/or wide variational ranges regarding rock types, their structures, weathering etc. are assigned, so their application for a specific site may generate more ambiguity rather than confidence. In studying such relationships it is strategically important to define the type of approximation functions to be estimated. In many cases they include a free member that makes them physically inadmissible as for '0' values of the argument parameters a non-zero value are produced if no functions' validity truncation is mentioned.

In this regard the current study is aimed but to establish basic and strictly local relationships aimed to enlarge and improve the statistical quality the data samples.

Two major relationships were studied: between UCS and PLT and between UCS and E_{el}.

Relationship between UCS and PLTs' results

The PLT is standardized by both in ASTM and ISRM for indirect estimation of the USC of rocks by the equation:

$$UCS = kI_{C(50)}, \quad (1)$$

where '*k*' is a linear conversion factor and $I_{S(50)}$ is the Point Load Stress Index normalized to core specimen's diameter 50 mm (NQ). The values of '*k*' usually are recommended as 20÷25 (mean 24) (Bieniawski, 1975; Broch and Franklin, 1972). ASTM 5731-05 (referring to ISRM, 1985) recommends the *k*-factors varying from 20 to 60 for 20mm to 60mm specimen diameters. In ISRM (2007) no such values are not presented but is mentioned that the *k*-factor for the different rock types may vary from 15 to 50, that is up to ±100% from the previous value of 24.

For defining a correct *k*-factor value for the gneiss rock, paired UCS tests and PLTs' were carried out on specimens from the same or adjacent rock samples (Table 1). The individual $I_{S(50)}$ values and *k*-factor values for each PLT were calculated. Further the integral *k*-factor values for the rock were defined both by averaging (Table 1) and by linear correlations between the paired values of USC and $I_{S(50)(II)}$ / $I_{S(50)(\perp)}$ – Fig. 2.

Table 1. *Results from paired USC tests and PLTs'.*

UCS	$I_{S(50)(II)}$	$I_{S(50)(\perp)}$	$k_{(II)}$	$k_{(\perp)}$
MPa	MPa	MPa	-	-
11.60	0.37	0.22	31.35	52.73
	0.25	-	46.40	-
18.10	0.88	0.44	20.57	41.14
	-	0.30	-	60.33
	-	0.58	-	31.21
0.31	0.04	0.04	7.75	7.75
10.10	0.17	0.18	59.41	56.11
	-	0.13	-	77.69
	-	0.09	-	112.22
19.70*	1.74*	3.02*	11.32*	6.52*
	4.04*	1.40*	4.88*	14.07*
57.90*	2.34	2.97*	24.74*	19.49*
	4.24*	3.08*	13.66*	18.80*
17.80	-	1.86*	-	9.57*
1.40	0.20	0.12	7.00	11.67
	0.14	-	10.00	-
2.92	0.28	0.07	10.43	41.71
4.07	0.07	0.04	58.14	101.75
11.59	0.47	0.37	24.66	31.32
	0.41	-	28.27	-
Average (all values)				
17.48	**1.04**	**0.88**	**23.91**	**40.83**
Average (without excluded values)*				
8.65	**0.30**	**0.22**	**27.63**	**52.14**

(*) The values were excluded from the data processing.

As the values show considerable scatter around the average a certain estimation for outliers of the data set was carried out. An initial Grubb's test (Grubb, 1950 - not presented here) showed not any like, but the graphical presentation (Fig. 2) revealed that for specimens with UCS values above 20 MPa the points were considerably shifted form the expected linear relationships. In this regard the *k*-factors values were averaged in Table 2 and correlated on Fig. 2 both for the complete set and the reduced set excluding the 'outliers' values (marked with '*' in Table 1 and with cross-hair marker on Fig. 2). The correlated values (Fig. 2), give k(II) = 12.0 and k(⊥) = 15.0 for all values sets and k(II) = 23.8 and k(⊥) = 39.9 for the reduced sets.

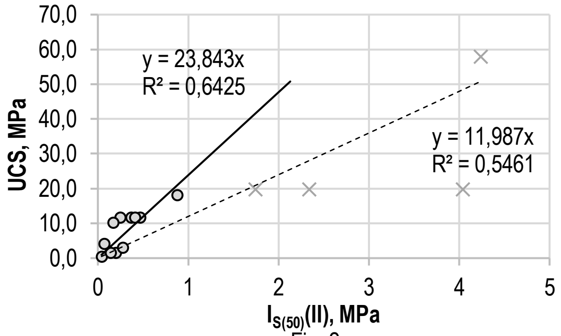

Fig. 2.a

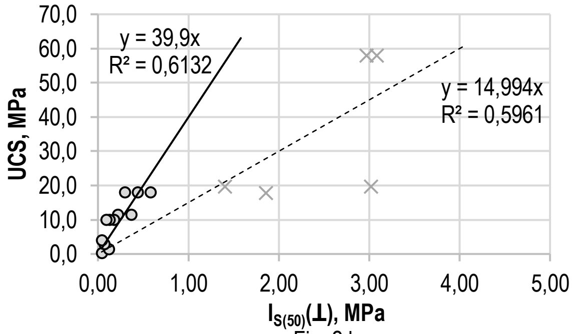

Fig. 2.b

Fig. 2. Relationships USC and a) $I_{S(50)}$(II) and b) $I_{S(50)}$(⊥).

Comparing the above results it can be concluded that the average calculations can considerably smooth up the scattered values while the linear correlation distinctly differentiates between them. As the reduced data sets correlations present much higher regression coefficients and as the majority of the unpaired PLTs' are with values of $I_{S(50)}$ less than 1.0-1.5 they are considered representative for the study. Further, the k-values form the reduced data sets are as twice as higher that these from the total data sets, that will result in higher estimated UCS that seems more reasonable for the project. The results revealed a marked anisotropy of the *k*-values in vertical to horizontal directions with anisotropy index $\mathbf{I_{a(50)}}$=1.25-1.60, that was recommended to be used in the tunnel's design.

Relationship between E_{el} and UCS

The most popular relationship between E_{el} and UCS is the Modulus Ratio MR = E_{el}/UCS. Hoek et al. (2006) recommend values for gneiss are in the range of 300-750, that was attributed to attributed to the high anisoptropy of the rock. Depending on the degree of weathering of gneisses Ekanayake et al. (2015) report even larger spreads of MR limits. Chang et al. (2006), Palchik (2011) and Alnuaim (2019) present some more complicated polynomic or power relationships but still with considerable scatter of the results.

In the current study the relationship between the E_{el} and UCS was estimated on 29 paired samples tested for both parameters (Table 2).

Table 2. *Results from paired USC and E_{el} tests.*

UCS	MPa	0.20	0.59	1.25	2.34	2.34	2.98	3.08
E_{el}	GPa	0.36	0.95	0.36	1.67	0.95	1.67	0.70
UCS	MPa	5.76	10.10	10.60	11.00	11.70	12.36	13.30
E_{el}	GPa	1.12	3.89	6.06	3.46	4.48	13.77	11.40
UCS	MPa	13.70	13.90	14.61	16.84	17.82	27.30	31.98
E_{el}	GPa	10.53	3.77	4.66	7.07	20.85	14.30	19.04
UCS	MPa	36.80	38.68	53.00	53.10	54.70	57.90	263.24
E_{el}	GPa	24.78	23.25	22.56	25.18	41.43	39.09	84.15

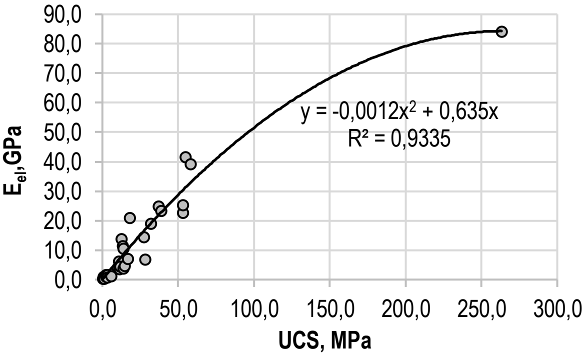

Fig3.a

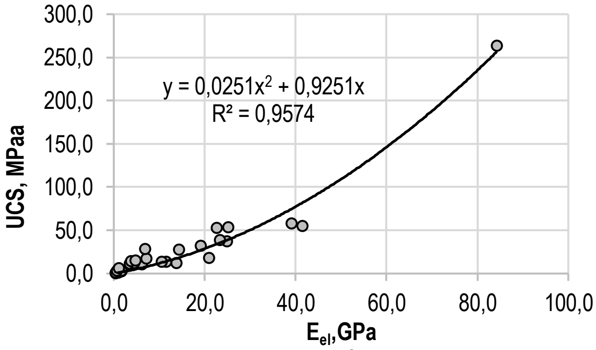

Fig. 3.b

Fig. 3. Relationships between a) E_{el} and USC and b) USC and E_{el}.

The obtained relationships (Fig. 3.a and b) are with very good strongness (correlation coefficients are above 0.95). The estimated curve functions are:

$$E_{el} = -0.0012UCS^2 + 0.635UCS \quad (2)$$

$$UCS = 0.0251{E_{el}}^2 + 0.925E_{el} \quad (3)$$

It should be mentioned that equations (2) and (3) are not mathematically reciprocal as the curves are forced to pass through the axes' origin.

The 'raw' laboratory dataset for USC was filled up with new values calculated with eq. (1) from the unpaired values of $I_{S(50)(II)}$ and $I_{S(50)(\perp)}$ applying the relevant *k*-factors $k_{(II)}$ and $k_{(\perp)}$ as well as with values calculated from the unpaired E_{el} values using eq. (3). The same was carried out for E_{el} values where eq. (2) was applied to the unpaired USC values, incl. these calculated from the PLT's.

Characteristic values

The concept of the characteristic values was introduced in Eurocode 7, that on statistical grounds (clause 2.4.5.2(1)) should be derived at probability levels not greater than 5% of the worse parameter value (lower or upper) that governs the occurrence of the limit state. For a given parameter values probability distribution that is equivalent to the lower confidence limit (LCL) and the upper confidence limit (UCL) to the population mean at 90% two-tailed probability.

Two types of distributions were tested towards the intact rock properties – normal and log-normal. The simplest way to check the distribution type is visually inspection of histograms. As the sample populations for the different parameters vary in size and shape this may not be enough. So the normality of the data distributions was also checked with Q-Q plots in the form of a Normal Quantile Plots relating the test values and the corresponding Z-score values based on the estimated quantiles Q of each test value with i-th rank in the sample:

$$Q = \frac{i-0.5}{n} \quad (4)$$

As theoretically for a normal distribution the Q-Q plot is a straight line the visual linear appearance of the trend should be the initial criteria for the normality of the distribution. Further the correlation coefficient R was used to establish the stronger correlation, especially for similarly looking trends.

Both Q-Q plots were created for the actual and log-values of the parameters, the criterion for best fitting being the better value of the correlation coefficient R.

The UCL and LCL for a normal distribution were calculated as:

$$\frac{UCL}{LCL} = AVE \ \pm t_{\alpha/2}\frac{SD}{\sqrt{N}} \quad (5)$$

where α is 0.1 for two-tailed probability of non-exceedance.

The issue for the efficient CLs' calculation of log-normal distribution can be solved based on different approaches (Olsson, 2005). The so called 'naïve' approach applies equation (5) to the normal log-values distribution parameters and antiloging the CL values. This approach is usually rejected due to unacceptable shifting the confidence interval towards the average value and even excluding it, what was observed in the study as well (not presented here). So, a modified Cox solution (Olsson, 2005) was applied where the UCL and LCL are calculated for the estimated log-values (ln) normal distribution parameters:

$$\frac{(ln)UCL}{(ln)LCL} = AVE(ln) \ \pm t_{\alpha/2}\sqrt{\frac{SD(ln)^2}{N} + \frac{SD(ln)^4}{2(N-1)}} \quad (6)$$

Further they are back-transferred to normal values by antiloging.

UCL and LCL calculations results

The calculation results for the UCL and LCL values corresponding to the upper and lower characteristic values of the main properties for the intact rock are presented in Table 3. It includes the statistics that are incorporated in eq. (5) and (6) both for normal and log-normal data distribution. The USC and E_{el} dataset values that were considerably extended with the inter-parametric calculations with 50 nos. and 30 nos. accordingly. The data histogram plots with the estimated normal and log-normal probability distribution curves as well as the corresponding Q-Q plots for the studied rock parameters are presented in the Appendix of this article.

Discusions

The presented study reveals that practically all parameters are characterized with log-normal distribution that can be visually estimated from most of the data histograms and is strongly supported by the Q-Q plots linear correlation coefficients R. An exception is observed for the UCS (dry) and E_{el} datasets where the correlations coefficient for normal and log-normal plots are high quite (above 0.94) but the normal Q-Q plots are with inacceptable curvature. The bulk density data distribution can be described with equal probability both as normal and lognormal distribution curves are practically identical with very good trends of the Q-Q plots. This results in practically identical upper and lower characteristic values.

As general tendency the log-normal distributions produce slightly higher confidence limits corresponding to higher characteristic values thus decreasing the conservativity in their estimation. For some parameters (saturated UCS) the normal distributions extend the lower confidence values within the negative scores that is physically inadmissible.

The cross-parameters data extension resulted in slight – about 10% - increase of the average value for dry UCS and more significant – about 35% - increase of the average value for E_{el}. However, the data variances increase as well, that is considered more relevant to the natural structure and properties variation in the rockmass.

Important issue is that not only the LCL's should be considered as characteristic values that govern the instability limit states in the rockmass. Depending on the stress state and limit state origin the bulk density through overburden weight can play both favourable and unfavourable role. As noted in Eurocode 7 clause 11.5.1(12) for overall slope stability the limit state should be tested for both lower and upper characteristic values. This consideration is appropriate to extend in the underground structures design as well. A specific aspect of the applicability of UCL's and LCL's is their effect on mathematically related parameters. Let consider the parameter 'm' from Hoek-Brown failure criterion. According to Cai (2000) m ≈ USC/BTS if this ratio is above 8. Calculated from the log-normal UCL and LCL 'm' equals to 8.0 and 11.8. This is an example where the UCL's values produce more unfavourable parameter value, so for the *m*-value so they should be considered as characteristic.

Conclusions

The intact gneiss rock from Zheleznitsa tunnel exhibits generally vary quite irregularly in the rockmass that can be explained with is intensive tectonic and seismic background, fracturing and jointing. The parameters variation magnitudes is from 10 to 1000 that are not typical for this rock type. Another unfavorble factor for the rockmass behaviour is the UCS degradation of the saturated rock from 400% to 600%, up to complete material degradation.

To overcome the shortage of good quality undisturbed samples for laboratory testing for the structurally disturbed drilling core intervals, indirect PLT's were carried out and representative correlative relationships with UCS and E_{el} were established.

Basic statistical methods including interpretation of histograms and Normal distribution Q-Q plots were applied to establish predominantly log-normal distribution of the mechanical parameters. Relative to the normal distribution the log-normal distribution amplifies the relative weight of the lower range values that reflects in considerably lower mean but results in more narrow confidence intervals with higher confidence limits values. It is demonstrated that both LCL's or/and UCL's can be assigned as characteristic values depending on their effect or that of related to them parameters on the rockmass limit states.

Table 3. *Calculation results for the LCL and UCL values.*

STATISTICS			NORMAL DISTRIBUTION							LOG-NORMAL DISTRIBUTION				
		N	R	AVE	SD	min	max	LCL	UCL	R	AVE (ln)	SD(ln)	LCL	UCL
Bulk Density	g/cm^3	92	0.99	**2.61**	0.23	1.89	3.13	2.56	2.66	0.99	0.96	0.09	**2.57**	**2.65**
UCS (dry)	MPa	102	0.94	**16.44**	28.96	0.2	207.72	10.75	22.13	0.99	1.97	1.35	**13.15**	**24.37**
UCS (sat.)	MPa	21	0.65	**7.13**	16.73	0.13	75.78	-0.48	14.75	0.97	0.61	1.58	**2.6**	**15.76**
BTS (dry)	MPa	56	0.83	**1.54**	2.17	0.02	11.06	0.96	2.13	0.99	-0.53	1.51	**1.12**	**3.03**
BTS (sat.)	MPa	8	0.88	**2.78**	3.41	0.17	10.25	-0.08	5.63	0.99	0.29	1.4	**0.91**	**14.01**
E_{el}	GPa	103	0.94	**9.21**	13.06	0.13	74.39	6.65	11.76	0.99	1.47	1.33	**7.79**	**14.17**
μ	-	30	0.93	**0.12**	0.07	0.01	0.37	0.09	0.14	0.97	-2.34	0.67	**0.10**	**0.15**

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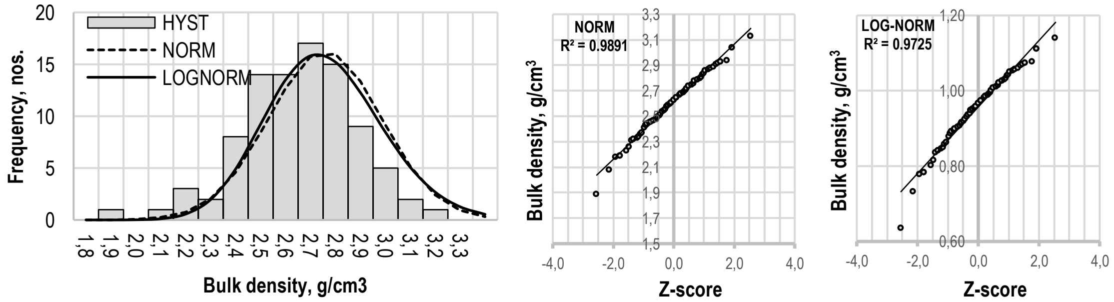
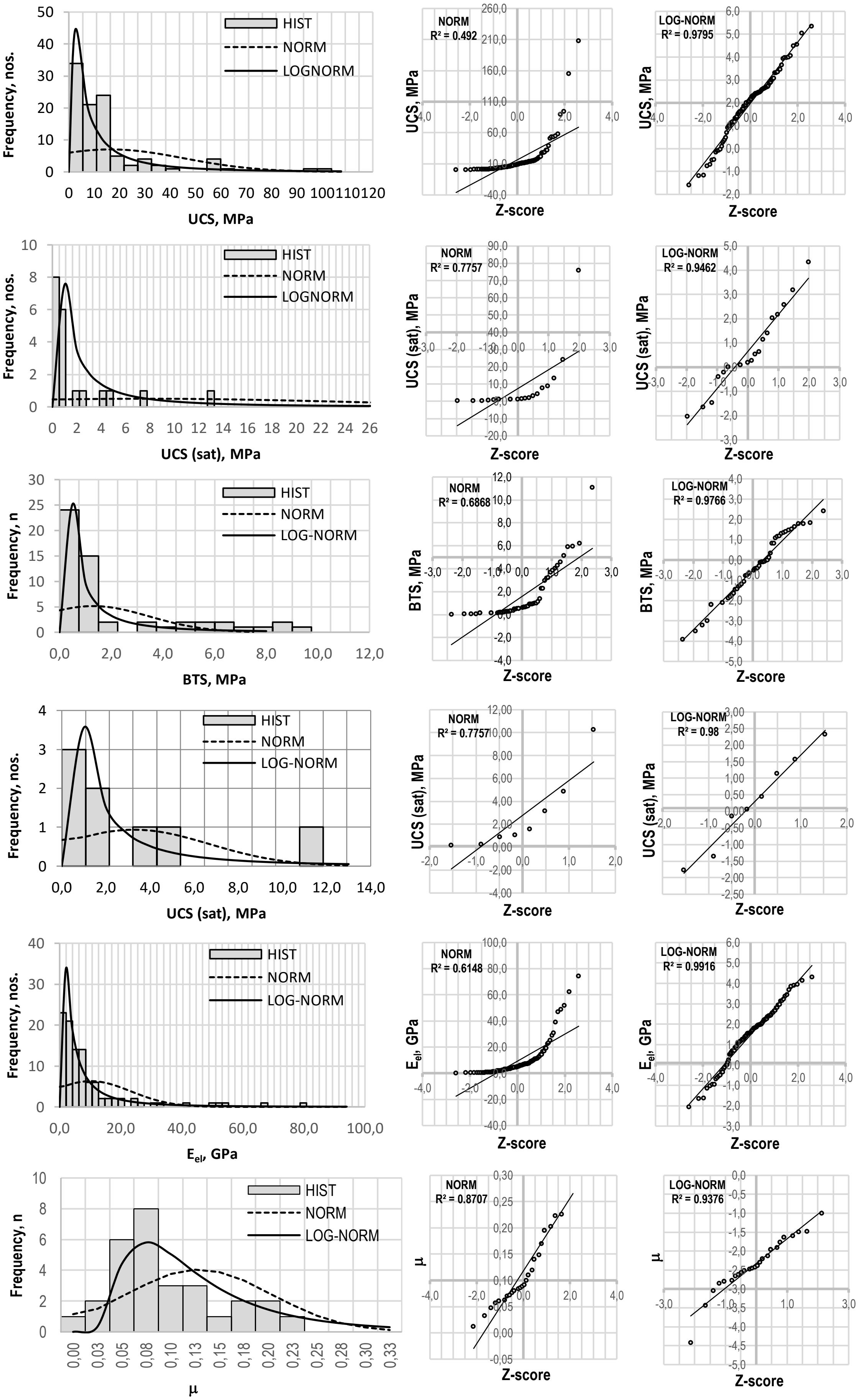
APPENDIX

Histograms with normal and log-normal distribution curves and Q-Q plots for the intact rock parameters




Frequency, nos.
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LOGNORM
UCS, MPa
NORM
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UCS, MPa
Z-score
LOG-NORM
R^2 = 0.9795
UCS, MPa
Z-score
Frequency, nos.
HIST
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LOGNORM
UCS (sat), MPa
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Z-score
LOG-NORM
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Z-score
Frequency, n
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LOG-NORM
BTS, MPa
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Z-score
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Z-score
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E_{el}, GPa
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E_{el}, GPa
Z-score
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NORM
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μ
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LOG-NORM
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μ
Z-score