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Scale effects or statistical misinterpretation: a critical assessment of UCS data

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Abstract

Despite significant improvements made on measurement techniques, testing capabilities, computer performance, and data acquisition systems, many rock engineering challenges still fall under the designation of “data-limited problems”. This means that, often, the number of tests is limited, which compromises statistical representativeness and interpretation. In contrast to other engineering disciplines, where materials can be selected based on the desired mechanical properties, in rock engineering, it is the design that adapts to the material. Consequently, the mechanical characterisation of rocks and rock masses represents a key step for successful rock engineering design.

In addition to the inherent heterogeneity associated with natural genesis, the mechanical behaviour of rock masses is scale- or size-dependent. As uniaxial compressive strength is a primary design parameter in rock engineering, its scale effect has been extensively studied, and several empirical correlations and size-effect laws have been proposed. However, many of these studies seem to suffer from the same pitfalls, specifically, a systematic reduction in the number of specimens with increasing physical specimen size, confounding the physical size effect with the effect of the statistical sample size, and the use of unsuitable statistical tests. It appears that in many cases, the data would allow multiple interpretations, and the presented correlations should be used with caution.

Keywords

UCS, Uniaxial compressive strength, Scale effect, Size effect, Review.

1 Introduction

Rock engineering design is inherently constrained by limited data availability, and engineering solutions must adapt to naturally occurring geological variability. Consequently, reliable characterisation and parameterisation remain fundamental requirements for rock engineering design. Despite advances in measurement techniques, laboratory testing and data acquisition systems, many rock engineering problems continue to be characterised by small datasets and significant uncertainty.

The mechanical behaviour of rock masses is widely recognised as scale-dependent, and numerous studies have investigated the influence of specimen size on the mechanical properties of intact rock. Among these, uniaxial compressive strength (UCS) has received particular attention due to its central role in empirical classification systems and design methods. A variety of empirical correlations and size-effect laws have been proposed (e.g., Mogi 1962; Lundborg 1967; Hoek and Brown 1980; Yoshinaka et al. 2008; Masoumi et al. 2016). A comprehensive review on the topic has been presented by Zhang et al. (2011).

However, interpretation of the size effect remains ambiguous. Often, increasing physical specimen size is accompanied by a systematic reduction in the number of tests conducted, primarily due to practical limitations with sampling, preparation and testing of large specimens. As a result, observed strength trends may reflect not only physical size effects but also variations in statistical confidence. This issue is of practical importance as while design parameters derived from large specimens often carry greater uncertainty, they also exert a stronger influence on engineering decisions, as they are considered more representative of block scale behaviour. Misinterpretation of statistical variability as a physical scale effect may lead to biased empirical correlations and inconsistent design practice. Furthermore, many proposed empirical correlations are based on inappropriate statistical tests that often overestimate the significance of the relationship. This study attempts to address these problems through a comprehensive statistical examination of published UCS datasets.

2 Review of existing data

This study presents the compiled results and statistical analysis of the results of 22 publications for a total of 2727 unique UCS results from 198 specimen groups, ranging from 1.5 mm to 1520 mm in lateral dimension, and representing 43 different igneous, sedimentary and metamorphic lithologies. Number of specimens in each group (grouped by lithology and size) range from 1 to 80. Various geometries are represented: mostly right circular cylinders, but also cubes, square rectangular prisms and even equilateral triangular prisms. Beyond physical size (lateral dimension), the effects of specimen shape and statistical sample size Nare studied.

2.1 Igneous rocks

This section presents the compiled results of 16 publications for a total of 913 UCS results from 91 size groups ranging from 1.5 mm to 294 mm (lateral dimension) and representing 23 different igneous lithologies. Table 1 shows the reviewed data sources, rock types, specimen shapes, as well as the average lateral dimension, number of specimens and the average UCS values by size group.

Table 1. Reviewed data sources for igneous rocks with the lateral dimension, number of specimens and average UCS value for each size group. Shapes: R = right circular cylinder, C = cube and T = equilateral triangular prism.

Reference	**Rock type**	**Shape**	**Lateral dimension (Number of specimens) Average UCS** [mm]/[-]/[MPa]			
Lundborg (1967)	Granite	R	19 (5) 215	28 (5) 208	38 (5) 173	58 (5) 171
Hoskins & Horino (1969)	Granite	R	25.4 (45) 337	50.8 (30) 327	76.2 (30) 302	
Nishimatsu et al. (1969)	Andesite A	R	24 (11) 108	35 (14) 112	50 (11) 99.4	56 (10) 99.7
			70 (11) 94.9			
	Andesite B	R	13 (12) 228	18 (16) 243	24 (12) 253	30 (12) 260
			70 (8) 213			
	Granite	R	13 (15) 179	18 (16) 188	24 (12) 175	30 (10) 196
			70 (7) 146			
Pratt et al. (1972)	Diorite	R/T	54 (6) 30.8	76 (3) 26.6	203 (4) 24.3	
	Granodiorite	R/T	54 (6) 193	76 (3) 189	203 (6) 74.5	
Bieniawski (1975)	Norite A	R	21.5 (20) 255	42 (20) 257	54 (45) 250	
	Norite B	R	21.5 (20) 318	42 (20) 313	54 (40) 312	

Table 1. continued Reviewed data sources for igneous rocks with the lateral dimension, number of specimens and average UCS value for each size group. Shapes: R = right circular cylinder, C = cube and T = equilateral triangular prism.

Abou-Sayed et al. (1976)	Quartz diorite	R	25 (11) 41.7	38 (8) 33.3	63 (2) 34.1	102 (7) 28.9
			146 (4) 27.4			
Jackson & Lau (1990)	Granite	R	33 (13) 195	45 (12) 171	63 (10) 199	100 (5) 190
			141 (8) 171	194 (4) 156	294 (4) 166	45 (39) 193
Panek & Fannon (1992)	Basalt	R	21 (27) 191	70 (9) 171	145 (8) 161	
da Silva & Hennies (1993)	Basalt	C	1.5 (20) 278	5 (15) 279	10 (5) 205	15 (10) 198
Thuro et al. (2001)	Granite	R	52 (4) 130	70 (4) 134	80 (4) 125	112 (4) 128
Masoumi (2013)	Granite A	R	19 (3) 183	25 (4) 208	38 (4) 233	50 (5) 218
	Granite B	R	19 (4) 203	25 (2) 183	38 (5) 255	50 (4) 251
			65 (5) 253	96 (2) 267		
Quiñones (2017)	Granite	R	13.9 (10) 62.4	29.3 (10) 84	53.6 (6) 122	98.6 (2) 112
Walton (2018)	Granite	R	43 (4) 142	63 (4) 131	75 (4) 131	
Grenow(2018)	Granite A	R	25.2 (5) 65.3	36.9 (5) 70.1	54.9 (5) 126	
	Granite B	R	25.5 (5) 144	37.1 (5) 168	54.1 (5) 154	
Durmekova et al. (2022)	Andesite	R	20 (10) 172	35 (7) 194	50 (6) 181	
	Granodiorite	R	20 (10) 112	35 (10) 113	50 (10) 115	
Kong et al. (2023)	Granite	C	10 (5) 288	15 (5) 260	20 (5) 234	25 (5) 188

2.2 Sedimentary rocks

This section presents the compiled results of 10 publications for a total of 1189 UCS results from 81 size groups ranging from 10 mm to 1520 mm (lateral dimension) and representing 15 different sedimentary lithologies and tuffs. Due to their similar mechanism of origin, tuffs are included with sedimentary lithologies rather than igneous. Table 2 shows the reviewed data sources, rock types, specimen shapes, as well as the average lateral dimension, number of specimens and the average UCS values by size group.

Table 2. Reviewed data sources for sedimentary rocks and tuffs with the lateral dimension, number of specimens and average UCS value for each size group. Shapes: R = right circular cylinder, C = cube.

Reference	**Rock type**	**Shape**	**Lateral dimension (Number of specimens) Average UCS** [mm]/[-]/[MPa]			
Bieniawski(1968)	Coal	C	19.1 (10) 29.4	25.4 (10) 32.8	50.8 (8) 33.6	68.6 (5) 31.5
			76.2 (6) 28.1	152 (7) 12.8	305 (4) 8	457 (2) 6.3
			610 (1) 5.5	711 (1) 5.3	914 (2) 4.9	1220 (2) 4.5
			1520 (2) 4.4			
Hoskins & Horino (1969)	Limestone	R	25.4 (80) 170	50.8 (70) 172	76.2 (40) 171	102 (25) 171
	Sandstone	R	25.4 (69) 48.4	50.8 (75) 50.3	76.2 (70) 52.4	102 (60) 51.4
			152 (30) 49.5	203 (10) 49.3		
Nishimatsu et al. (1969)	Tuff*	R	17 (13) 65.7	20 (10) 67	25 (13) 70.4	29 (12) 68.8
			35 (10) 72.7	40 (12) 70.1	70 (7) 57.5	
	Sandy tuff*	R	13 (37) 42.7	18 (43) 41.6	24 (32) 38.9	30 (25) 44
			70 (29) 41.6			
Dhir & Sangha (1973)	Sandstone	R	25 (6) 70	50 (6) 72	75 (6) 72	100 (6) 71
Yuki et al. (1995)	Welded tuff* ∥	R	30 (13) 3.7	50 (15) 8.0	150 (12) 9.1	160 (12) 9.3
	Welded tuff* ⊥	R	30 (15) 6.9	50 (15) 8.8	100 (12) 8.9	150 (12) 9.4
	Rhyolitic welded tuff* ∥	C	30 (12) 7.8	50 (12) 6.8	100 (12) 8.0	150 (12) 8.5
			300 (3) 9.7	400 (3) 9.9		
Thuro et al. (2001)	Limestone	R	45 (4) 186	51 (4) 201	55 (4) 203	63 (4) 188
			70 (4) 206	80 (4) 196		
Pells (2004)	Sandstone	R	18 (14) 25.1	45 (9) 25.4	51 (6) 27.7	144 (6) 31.3
Masoumi (2013)	Sandstone	R	19 (6) 34.6	25 (4) 33.1	31 (6) 42.3	50 (3) 54.6
			65 (7) 58.8	96 (2) 56	118 (4) 54.7	145 (2) 54.2
Durmekova et al. (2022)	Limestone	R	20 (10) 98.5	35 (10) 91.9	50 (10) 106	
	Sandstone	R	20 (10) 136	35 (10) 160	50 (10) 138	
Kong et al. (2023)	Sandstone	C	10 (5) 82.7	15 (5) 85.6	20 (5) 87.6	25 (5) 92.5

*Grouped with sedimentary rather than igneous rocks due to the mechanism of origin

2.3 Metamorphic rocks

This section presents the compiled results of 5 publications for a total of 625 UCS results from 26 size groups ranging from roughly 14 mm to 146 mm (lateral dimension) and representing 5 different metamorphic lithologies. Table 3 shows the reviewed data sources, rock types, specimen shapes, as well as the average lateral dimension, number of specimens and the average UCS values by size group.

Table 3. Reviewed data sources for metamorphic rocks with the lateral dimension, number of specimens and average UCS value for each size group. Shapes: R = right circular cylinder, S = square rectangular prism.

Reference	Rock type	Shape	Lateral dimension (Number of specimens) Average UCS [mm]/[-]/[MPa]			
Mogi (1962)	Marble	S	20 (32) 88.3	30 (54) 87.3	40 (34) 81.1	60 (35) 78.7
			100 (22) 79.9			
Hoskins & Horino (1969)	Marble	R	25.4 (60) 107	50.8 (80) 108	76.2 (51) 105	102 (40) 106
			146 (30) 101			
Panek & Fannon (1992)	Metadiabase	R	28 (14) 239	51 (18) 185	145 (8) 128	
Masoumi (2013)	Marble	R	25 (4) 69.5	38 (8) 74.5	50 (7) 72.2	65 (5) 78.3
			96 (5) 81	118 (4) 69.9		
Alejano et al. (2018)	Migmatite	R	13.9 (38) 40.7	22.2 (35) 59.7	29.6 (8) 54.8	42.6 (19) 62
			49.9 (8) 81.2	60.2 (4) 72.5	101 (2) 69.8	

2.4 Statistical analysis

Statistical analysis of the compiled dataset was performed in the R statistics environment (R Core Team 2025). The data were evaluated using cumulative plots, cross-plots descriptive statistics (including specimen shape, dimensions, volume, mean UCS value and standard deviation of the UCS values) and statistical tests, namely the Spearman rank correlation coefficient and Partial Spearman. As most publications did not report individual specimen data, analyses were conducted using the average values reported for each lithological/size group.

The analysis revealed two principal data limitations. First, a systematic decrease in statistical sample size with increasing physical specimen size was observed (Figure 1), resulting in wide confidence intervals that permit multiple empirical models to appear consistent with the data. Most data correspond to specimens with lateral dimensions between 25 and 60 mm, whereas specimens smaller than 14 mm or larger than 146 mm in the lateral dimension are rare.

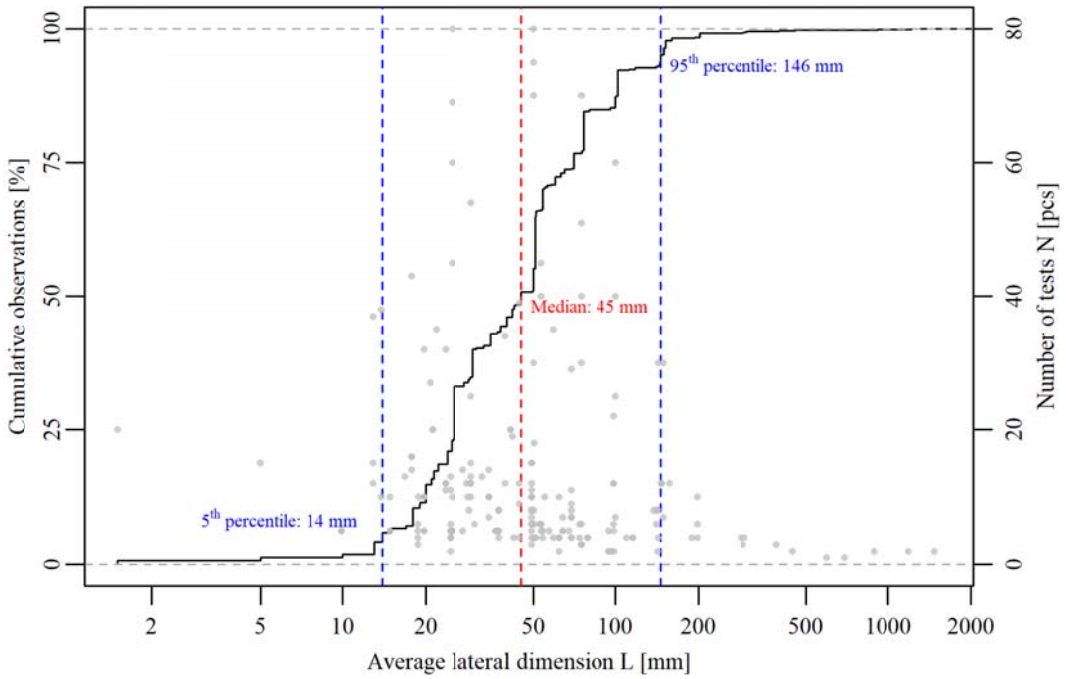


Fig. 1 Cumulative distribution of the total number of observations with respect to physical specimen size (black line), and the number of tests in each specimen group with respect to the average lateral dimension of the group (grey dots). Compiled from the sources listed in Tables 1–3.

The second principal issue concerns the misuse of the Pearson correlation coefficient and insufficient consideration of the assumptions underlying statistical inference. Spearman's rank correlation coefficients between average UCS, average lateral dimension L and number of tests N were calculated for each lithological group and the combined dataset, with significance evaluated using the false discovery rate adjusted p-values. Further, partial Spearman's rho values for the relationship between average UCS and L were calculated controlled for N, thereby isolating the relationship UCS and L independent of N. Figure 2 shows the compiled data and Table 4 shows the results of the statistical tests.

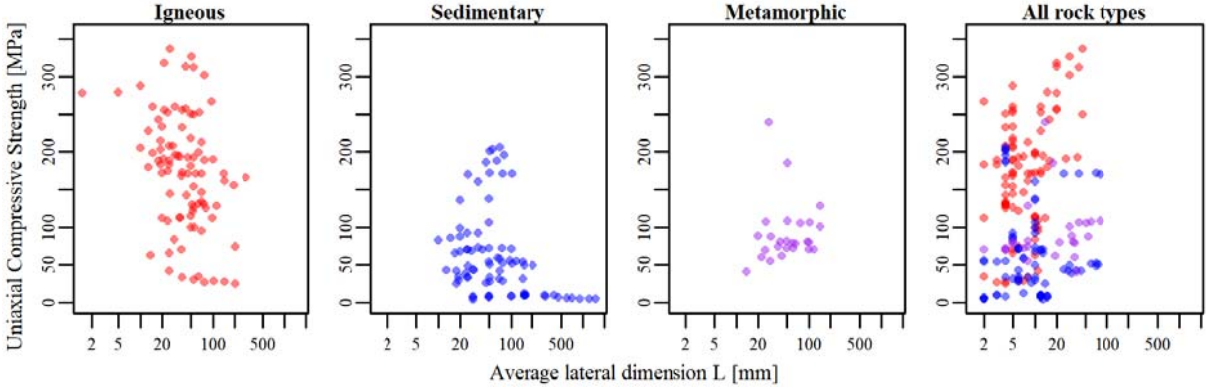


Fig. 2. Uniaxial compressive strength (UCS) vs specimen lateral dimension for igneous, sedimentary and metamorphic rocks, as well as all observations combined. Compiled from the sources listed in Tables 1–3.

For igneous rocks, statistically significant associations were identified between average UCS value and both L and N. However, even after controlling for N, the relationship remains significant. For sedimentary rocks, no significant relationship between N and UCS was observed. There is a statistically significant relationship between UCS and L, which remains relatively stable after controlling for N. For metamorphic rocks, no significant relationship between UCS and L or N was initially observed. However, after controlling for N, a borderline statistically significant relationship between UCS and L is revealed.

Table 4. Results of the statistical tests. UCS is the average UCS value, L is the average lateral dimension, rho is the value of the Spearman rho, Partial rho is the value of the Spearman rho controlled for R and p-FDR is the false discovery rate adjusted p-value for the corresponding test. Shown for igneous, sedimentary and metamorphic separately, and for all together.

	UCS vs L				**UCS vs N**	
	rho	p-FDR	Partial rho	p-FDR	rho	p-FDR
Igneous	-0.363	0.002	-0.279	0.010	0.328	0.003
Sedimentary	-0.357	0.003	-0.368	0.002	0.036	0.750
Metamorphic	0.255	0.250	0.411	0.041	0.396	0.068
All	-0.313	8.5E-5	-0.312	3.3E-5	0.055	0.485

3 Discussion and concluding remarks

Analysis of the compiled data indicates that existing empirical size-effect relationships are affected by two recurring issues: a systematic reduction in statistical sample size with increasing physical specimen size, and insufficient rigour in the selection and use of statistical tests. Both factors can distort the apparent significance of relationships between UCS and specimen size. Substantial variability was also observed in the specimen dimensions and slenderness ratios within individual groups. Consequently, multiple interpretations are possible, and the presented correlations should be used with caution.

Studies investing scale-effect should be designed with statistical considerations in mind. Specifically, the statistical sample size should be kept constant across physical specimen size groups, appropriate statistical tests should be selected, and their assumptions routinely evaluated against the dataset. In the combined dataset, negative associations were revealed for igneous and sedimentary rocks, whereas a positive association was observed for metamorphic rocks. These findings do not imply the existence of a universal relationship between UCS and specimen size, nor that such a relationship can be reliably represented by a numerical formula. The database spans numerous locations, rock types, grain sizes, laboratories and seven decades of testing, resulting in pronounced heterogeneity. Such variability, both within and between groups limits the ability to isolate and interpret scale-effects and highlights the importance of incorporating statistical considerations at the experimental design stage.

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