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TECHNICAL NOTE

Calculation of Mohr-Coulomb Parameters for Rocks of Doha, Qatar

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Abstract

Among practitioners, designers and researchers, modern-day geotechnical software packages still predominantly use Mohr-Coulomb (MC) input modelling parameters, despite the immense computing power of today's software and hardware components. The same particularly applies to this field of work in the state of Qatar. The goal of this technical note is to demonstrate the most appropriate derivation method for Mohr-Coulomb parameters, by proving that this must ensue by first obtaining or estimating proper Hoek-Brown parameters, followed by appropriate method for conversion. Only such an approach can remove uncertainty and high variability of results in geotechnical estimations and design inputs.

Keywords: Qatar; Doha; Rocks; Calculation; Mohr-Coulomb; Hoek-Brown

1 Introduction

This technical note is based on the data and results from Vucemilovic et al. (2021), previous works and publications of Evert Hoek and his co-researchers, and on previous publications on Qatari rock masses that have dealt with providing Mohr-Coulomb parameters. Previous works on this particular subject thus include Fourniadis (2010), Karagkounis et al. (2016) and Vucemilovic et al. (2021). Their results are summed up in table 1, and include cohesion and friction angle values for three geological members/ layers of rock masses of Doha Qatar, which are Simsima Limestone (SL), Midra Shale (MSH) and Rus Formation (RUS).

In his paper Fourniadis (2010) cites Hoek et al. (1995) as the conversion method, whereas Karagkounis et al. (2016) cite Hoek et al. (2002) along with Carter et al. (2008) and Latapie and Lochaden (2016). Karagkounis et al. (2016) also mention "adequate maximum confining stresses" in relation to their findings but it is unclear if triaxial tests were used or not, however no such result data were presented. Neither of two (groups of) authors gave any further specifics in terms of equations or data except the final value ranges. As we can see in table 1, data reported by Vucemilovic et al. (2021) are significantly different than those for other two authors, and the authors indicated that these results were obtained by improper conduction of triaxial tests, where confinement σ_3 loads were insufficiently large, except by chance, for RUS member. Results from final three rows of the table 1 are calculated and elaborated further down the contents of this paper.

Table 1. Mohr-Coulomb data from previous authors on Qatari rock masses and this technical note

Author	**Layer/Member**	***c* [MPa]**	***φ* [deg]**
Fourniadis (2010)	SL	0.14 – 0.65	21 – 32
Karagkounis et al. (2016)	SL	0.03 – 0.44	21 – 47
	MSH	0.04 – 0.35	33 – 46
	RUS	0.03 – 0.20	30 – 48
Vucemilovic et al. (2021)	SL	0.10 – 3.00	53 – 79
	MSH	0.50 – 3.20	55 - 73
	RUS	0.10 – 2.60	42 - 79
This technical note	SL	1.12	24.57
	MSH	0.82	25.39
	RUS	0.69	28.94

In their paper, Vucemilovic et al. (2021) have stated that rock masses of Doha, Qatar, should be treated as applicable for Hoek-Brown (HB) criterion, since they are sufficiently strong and above the transition zone towards soils according to classification proposals by Carter et al. (2008) and Carvalho et al. (2007). The only exception is the RUS member which can be considered as falling under the top region of this zone, but even so, the Carvalho et al. (2007) transitional parameters are hardly changed from Hoek et al. (2002) outset parameters s, a, and m_b (Vucemilovic et al. 2021). The table 2 shows the intact rock parameters obtained by Vucemilovic et al. (2021), where the authors, deprived of possibility to obtain HB parameters for SL and MSH geological members, resorted to auxiliary solutions from other authors (Arshadnejad and Nick 2016 and Cai 2010). The addition to the table as it appeared in Vucemilovic et al. (2021) is the "This tech. note" column.

Table 2. Summary of the derived m_i and related values from equations by several authors[a] (Vucemilovic et al. 2021) with added adopted values of m_i

		HOEK and BROWN 1980a		HOEK et al. 2002			ARSHADNEJAD and NICK 2016		CAI 2009	This tech. note	CARVALHO et al. 2007			
	n	σ_{ci}	m_i	a	s	m_b	m_b	m_i	*R index (UCS/ BTS)*	**Adopted values of m_i**	$f_T(UCS)$	s^*	a^*	m_b^*
SL	123	12.54	*179.2*	0.51	0.00127	*21.02*	0.774	**6.60**	**7.75**	**6.50**				
MSH	33	14.41	*78.0*	0.51	0.00142	*9.48*	0.843	**6.94**	**8.36**	**7.00**				
RUS	57	18.15	**8.23**	0.50	0.00345	**1.33**	**1.457**	**9.01**	**12.51**	**8.50**	0.00213	0.00557	0.501	**1.35**

[a] *italic* = incoherent results; **bold** = good agreement; **bold** = adopted values

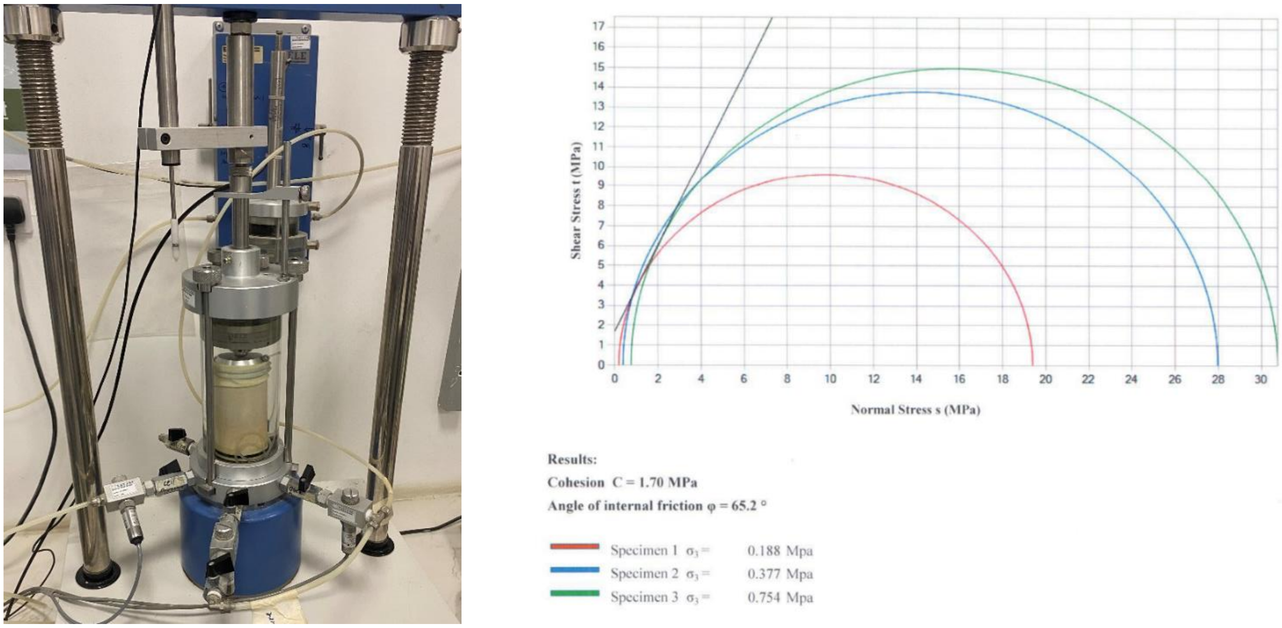

Figure 1. Inappropriate devices (left) and methods (right) for execution and elaboration of triaxial tests reported by Vucemilovic et al. (2021)

The triaxial data reported by Vucemilovic et al. (2021), as all other triaxial data to author's best knowledge, were obtained with above shown (figure 1) equipment and method, by local commercial geotechnical laboratories. The figure 1 (left) shows a triaxial apparatus which is elsewhere in the world used for soft soil (clays) testing. It is capable of reaching a confinement load of maximum 1.7 MPa which is insufficient for local rock samples and it produces the pressure with water. Figure 1 (right) shows the method of obtaining MC parameters *c* and *φ*. The $\sigma_1 - \sigma_3$ data pairs are graphically plotted and Mohr circles are drawn from them, however with insufficiently large confinement load, the tangent gives very steep *φ* angles. This derivation method is described in ASTM D7012-10 (2010) standard.

2 HB criterion and MC conversion

During the development of the Hoek-Brown criterion, between 1983 and 2002, Hoek (et al.) gave a total of six different methods of conversion to MC parameters, for equal number of HB criterion major development steps. These methods were laid out in Hoek (1983), Hoek (1990), Hoek et al. (1992), Hoek et al. (1995), Hoek and Brown (1997) and Hoek et al. (2002). Of these six, only two of the methods are applicable for the problem at hand, where triaxial data pairs σ_1 and σ_3 are available only, as opposed to proposals where effective stresses are known, e.g. for slope, tunneling and other problems. These are Hoek (1983) and Hoek & Brown (1997) approaches. The expressions for Hoek (1983) are as follows:

$$\sigma_n' = \sigma_3' + \frac{\left(\sigma_1' - \sigma_3'\right)^2}{2\left(\sigma_1' - \sigma_3'\right) + \frac{1}{2} m\sigma_c} \tag{1}$$

$$\tau = \left(\sigma_1' - \sigma_3'\right)\left(1 + \frac{m\sigma_c}{2\left(\sigma_1' - \sigma_3'\right)}\right)^{1/2} \tag{2}$$

$$\phi_i^{'} = 90 - \arcsin\left(\frac{2\tau}{\left(\sigma_1^{'} - \sigma_3^{'}\right)}\right) \tag{3}$$

If equations (1) to (3) are applied to triaxial results for RUS member from Vucemilovic et al. (2021), incoherent results are obtained, in spite of the fact that the triaxial results yielded a coherent m_i parameter result. Only the first five data point results are shown in table 3, and it is visible in the right-most column that such results are obtained where the argument of the arcsin function, from equation (3) is larger than unity. Thus, the method cannot give the desired results, since data do not allow it.

Table 3. Sample calculation of MC values from triaxial test results for RUS member, from Hoek (1983) equations (1) to (3)

σ_3 = X	**σ_1**	**Y**	**XY**	**X^2**	**Y^2**	**σ_n**	**τ**	**$2\tau/(\sigma_1 - \sigma_3)$**
0.3	9.41	82.99	24.90	0.09	6887.69	1.46	23.81	5.23
0.3	25.00	610.09	183.03	0.09	372209.81	6.25	43.84	3.55
0.65	10.41	95.26	61.92	0.42	9074.01	1.96	24.77	5.08
0.6	15.68	227.41	136.44	0.36	51713.67	3.33	32.07	4.25
0.4	6.88	41.99	16.80	0.16	1763.19	1.04	19.65	6.06

The only other approach which is applicable for MC values to be obtained from principal stresses from triaxial tests is that of Hoek & Brown (1997). This approach is the reverse of core Hoek-Brown principle where m_i constant is calculated from triaxial test results. Triaxial data pairs are simulated to produce eight data pairs in the range $0 < \sigma_3 < 0.25$ *UCS*. The full details of the procedure are laid out in Hoek & Brown (1997), Appendix C. Theoretical equations that represent the method, which are an amalgam of Hoek & Brown (1997) and earlier works, are equations (4) to (16). In this approach one must know, or correctly assume the m_i value. In our case, we must make the best assumption for the intact rock constant m_i values based on the results from table 2, which is not a straightforward task, and there are no guarantees that the chosen values are the optimal. The chosen values are shown in table 2 under "this tech. note" column, and are estimated from obtained value of m_i for RUS, Arshadnejad & Nick (2016) values and on Cai (2009) *R-index* values and how they relate to each other for three geological members. It is also visible that the values increase with depth.

$$\tau = A\sigma_{ci}\left(\frac{\sigma^{'} - \sigma_{tm}}{\sigma_{ci}}\right)^B \tag{4}$$

$$\log\left(\frac{\tau}{\sigma_{ci}}\right) = \log A + B\log\left(\frac{\sigma^{'} - \sigma_{tm}}{\sigma_{ci}}\right) \tag{5}$$

$$Y = \log A + BX \tag{6}$$

$$\sigma_{tm} = \frac{\sigma_{ci}}{2}\left(m_b - \sqrt{m_b^2 + 4s}\right) \tag{7}$$

$$\sigma_{cm} = \sqrt{s\sigma_c} \tag{8}$$

$$\sigma_1^{'} = \sigma_{cm} / \sigma_{ci} + k\sigma_3^{'} \tag{9}$$

$$\sin\phi^{'} = \frac{k-1}{k+1} \tag{10}$$

$$c^{'} = \frac{\sigma_{cm}}{2\sqrt{k}} \tag{11}$$

$$\sigma_n^{'} = \sigma_3^{'} + \frac{\sigma_1^{'} - \sigma_3^{'}}{\partial\sigma_1^{'}/\partial\sigma_3^{'} + 1} \tag{12}$$

$$\tau = \left(\sigma_1^{'} - \sigma_3^{'}\right)\sqrt{\partial\sigma_1^{'}/\partial\sigma_3^{'}} \tag{13}$$

$$\frac{\partial\sigma_1^{'}}{\partial\sigma_3^{'}} = 1 + \frac{m_b\sigma_{ci}}{2\left(\sigma_1^{'} - \sigma_3^{'}\right)} \tag{14}$$

$$B = \frac{\sum XY - \frac{\sum X \sum Y}{T}}{\sum X^2 - \frac{\left(\sum X\right)^2}{T}} \tag{15}$$

$$A = 10^{\wedge}\left(\sum Y / T - B\sum X / T\right) \tag{16}$$

3 Conversion for SL, MSH and RUS geological members

Below, the conversion to Mohr-Coulomb parameters is demonstrated according to Hoek & Brown (1997), Appendix C, by combining applicable data from table 2, and Vucemilovic et al. (2021).

Input SL

UCS = sigci =	26.7 MPa		m_i = mi =	6.5		GSI =	40

Output SL

m_b = mb =	0.76		s =	0.0013		a =	0.5	
σ_{tm} = sigtm =	- 0.0445	MPa	A =	0.3991		B =	0.6850	
k =	2.48		φ = phi =	25.20	deg	c = coh =	0.839	MPa
σ_{cm} = sigcm =	2.64	MPa	E =	2905.7	MPa	scme =	3.7	MPa

Tangent output SL

σ_{ni} = signt =	5.17	MPa	φ_t = phit =	**24.57**	deg	c_t = coht =	**1.12**	MPa

Input MSH

UCS = sigci =	18.8 MPa		m_i = mi =	7.0		GSI =	41

Output MSH

m_b = mb =	0.85		s =	0.0014		a =	0.5	
σ_{tm} = sigtm =	- 0.0314	MPa	A =	0.4164		B =	0.6874	
k =	2.57		φ = phi =	26.06	deg	c = coh =	0.614	MPa
σ_{cm} = sigcm =	1.97	MPa	E =	2582.7	MPa	scme =	2.8	MPa

Tangent output MSH

σ_{ni} = signt =	3.70	MPa	φ_t = phit =	**25.39**	deg	c_t = coht =	**0.82**	MPa

Input RUS

UCS = sigci =	12.9	MPa	m_i = mi =	8.5		GSI =	49

Output RUS

m_b = mb =	1.38		s =	0.0035		a =	0.5	
σ_{tm} = sigtm =	-0.0324	MPa	A =	0.4962		B =	0.6936	
k =	2.97		φ = phi =	29.71	degrees	c = coh =	0.520	MPa
σ_{cm} = sigcm =	1.79	MPa	E =	3390.7	MPa	scme =	2.8	MPa

Tangent output RUS

σ_{ni} = signt =	2.71	MPa	φ_t = phit =	**28.94**	deg	c_t = coht =	**0.69**	MPa

Table 4. Calculation results for MC parameters for SL (top), MSH (middle) and RUS (bottom) according to Hoek & Brown (1997)

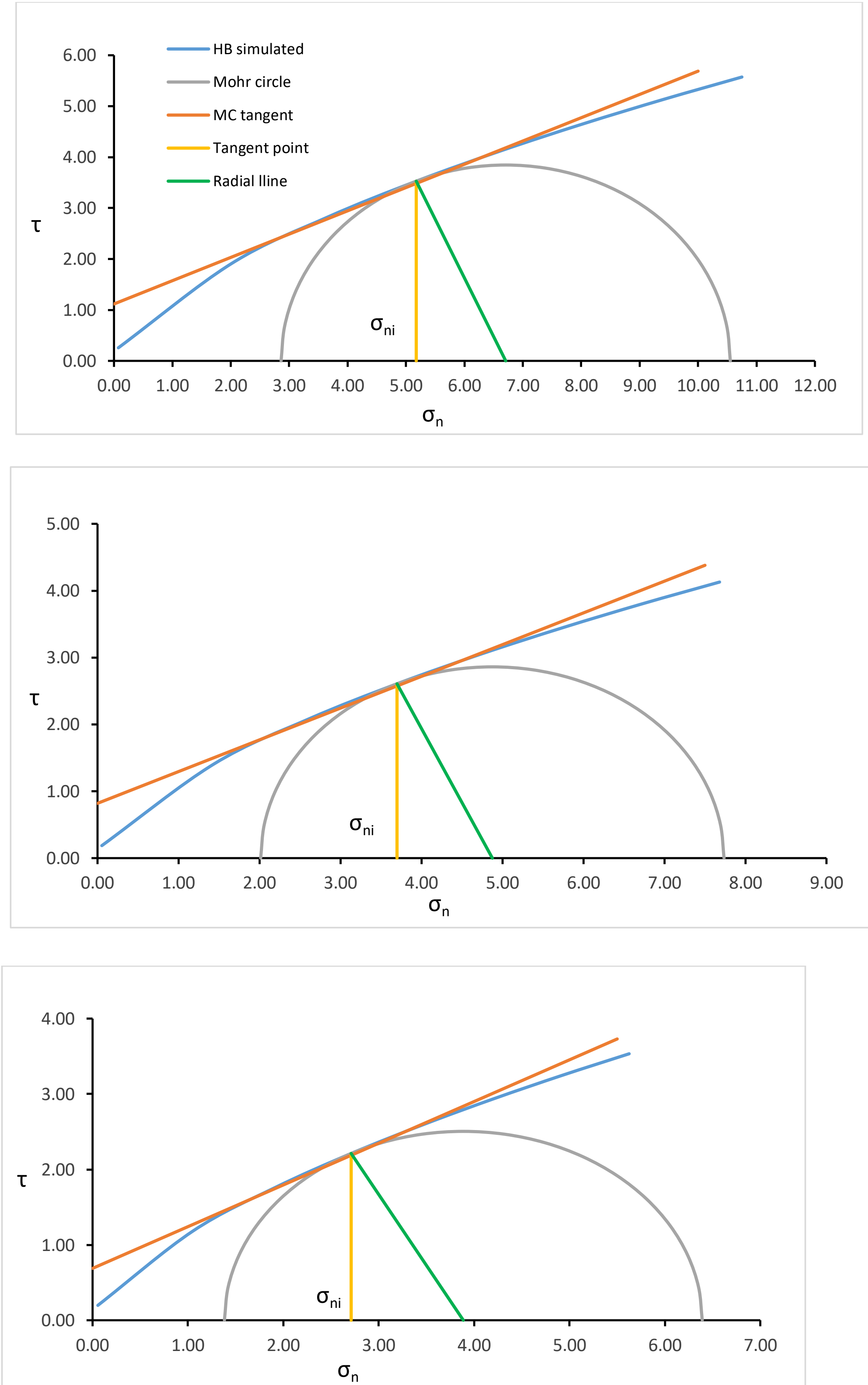

Figure 2. Graphics of MC conversion for SL (top), MSH (middle) and RUS (bottom) according to Hoek & Brown (1997)

4 Verification

In comparing the above methods, for results on Qatari rocks (table 1), we first have to note the result ranges and variability which is present with all methods, except for Hoek & Brown (1997) approach. As already mentioned earlier, the method of converting directly from triaxial tests with low confinement loads gives exceedingly high friction angles, whereas the cohesion results are in reasonable agreement with Hoek & Brown (1997) method. Cohesion values from Fourniadis (2010) and Karagkounis et al. (2016) are considerably lower. From all this, we can only preliminarily conclude that Hoek & Brown (1997) method likely gives the most realistic MC values. Reservations still remain however, being that in this case Hoek & Brown (1997) approach can only provide the simulated triaxial values, based on the most educated estimates of m_i from table 2. The author reiterates here that correctly performed triaxial tests, with confinement load of up to 50 % of average *UCS* value are the most accurate method of determining HB parameters, followed by conversion to MC parameters.

However, if we compare the results from this technical note with results of other selected authors who obtained MC values for sedimentary rocks, we can observe the findings in the below table 4. We can see that friction angle values reach above 35 degrees, predominantly only for substantial cohesion values. For cohesion values just above zero or on the lower side, the friction angles rarely exceed 30 degrees, or only go slightly over. We can say that this confirms with greatest probability that Hoek & Brown (1997) approach gives the most accurate cohesion and angle of friction values. This further puts values of Fourniadis (2010) within acceptable range, whereas Karagkounis et al. (2016) value ranges are likely exceedingly high.

In their work Latapie and Lochaden (2016) have criticized the Hoek & Brown (2002) conversion method to MC parameters, citing the fact that it only uses confinement stress range up to 0.25 *UCS*, as a shortcoming (in the same manner as Hoek & Brown 1997 procedure), in particular for slope and retaining wall problems. They also cited the fact that Intermediate Ground materials are governed by shear strength of the rock mass, rather than by discontinuities, as is often the case for hard, more intact rocks, and Karagkounis et al. (2016) have implicated that this applies to Qatari rock masses. What concerns this issue, it was already shown by Vucemilovic et al. (2021) that Qatari rock masses, for most part, are not Intermediate Ground material, and even softest RUS member characteristics conform to a very limited extent to its' criteria (average UCS was recorded at 12.9 MPa and transitional HB variables' changes from Carvalho 2007 are minor as seen in table 2). Furthermore, if we consider the tendencies of most triaxial test results, further moving along the HB envelope curve towards higher $\sigma_1 - \sigma_3$ pairs only yields a flatter tangent (smaller φ) and a slight increase in cohesion. Thus, employing of a σ_3 range higher than $0 < \sigma_3 < 0.25$ *UCS* would presumably not yield higher φ values.

Table 5. Summary of MC parameters for sedimentary rocks from other selected authors

Author	**Rock type**	***UCS* magnitude/ range [MPa]**	***φ* magnitude/ range [deg]**	***c* magnitude/ range [MPa]**
Bejarbaneh et al (2015)	Iranian shale	17.45	32.4	5.83
Armaghani et al. (2014)	Iranian shale	19.0 – 47.0	20.5 – 40.1	-
Bell (2007)	Kirkheaton mudrock	34.4 – 69.9	38 – 47	0 – 5.0
Shen et al. (2012)	theoretical	30.0	20.96 – 26.71	0.15 – 0.21
Goodman (1989)	Bartesville sandstone	-	37.2	8.0
Goodman (1989)	Indiana limestone	-	42.0	6.7
Goodman (1989)	Hasmark dolomite	-	35.5	22.8
Goodman (1989)	chalk	-	31.5	0
Miščević & Vlastelica (2009)	Croatian marl	-	32.0 – 35.0	6.0 – 7.0
This technical note	Qatari rocks	12.9 – 26.7	24.6 – 28.9	0.69 – 1.12
Fourniadis (2010)	Qatari rocks (SL only)	5.0 – 12.0	21.0 – 32.0	0.14 – 0.65
Karagkounis et al. (2016)	Qatari rocks	4.0 – 23.0	21.0 – 48.0	0.03 – 0.44

5 Conclusions

- Calculation of Mohr-Coulomb parameters for Qatari rocks should follow either after correctly performing triaxial tests (confinement load up to 0.5 *UCS* after Hoek 1980a), and after obtaining the resulting m_i values; OR after correctly estimating the m_i values via other means, and simulating the triaxial results with m_i, *GSI* and *UCS* results as per this technical note in accordance with Hoek & Brown (1997), Appendix C procedure.
- This paper has also demonstrated that m_i values follow the tendency of the *R-index* which represents the ratio of compressive to tensile intact strength, and that tensile strength of subject Qatari rocks drops more pronouncedly with depth than the drop of compressive strength (as shown in Vucemilovic et al. 2021) which points to m_i increasing with depth, at least down to RUS Calcareous layer.
- This method gives a range of friction angles for Doha intact rocks between 24.0 – 30.0 degrees whereas the cohesion values are between 0.5 – 1.5 MPa. The values are reported down to deepest layer which is RUS calcareous.

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Declarations

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Availability of data and material: The datasets generated during and/or analyzed during the current study are not publicly available due to proprietary confidentiality but are available from the author on reasonable request.

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