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COMMISSION 38

C38 "Rockmass Characterization with Emphasis in Rock Slope Hazards"

How Reliable Are Hand Calculation Methods Used for Selection of Strength of Geomaterials for Slope Design?

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WORKSHOP
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IAEG Commission C38 "Rock slope hazards"

Geomaterial is any natural material occurred by the geological processes.
Soil is uncemented grained geomaterials including grain size from clay to boulder
Rock mass is a geomaterial composed of combination of rock material (intact rock) and discontinuities.
Complex geological formations is used to define any kind of geological complex materials such as melanges and mixed masses with blocks-in-matrix fabrics.

↓

There is an unlimited variety of geological materials in nature.

↓

Strength and deformation parameters of geological materials are the fundamental parameters used in design of engineering application.

↓

Realistic design is only possible when your input parameters are reliable and representative for in-situ conditions of geomaterials.

By laboratory studies:

✓Soils → are commonly suitable geomaterials to investigate their engineering properties in laboratory. However, some acceptable design parameters can also be obtained by in-situ test such as STP, CPT, plate loading test etc.

X Complex formations → The most difficult geological materials for engineering design. It is almost impossible to select design parameters without engineering experiences.

- Jointed rock mass → Limited number of laboratory tests are available in literature. It requires specific test equipment. However, their reliability are generally questionable due to the scale effect

↕

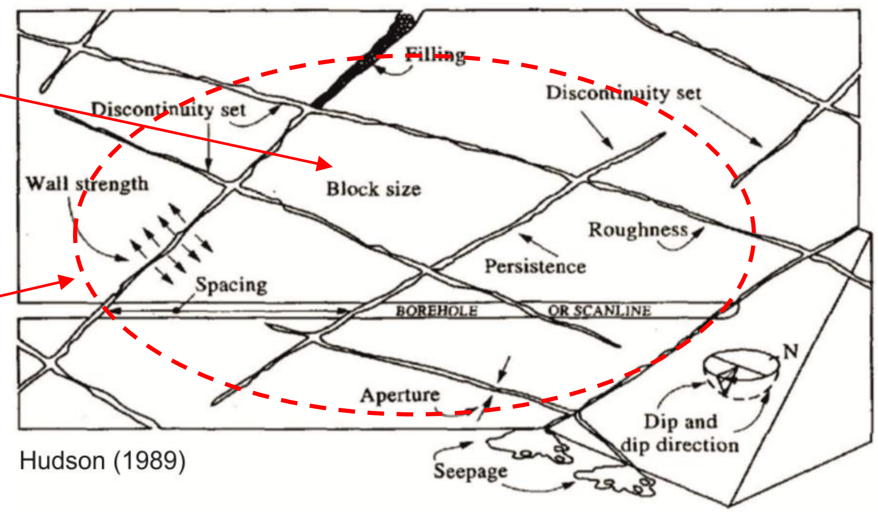
Lets focus on jointed rock mass in this presentation for reliability evaluation of the strength determination used in engineering design.

Jointed rock mass is a geomaterial composed of rock material (intact rock) and rock discontinuities.

- ✓ Determination of strength parameters of **intact rock** generally can be determined by laboratory studies.

However,

- ✓ Determination of strength parameters of **rock masses** including joint pattern are almost impossible by laboratory test due to the difficulties encountered in preparation of undisturbed samples and generally unavailability of suitable testing equipment in usual testing laboratories.



Hudson (1989)

Engineering properties of jointed rock mass is controlled by both:

intact properties + properties of discontinuties

- To overcome this difficulty, empirical approaches have been developed as user-friendly design tools after the 1950s.
- Because, we try to make simplification in the complexity of nature by classifying rock masses into similar groups in terms of geomechansics.

Some of known classifications

Classification System	Reference
Rock Load	Terzaghi (1946)
Stand-up time	Laufer (1958)
New Australian Tunnelling Method (NATM)	Rabcewicz (1964/65)
Rock Quality Designation (RQD)	Deere et al. (1968)
Rock Structure Rating	Wickham et al. (1972)
Rock Mass Rating (RMR)	Bieniawski (1973, …, 1989)
Modified Rock Mass Rating (M-RMR)	Unal and Ozkan (1990)
Rock Mass Quality (Q)	Brton et al. (1974, .., 2002)
Strength-Block Size	Franklin (1975)
Rock Mass Strength (RMS)	Stille et al. (1982)
Slope Mass Rating (SMR)	Romana (1993)
Rock Mass Index (RMi)	Palmström (1996)
Geological Strength Index (GSI)	Hoek and Brown (1997)
Anisotropic Rock Mass Rating (ARMR)	Saroglou et al (2018)

+

Empirical equations

Ratings from classifications such as RQD, RMR, Q, GSI have been **widely used** as an input for development of empirical equations and empirical criteria for predicting of overall strength and deformation modulus of rock masses

Let's remind reliability and probability of failure

Reliability of any geomechanical parameters can be defined as a **degree of representability of in-situ conditio**n.

For example:

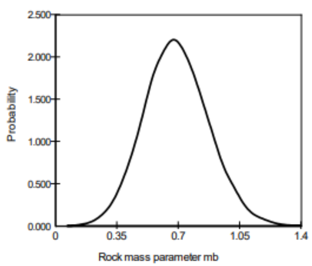
UCS=75 MPa; the question is how much this value is reliable ?

Obtained from:
- Direct measurement on standard core samples
- Point load tests
- Schmidt hammer values
- Block Punch Index
- ....

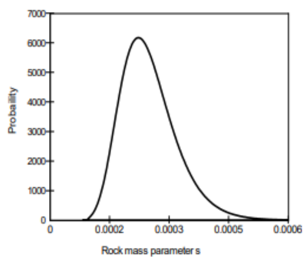
GSI=48, the question is how much this value is reliable ?

Obtained from:
- Expert base original GSI chart
- Quantified GSI charts
  - Sonmez and Ulusay (1999 or 2002)
  - Cai et al. (2004)
  - Russo (2009)
  - Hoek et al. (2013)
  - Schlotfeldt and Carter (2018)
  - ....

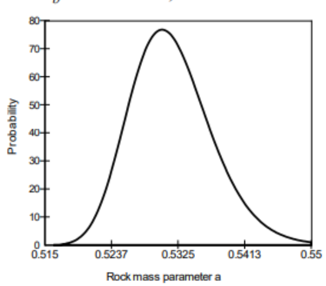
Probability of failure (P): It defines event is how much close to occurrence ? The value of P varies between 0 and 1. But, it never meets to 0 or to 1.



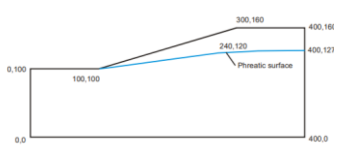
m_b - Mean 0.689, Stdev 0.183



s – Mean 0.00025, Stdev 0.00007

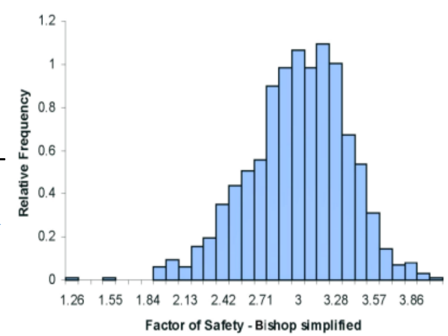


a – Mean 0.532, Stdev 0.00535



Example from Hoek's Corner in Practical Rock Engineering

Probabilistic calcu-lation tool in Slide



Probability of failure goes to ZERO, it means that this case is safe based on probabilistic calculations.

Factor of Safety (FOS) and what it means with its probability distribution?

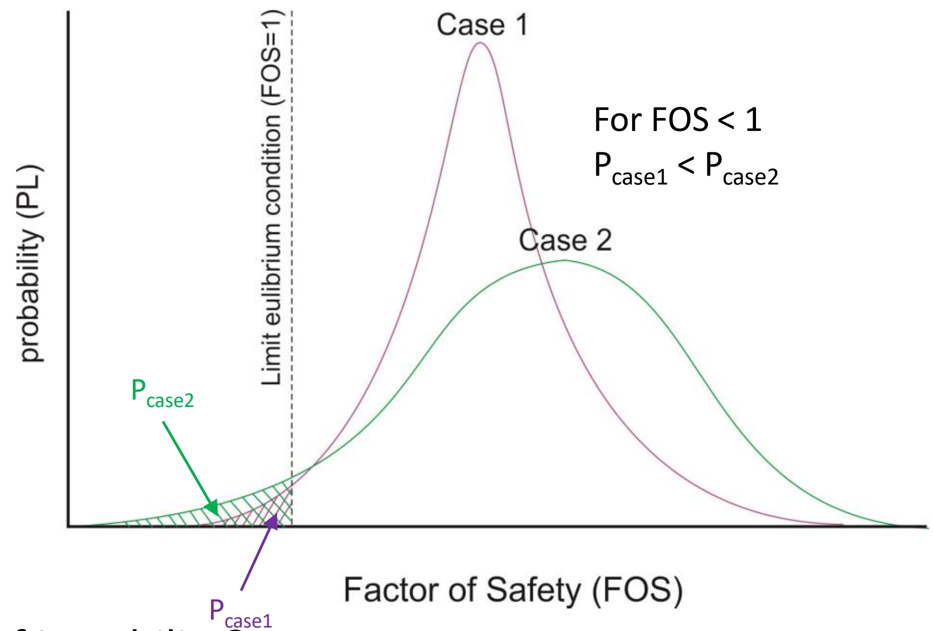
We can compare them by the results of two hypothetic slope cases

In deterministic approach, average values of inputs are used.

Case 1	Case 2
$FOS_{average}$=1.6	$FOS_{average}$=2.0

Q: Which one have better safety condition ?
A: Case 2 ☺

The probabilistic based outputs of FOS is obtained by using statistical distribution of inputs.



Q : which case have higher probability of instability?
A: Case 1 ☺

(modified from an example given at http://www.ib.pwr.wroc.pl/wpula/W11.pdf)

Therefore, probabilistic safety calculations in slope design is strongly dependent to the statistical distribution of inputs.

- Of course, probabilistic approaches are scientifically important.
- But, sufficient large database of inputs are necessary to obtain meaningful statistical evaluations.
- The reliability of input parameters are very important.

Let's take into consideration of reliability concept on the Hoek and Brown failure criterion ?

Inputs of HB

UCS → obtained from mainly laboratory tests or from some index tests (degree of uncertainty or probability distribution may be determined without personal experiences).

mi → obtained from evaluations of triaxial test results employed on intact cores, or can be selected based on type of rock from the published charts. (degree of uncertainty or probability distribution may be determined without personal experiences).

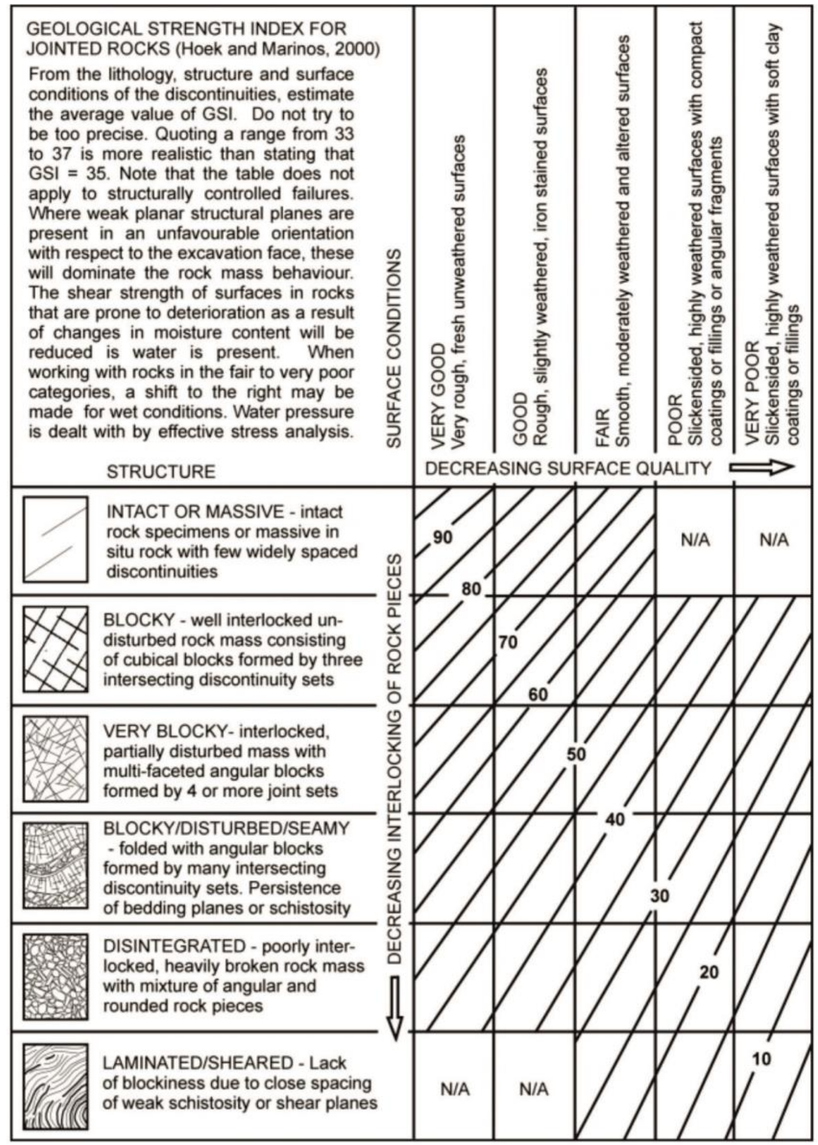
D: disturbance factor. Although some guides were given literature, expert base selection is required.

GSI → from original chart or from any quantified chart? What about its reliability ?

Brief History of Geological Strength Index (GSI)

- ✓ Rock Mass Rating (RMR) had been used in the Hoek and Brown criterion until the beginning of 1990s.
- ✓ However, although the Hoek and Brown failure criterion has capability of the use of quality of rock mass between 0 to 100, RMR is not sensitive for weak to very weak rock masses especially RMR<25.
- ✓ To overcome this difficulty, Hoek and Brown (1997) presented the first version of the GSI chart.
- ✓ Then, Marinos and Hoek 2000, Marinos and Hoek 2001 proposed the latest form of the GSI chart.

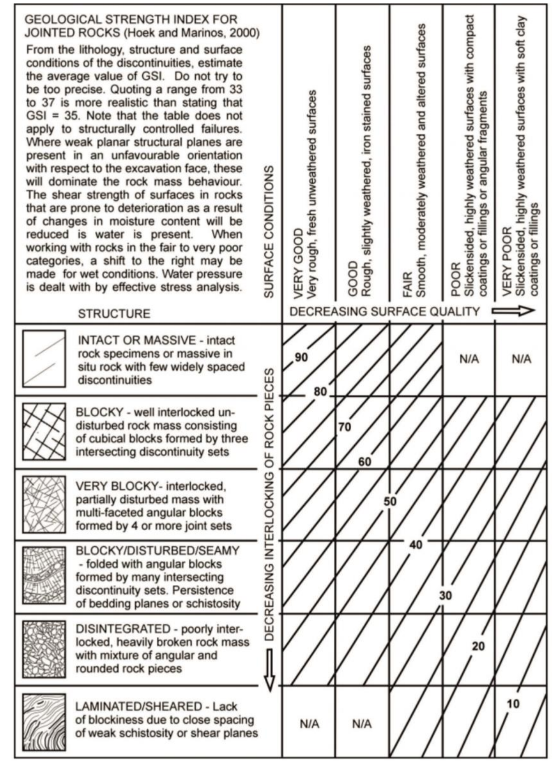
Some additional efforts were also spent by P. Marinos, E. Hoek and V. Marinos for adapting of GSI chart to heterogeneous rock masses.



CAUTION by the authors

GEOLOGICAL STRENGTH INDEX FOR JOINTED ROCKS (Hoek and Marinos, 2000)

From the lithology, structure and surface conditions of the discontinuities, estimate the average value of GSI. Do not try to be too precise. Quoting a range from 33 to 37 is more realistic than stating that GSI = 35. Note that the table does not apply to structurally controlled failures. Where weak planar structural planes are present in an unfavourable orientation with respect to the excavation face, these will dominate the rock mass behaviour. The shear strength of surfaces in rocks that are prone to deterioration as a result of changes in moisture content will be reduced is water is present. When working with rocks in the fair to very poor categories, a shift to the right may be made for wet conditions. Water pressure is dealt with by effective stress analysis.



- The originator of the system do not proposed to be too precise ?

Why ?

- Because of some possible uncertanities of the geology

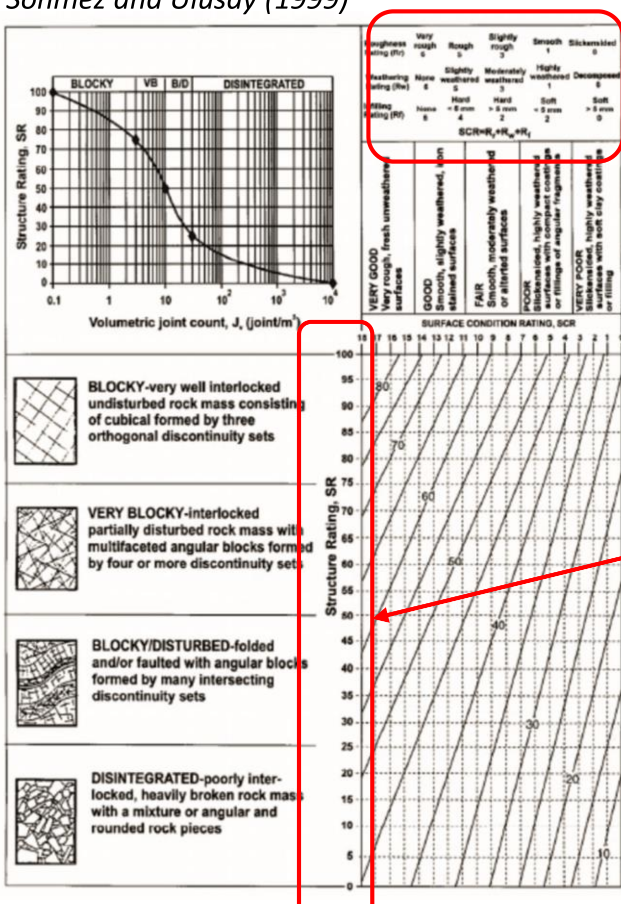
The original form of GSI should not be used by limited experienced practitioner. **Besides, it may be evaluated as rough for probabilistic approach**. Standart deviation of GSI may be expected high when we use the original GSI chart.

Quantification studies on GSI

Requirements of quantification study performed by Sonmez and Ulusay (1999)

- The original form of GSI was applicable by the limited experienced practitioner.
- To minimize the necessity of experience and/or judgement and also avoiding of possible incorrect assessments.
- In the original GSI chart → While the GSI varies continuously from 0 to 100 on the original GSI chart, only 20 boxes is defined by using some definition of rock mass structure and surface condition of discontinuities.

Sonmez and Ulusay (1999)

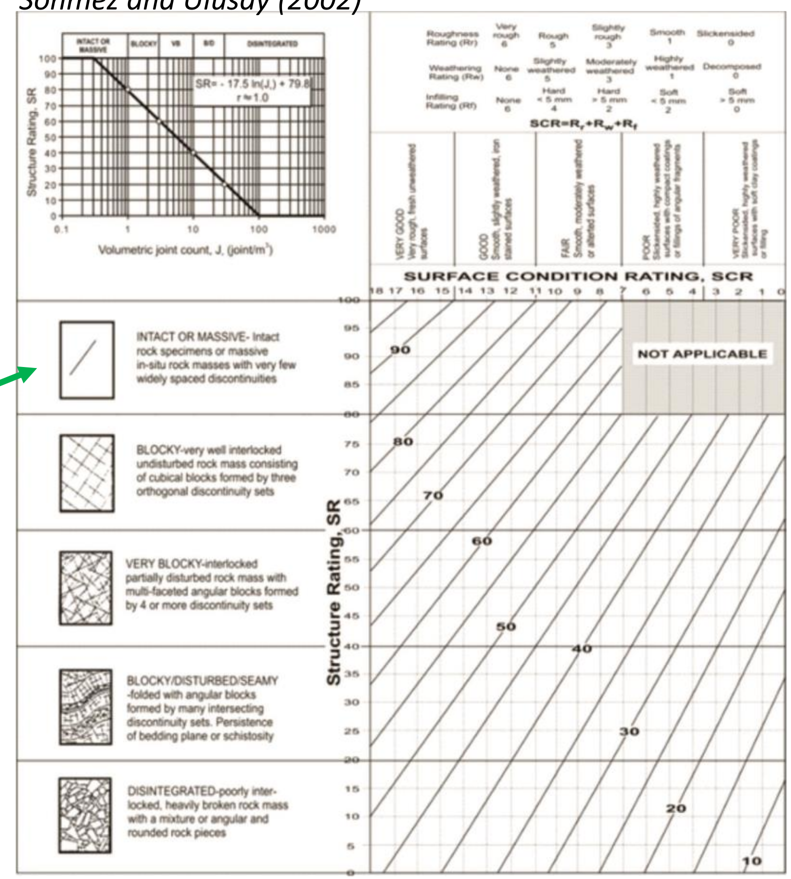


Surface Condition Rating (SRC=R_r+R_w+R_f) based on ratings of roughness, weathering and infilling given by Bieniawski (1989)

Intact or massive rock mass structure was added.

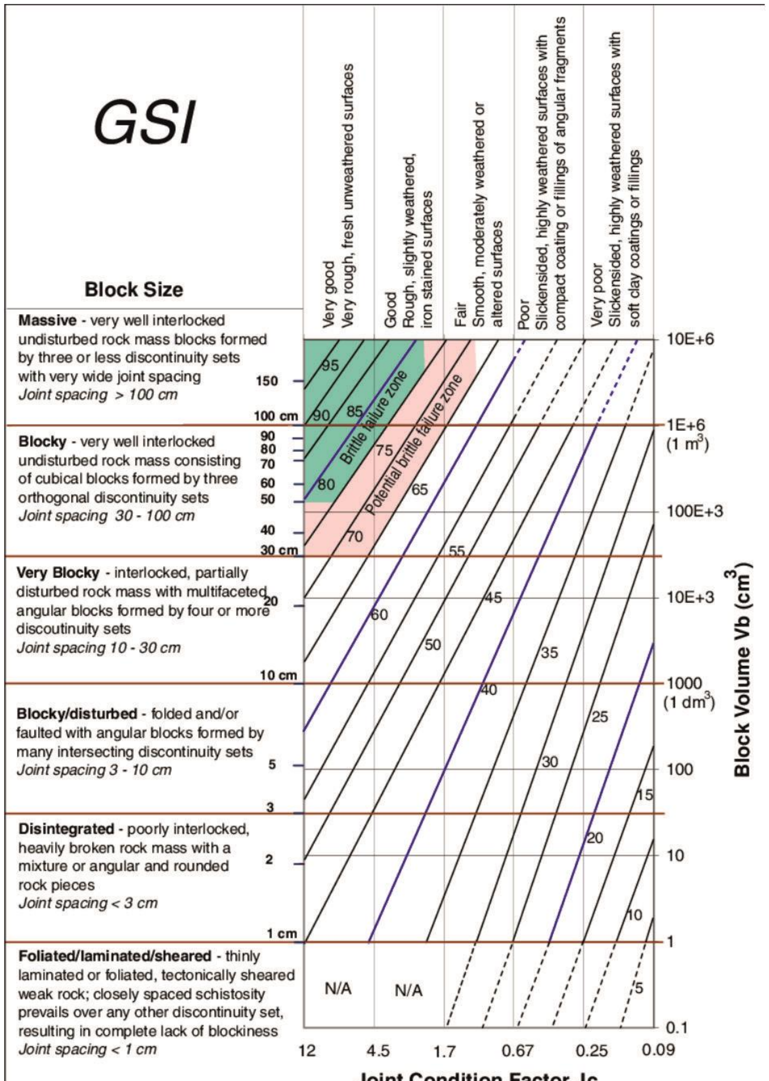
Stucture Rating (SR) considering the definition of rock mass classes based on volumetric joint count by ISRM (1981)

Sonmez and Ulusay (2002)

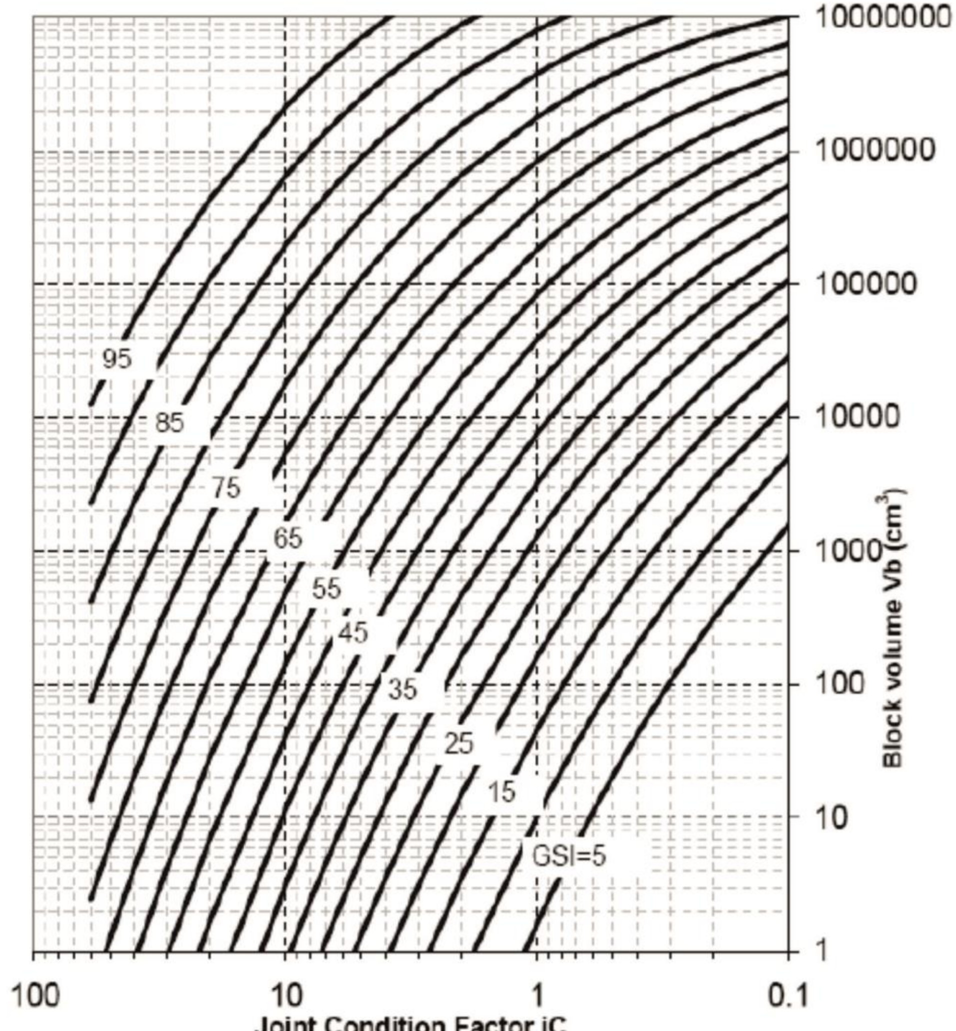


The studies have been continued about quantification of GSI chart as an attractive research subject among the rock mechanics community.

Cai et al. (2004)

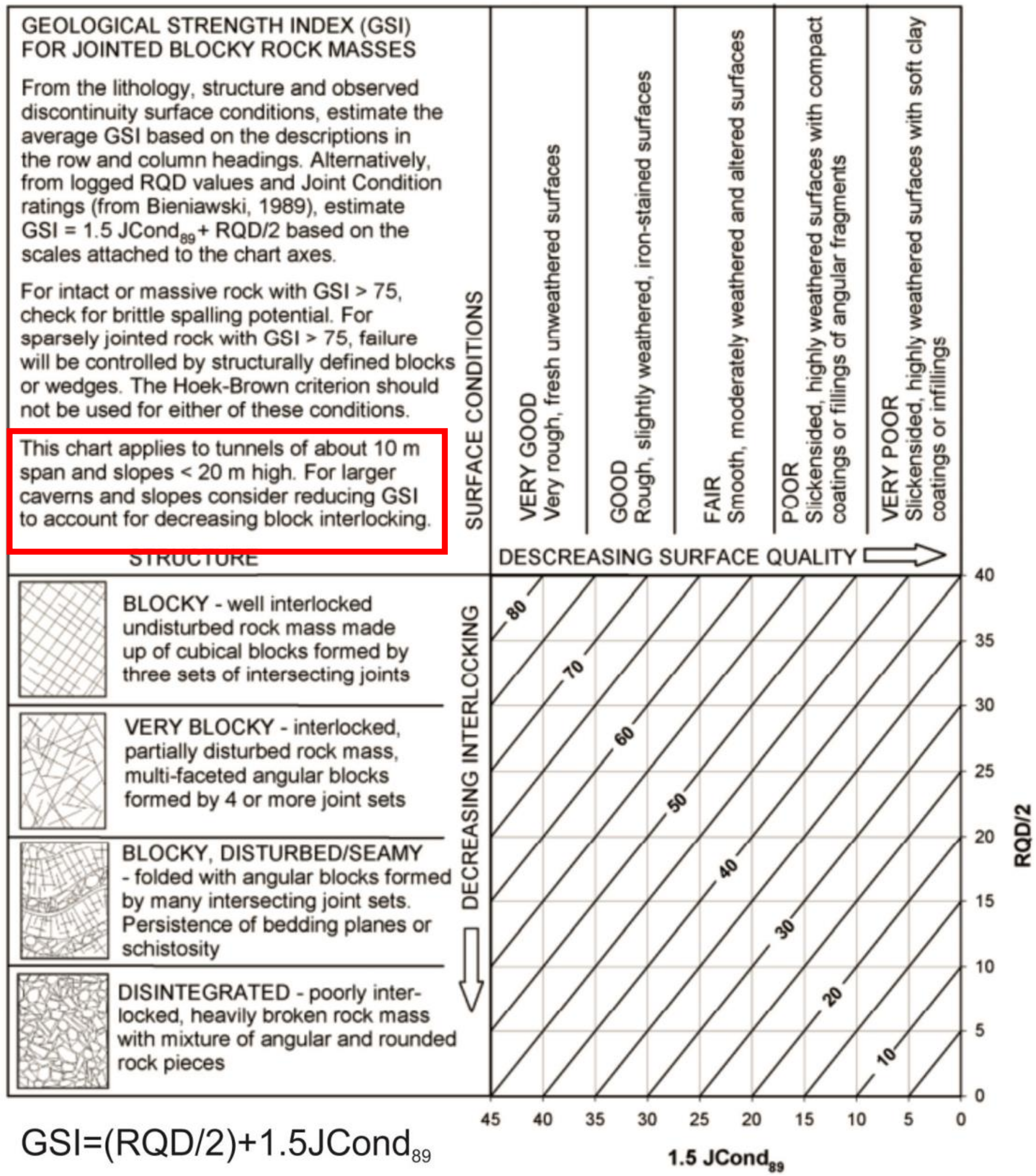


Russo (2009)



Quantification of GSI by Hoek et al. (2013)

- ✓ Hoek et al. (2013) indicated that **the original Geological Strength Index (GSI)** chart was constructed on the observations performed by **the qualified and experienced geologist or engineering geologist.**
- ✓ After the first attempt by Sonmez and Ulusay (1999), **Hoek et al. (2013) have also admitted that the quantification of GSI has been a necessity to improve its popularity and applicability.**



$GSI=(RQD/2)+1.5JCond_{89}$

Limitations:

i. The use of RQD alone for structure

ii. Limitation based on engneering dimension

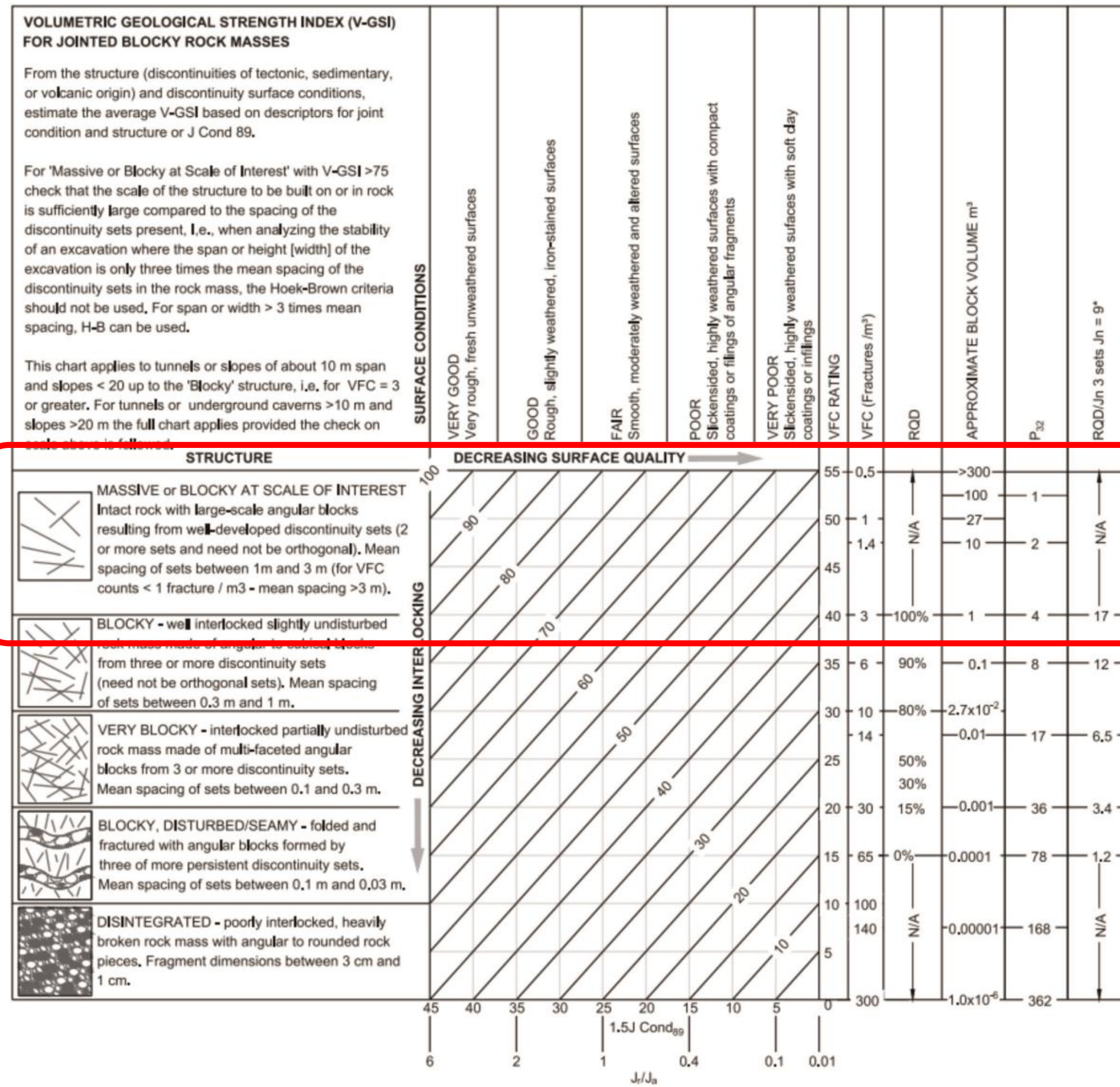
More recent study by Schlotfeldt and Carter (2018)

i. Based on Hoek et al.'s (2013) chart.

ii. In addition to RQD, VFC and Block volume are considered for structure

iii. Rock mass group «Massive or Blocky at scale interest» was added as upper row.

Improvements are mainly focussed on:



Renamed as Volumetric GSI ?

V-GSI rating = 1.5JCond89 + 50 - 8.5 ln(VFC)

Roughly can be assumed as Jv = ~ VFC

The following outcomes can be put forward as a summary for quantification studies of GSI from 1999 to recent:

- The original Geological Strength Index (GSI) chart was constructed on the observations performed by the qualified and experienced geologist or engineering geologist (Hoek et al, 2013).
- After the first attempt by Sonmez and Ulusay (1999), Hoek et al., (2013) also indicated that the quantification of GSI has been a necessity to improve its popularity and applicability. It is important for indication of necessity of quantification on GSI as originator of the HB criterion.
- Every proposal of the quantified GSI charts published in literature has its own assumptions especially on the evaluation of structure of rock masses.
- Therefore, **different GSI values** are obtained from **each other**.

Now we have to think about:

How about the reliability of GSI obtained from different quantifications ?

It seems difficult to answer this question ?

- it is not as difficult as the first thought.

- Each study in the literature has contributed to **valuable improvements on the quantification of GSI chart**.
- However, there is not a sufficiently defined procedure to cover all these scientific efforts.

We have no doubt:

Every quantification procedure of GSI yields their best based on their assumptions.

The rest of this presentation is a part of the research study performed by the following research group.

- Dr. Harun Sonmez
- Dr. Murat Ercanoglu
- Dr. Yılmaz Ozcelik
- Dr. Gulseren Dagdelenler

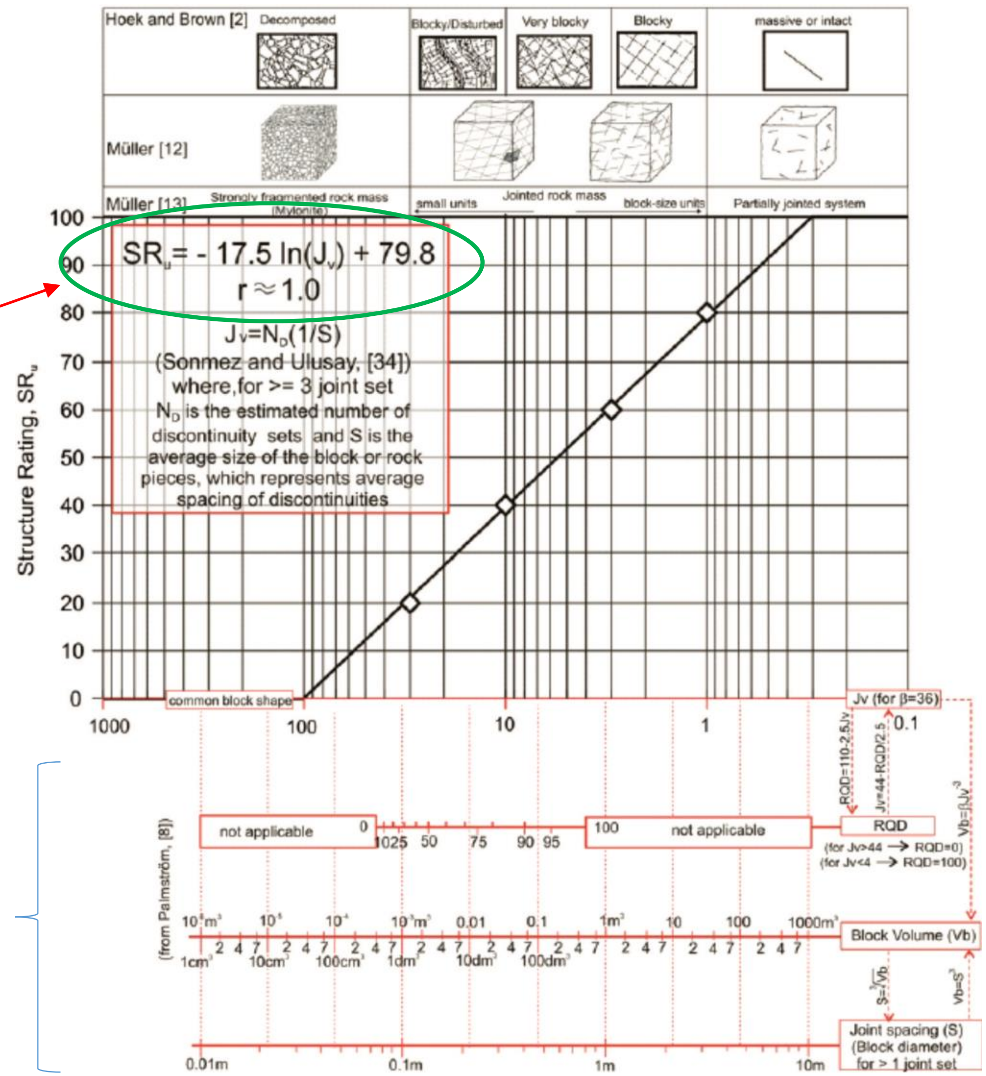
IMPORTANT NOTE:
Until the full text paper is published in a peer review journal, please cite this presentation as follows:

Sonmez H., Ercanoglu M., Ozcelik Y. and Dagdelenler G. 2021. "How Reliable Are Hand Calculation Methods Used for Selection of Strength of Geomaterials for Slope Design?" presented in the Workshop 'Rockmass Characterization with Emphasis in Rock Slope Hazard' of Commission 38 (C38-IAEG) in 3rd European Regional Conference of IAEG.

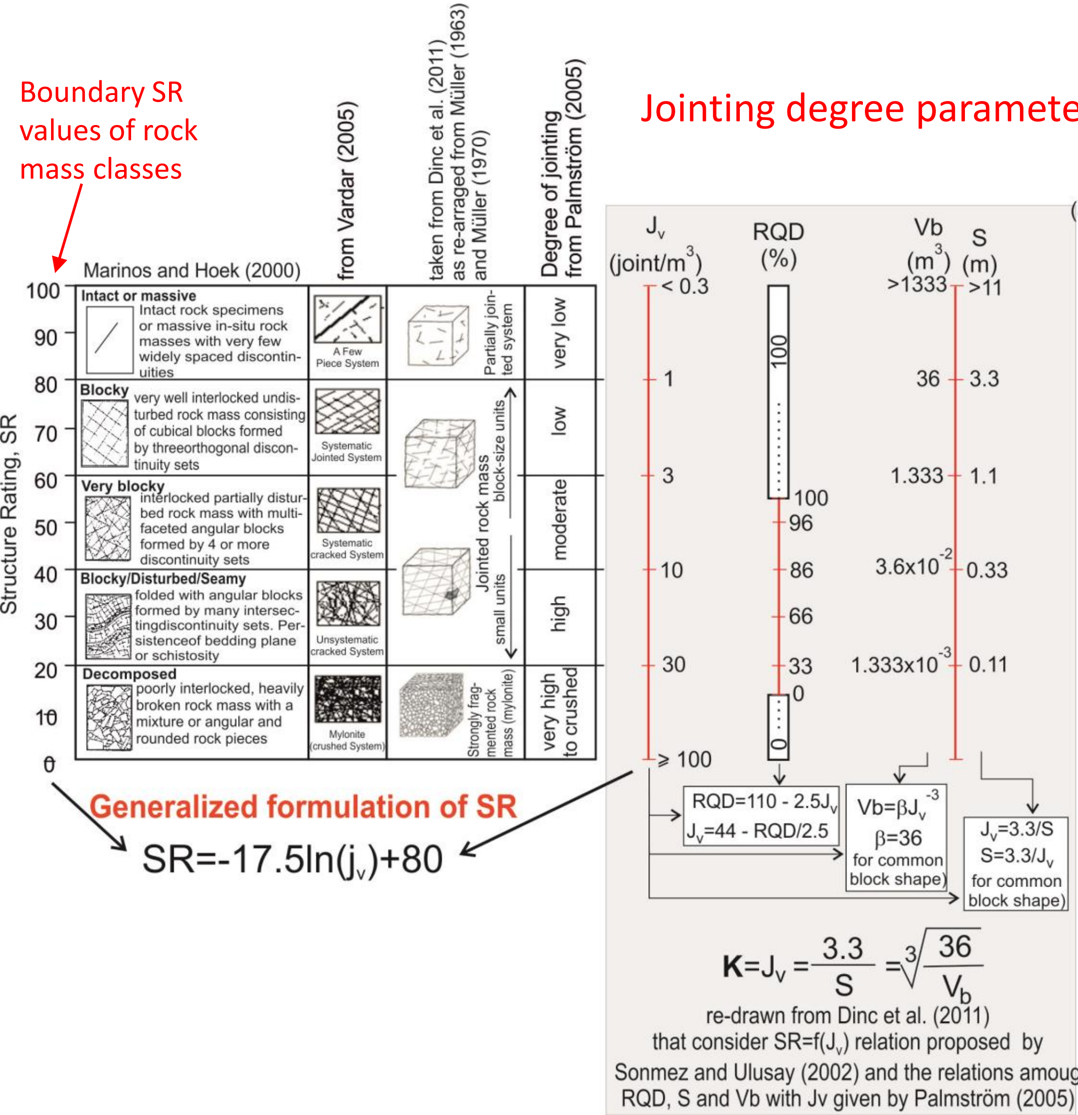
A modification to SR is developed by using SR formulation by Sonmez and Ulusay (2002), and its updating by Dinc et al. (2011)

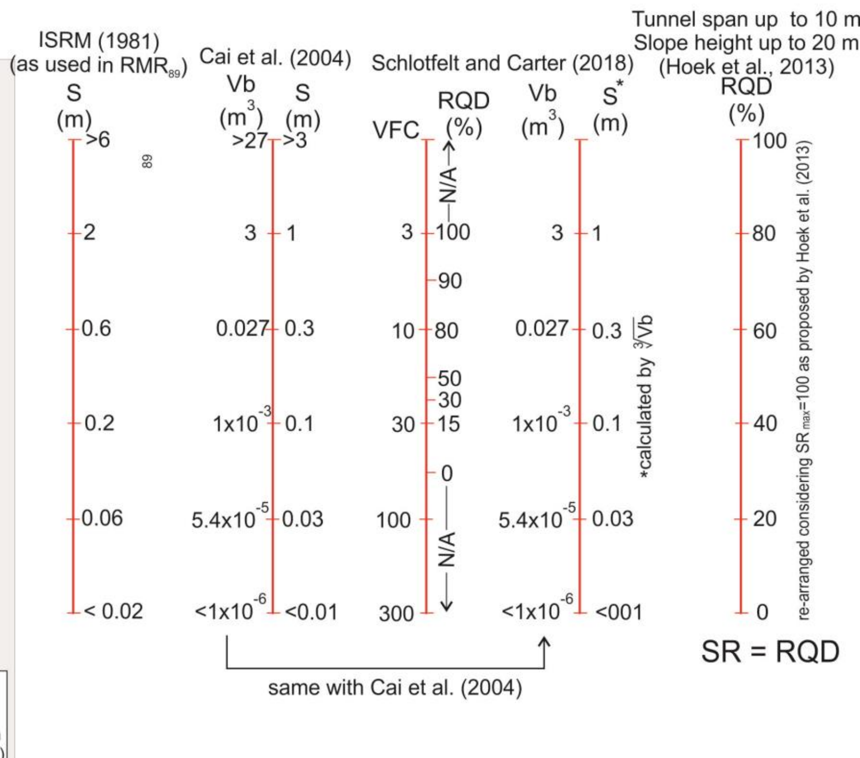
Proposed relation between Jv and SR by Sonmez and Ulusay (2002)

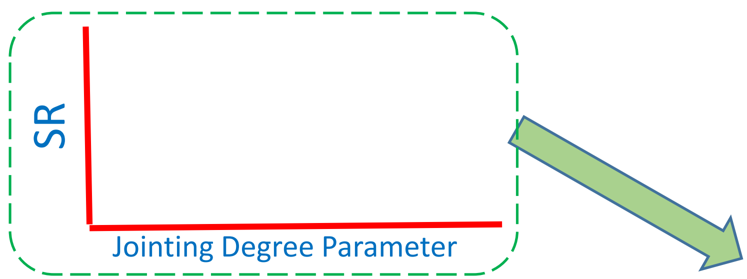
From Palmström (2005)



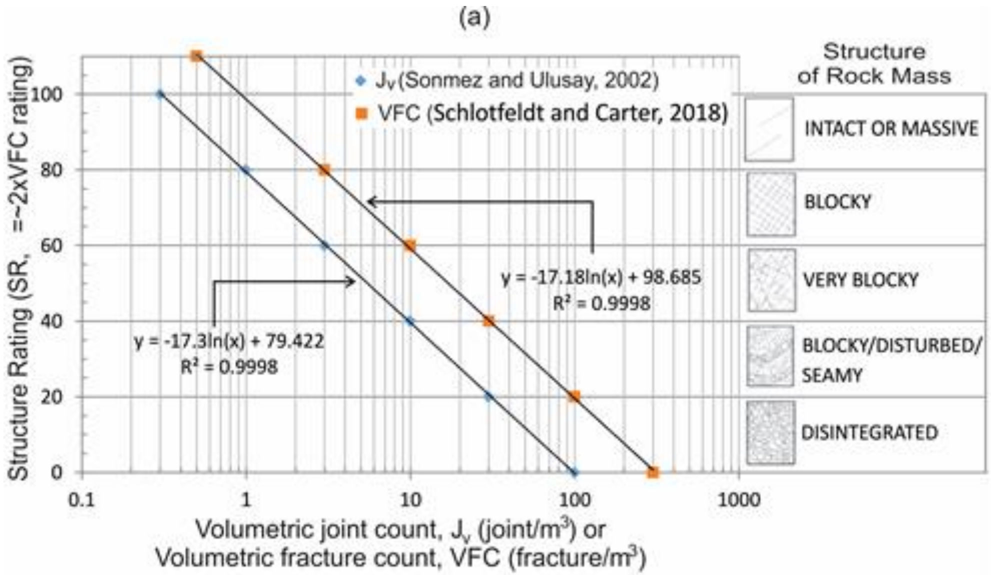
Jointing degree parameters proposed by the various studies in literature







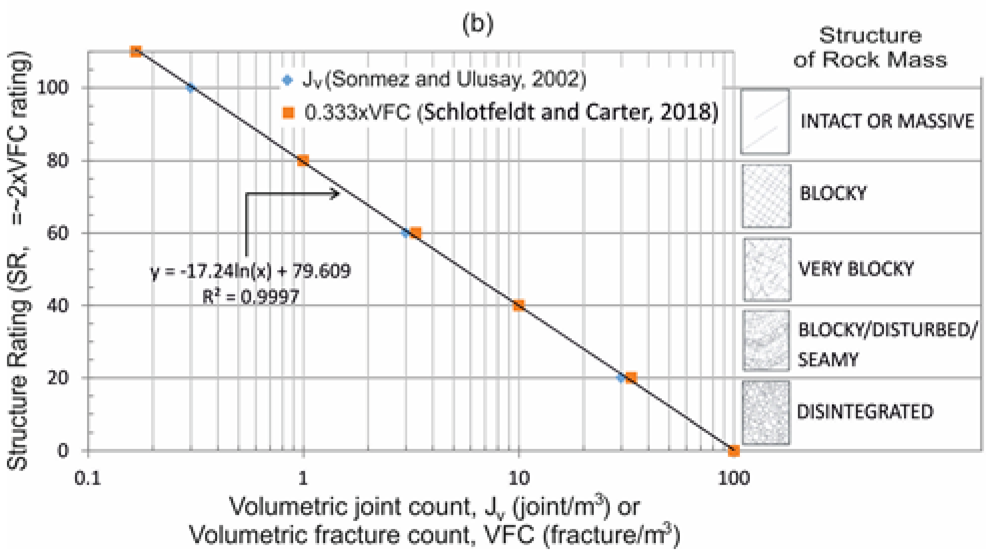
The use of Jv (=~VFC) in SR equation.



Jv is used by Sonmez and Ulusay (2002)
VFC is used by Schlotfeldt and Carter (2018)

(a) Relations of SR (=~2xVFC rating) based on J_v and VFC

when the values of VFC multiplied by 0.333, then **both proposals are overlapped**.

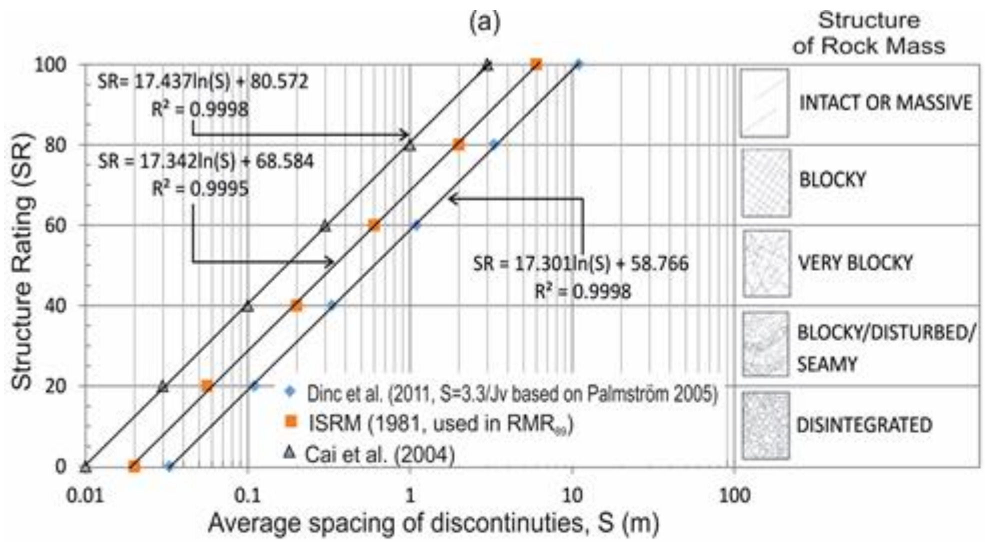


(b) Relations of SR (=~2xVFC rating) based on J_v and 0.333xVFC as input

Multiplier = 0.333

For *Schlotfeldt and Carter, 2018*

The use of discontinuity spacing ($S_{average}$) in SR equation.

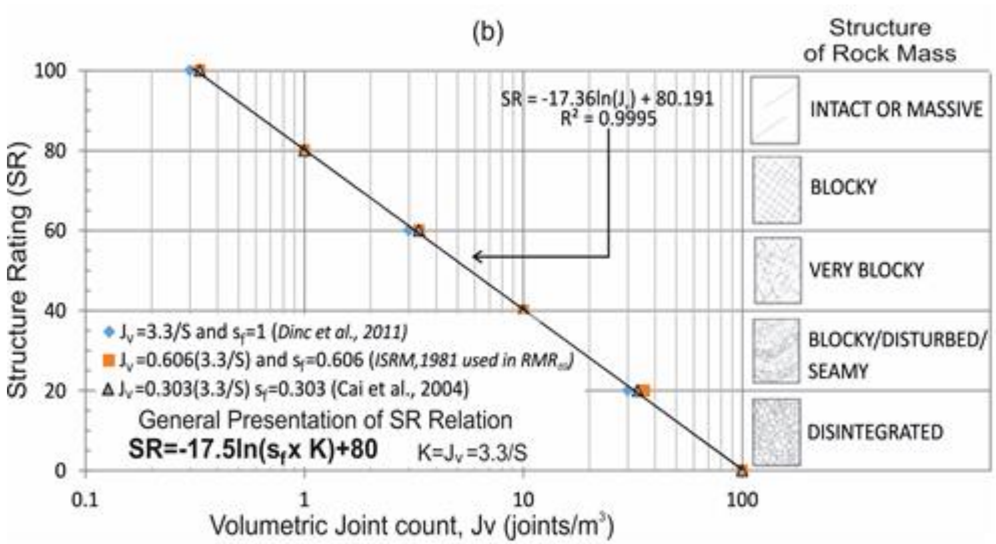


Blue points (Dinc et al.,2011)

Brown points (ISRM 1981)

Black points (Cai et al., 2004)

(a) Relations of SR based on intervals suggestions of S by Dinc et al. (2011), ISRM (1981) and Cai et al. (2004)



(b) the relations are overlapped when the multipliers used based on the relation between Jv and $S_{average}$.

Mutipliers

1 for Dinc et al. (2011)

0.666 for ISRM (1981)

0.333 for Cai et al. (2004)

The use of Block Volume (Vb) in SR equation.

- ✓ Block volume distribution of jointed rock mass is controlled by number, orientations and true spacing of joint sets. Therefore, determination of average block volume needs sufficient measurements including these three properties of joints and statistical evaluations of the collected data.

- ✓ On the other hand, the shape of rock blocks may be expected close to equidimensional in the isotropic jointed rock mass. Therefore, for almost isotropic jointed rock masses, the average volume of block in rock mass can practically be calculated by $V_b=S^3$. This assumption was also taken into consideration by Cai et al. (2004) for the use of V_b in their quantified GSI chart proposal.

- ✓ Therefore, the relation of $S = \sqrt[3]{V_b}$ can be used in determination of SR as a practical assumption for anisotropic rock masses.

The use of RQD in SR equation.

- Hoek et al. (2013) preferred the use of directly RQD/2 in the quantification of rock mass structure.
- The use of RQD/2 proposed by Hoek et al. (2013) was re-arranged as SR=RQD by considering RQD=0% for SR_{min} =0 and RQD=100% for SR_{max}=100 values.
- Limitations of the use of RQD from disintegrated to intact or massive rock mass structures? It seems difficult to cover all rock mass classes in GSI chart.
- Although spacing of joints has generally negative exponential statistical distribution, Hoek et al. (2013) assigned the boundary values of RQD/2 by a range of 10% for the rock mass classes defined in the original GSI chart.

Alternative relations used for determination of RQD

$$\left.\begin{aligned} RQD &= 110 - 2.5J_v \\ RQD &= 115 - 3.3J_v \end{aligned}\right\}$$ Plamström's equations

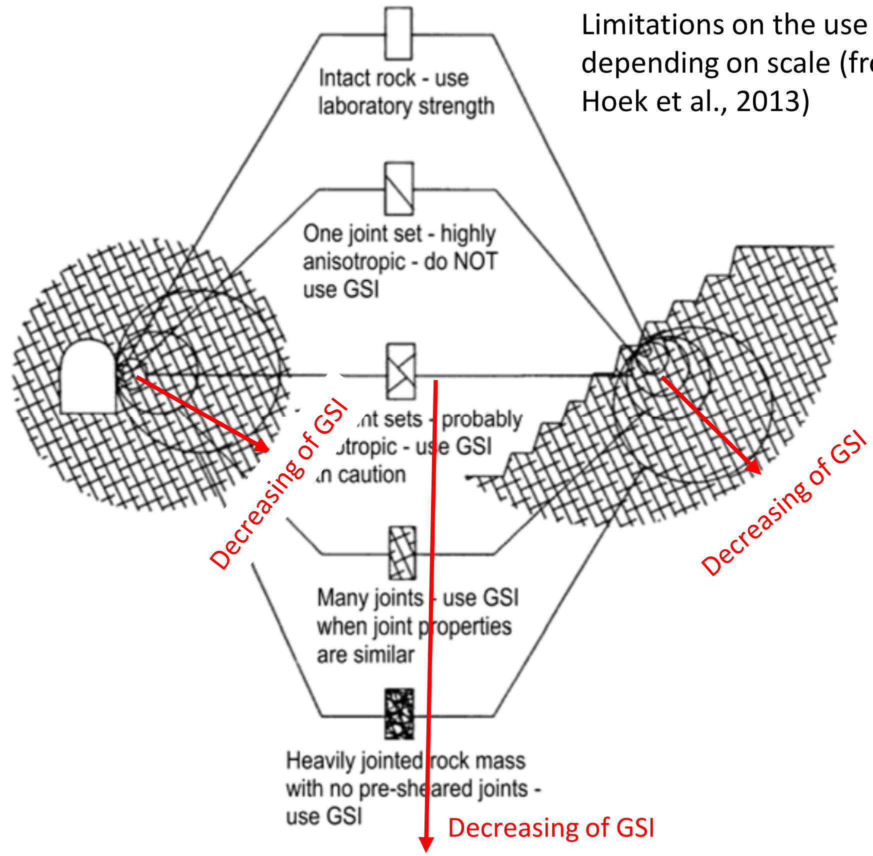
$$RQD = 100e^{-0.1\lambda}(0.1\lambda + 1)$$ Priest and Hudson (1976)

$$RQD = 110.4 - 3.68\lambda$$ Priest (1993)

Definition of scale effect on SR by using multipliers

- Hoek et al. (2013) highlight the following shortcoming in the quantified GSI charts including their study as follow:

The use of RQD by the authors or some variation of the volumetric joint count J_v or the block volume V_b, by the other authors, limits the definition of rock structure to the dimension of the blocks. ***This takes no account of the ratio of block size to the size of the tunnel or slope which, as shown in Figure, has a significant influence on the application of the GSI chart for characterizing the rock mass.***



Limitations on the use of GSI depending on scale (from Hoek et al., 2013)

✓ Some cautions were also proposed by Schlotfeldt and Carter (2018)

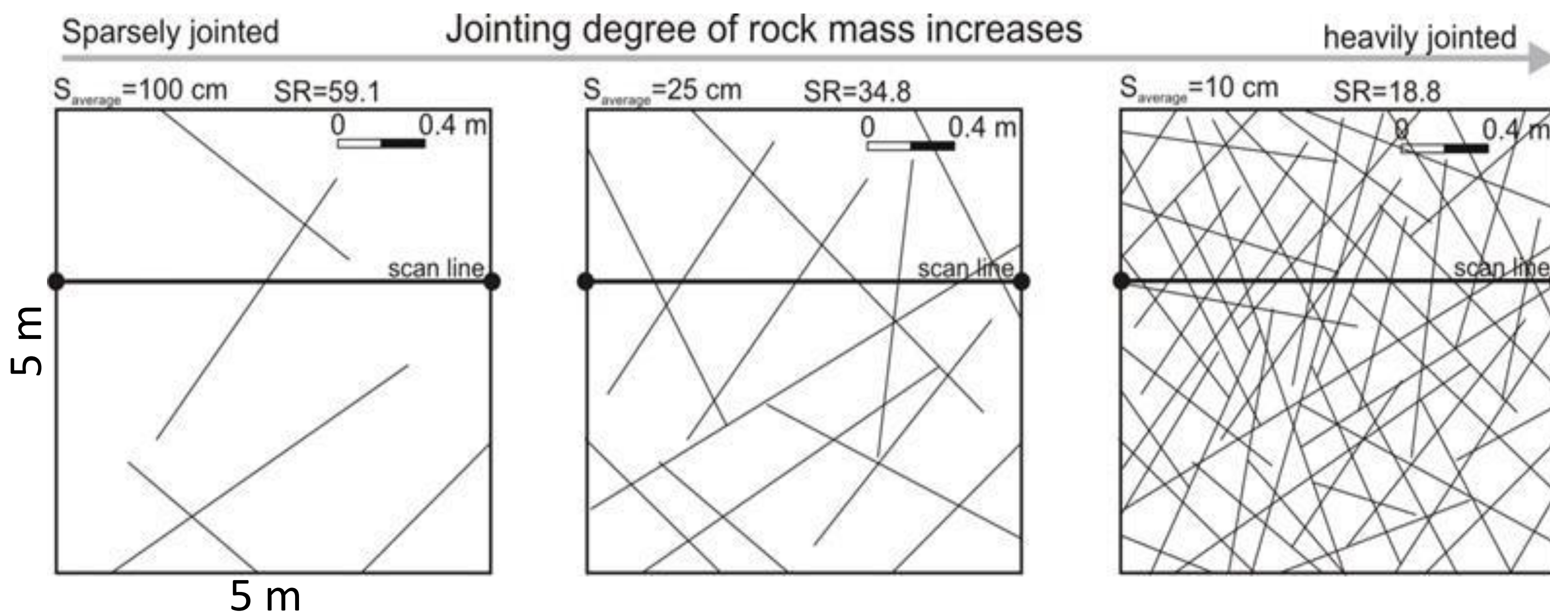
When engineering dimension increases, decrease in GSI should be expected !

- Hoek et al. (2013) limited the use of their quantified GSI chart for tunnels of about 10 m span and slopes <20 m height, and they suggested to reduce GSI value for larger caverns or slopes (caution should be given in left upper part of the quantified GSI chart.

This caution indicates the scale dependency of their GSI chart

When the volume of rock mass is kept as same:

Generally, this approach has been taken into consideration in literature



Outcome → GSI is a scale dependent parameter

<u>In fact, scale dependent component of GSI is **SR**</u>

General form of scaled SR formulation

This equation has capability to cover the known quantification efforts on GSI chart.

Scale factor (replaced by multiplier)

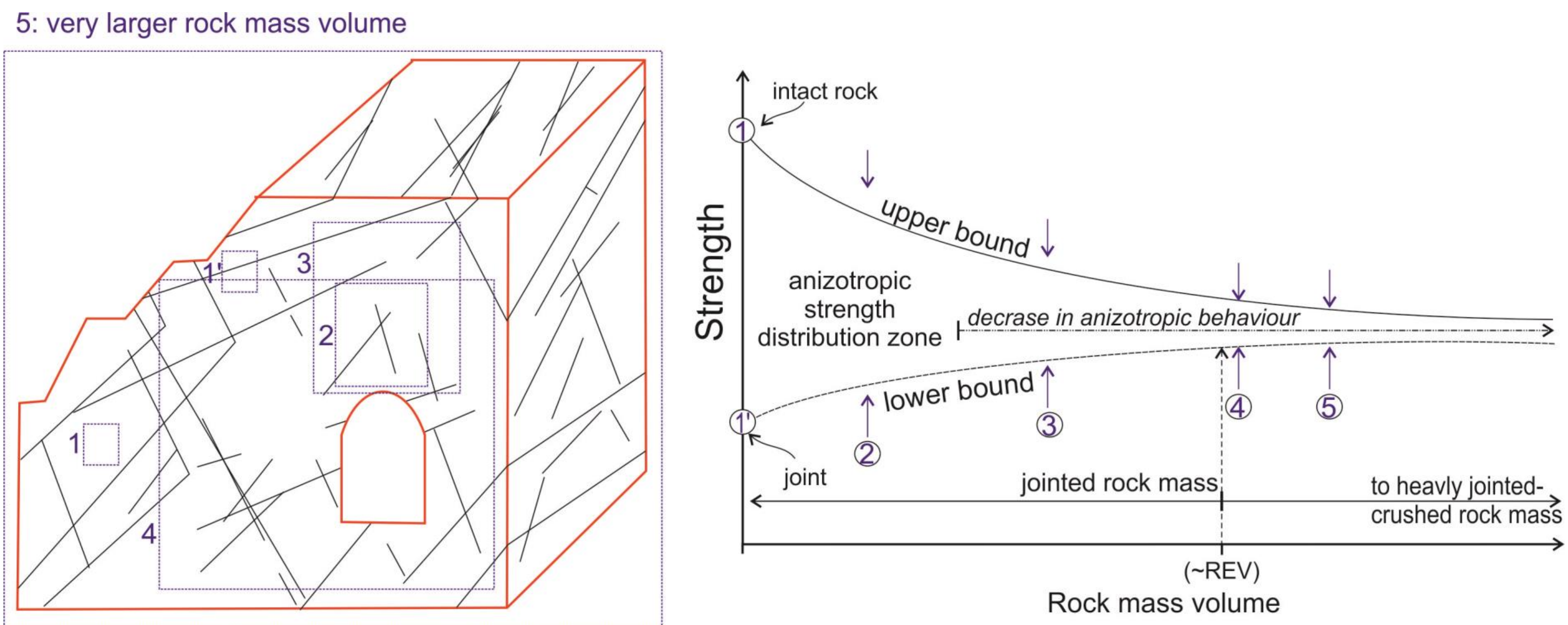
$$SR = -17.5\ln\left(s_f K\right) + 80$$

Jointing parameter

$K = J_v$ or $K = \frac{3.3}{S}$ or $K = 3.3\lambda$ or $K = \frac{3.3}{\sqrt[3]{V_b}}$ from Dinc et al. (2011, based on Palmström 2005)

where SR: Structure rating, K: Jointing parameter, s_f: Scale factor from 1 towards zero, J_v: Volumetric joint count (joints/m^3), S: average joint spacing (m), l: joint frequency (joints/m), V_b: Average rock block volume (m^3).

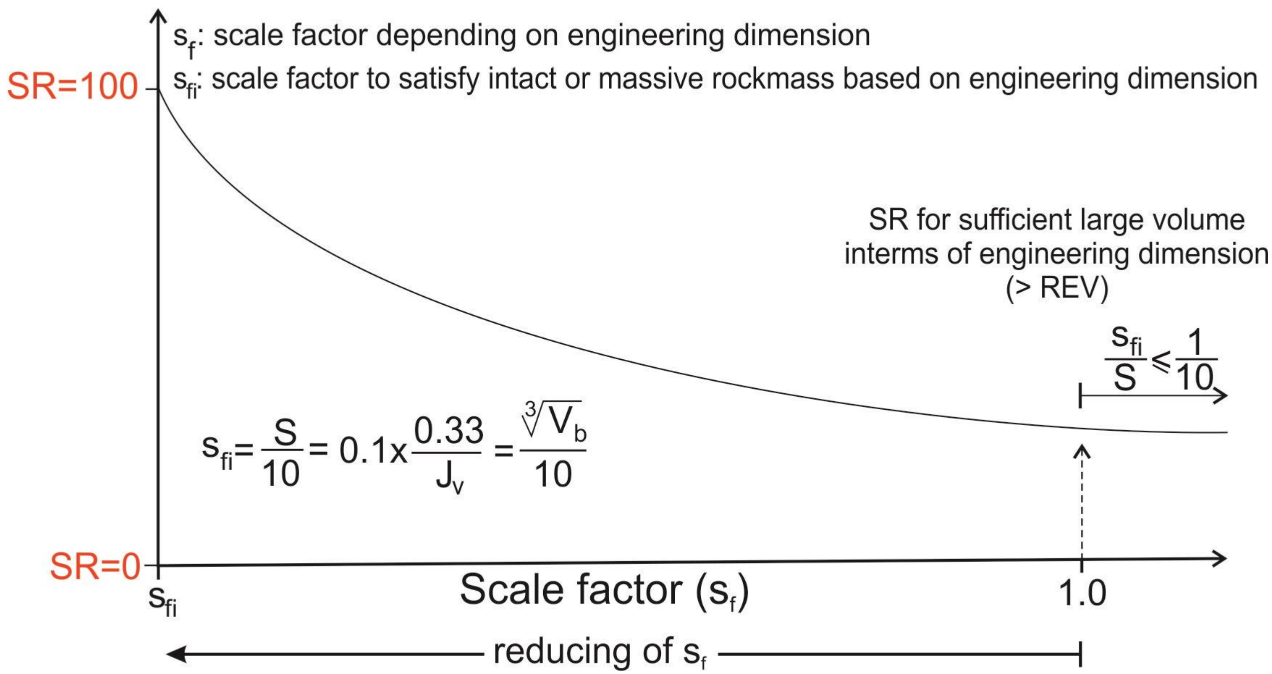
Representative Elementary Volume (REV)



Rock mass volume and strength relation depending on scale effect (modified from the studies by Farahmand et al., 2017 and Cunha, 1993)

- ✓ REV is mentioned from **<u>6 to 20</u>** in terms of applicability of the HB criterion by different researchers (Duran, 2016).
- ✓ Schlotfeldt and Carter (2018) indicated that exceedance of scale to block dimension should be **<u>at least 10</u>** or more for applicability of their V-GSI chart.

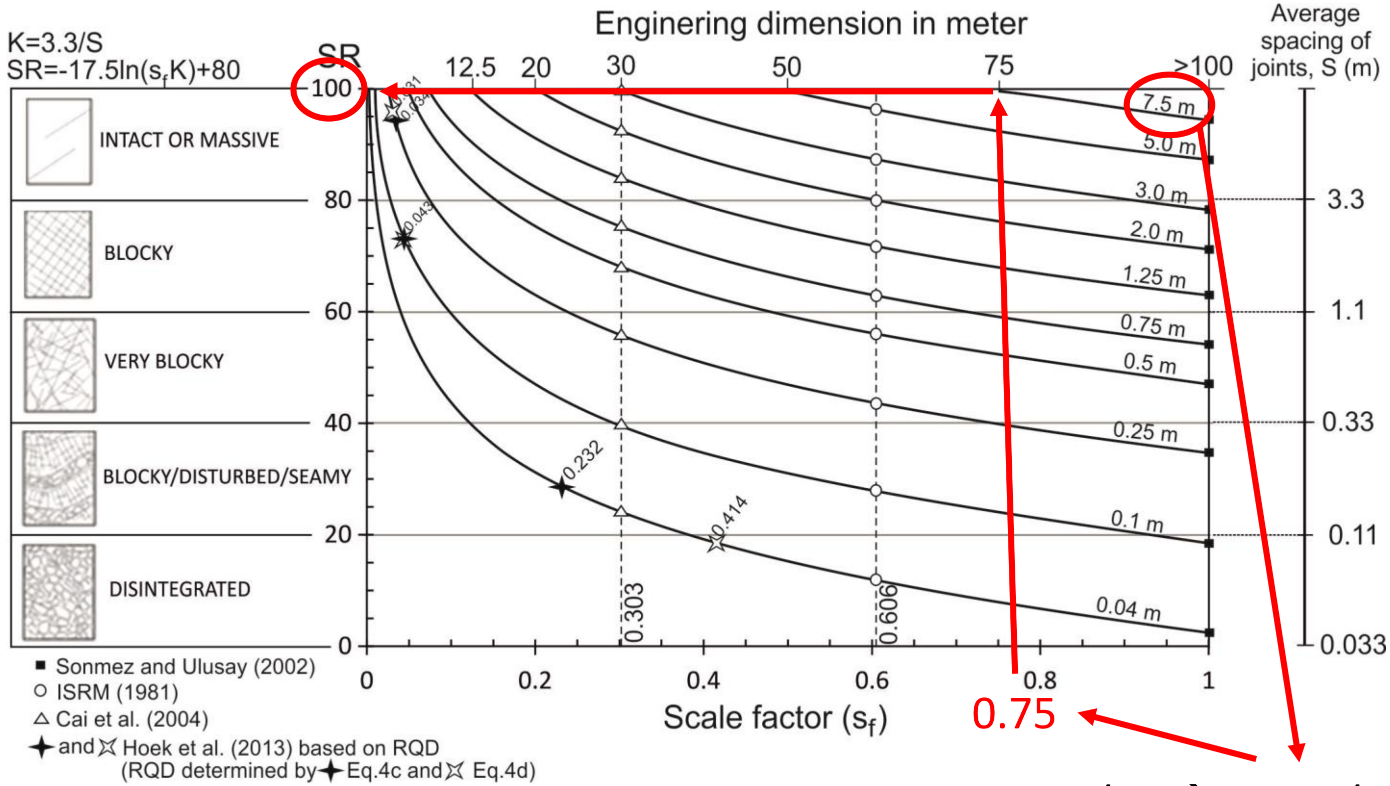
Scale factor – REV – SR relation



It was a surprising result obtained in this study that SR is determined almost equal to 100 by using generalized-scaled formulation of SR when scale factor (denoted as s_{fi}) is considered by using the ratio 1 to 10 between s_f and S

How ?

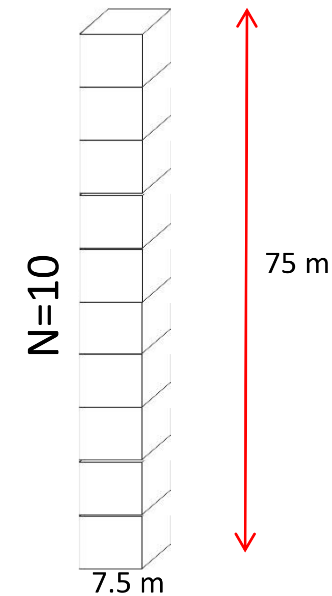
it means that when s_f is used as S/10 in SR formulation, SR is obtained almost equal 100



0.75

$s_f = S/10 \rightarrow s_f = 7.5/10 = 0.75$

10 rock blocks in Engineering dimension

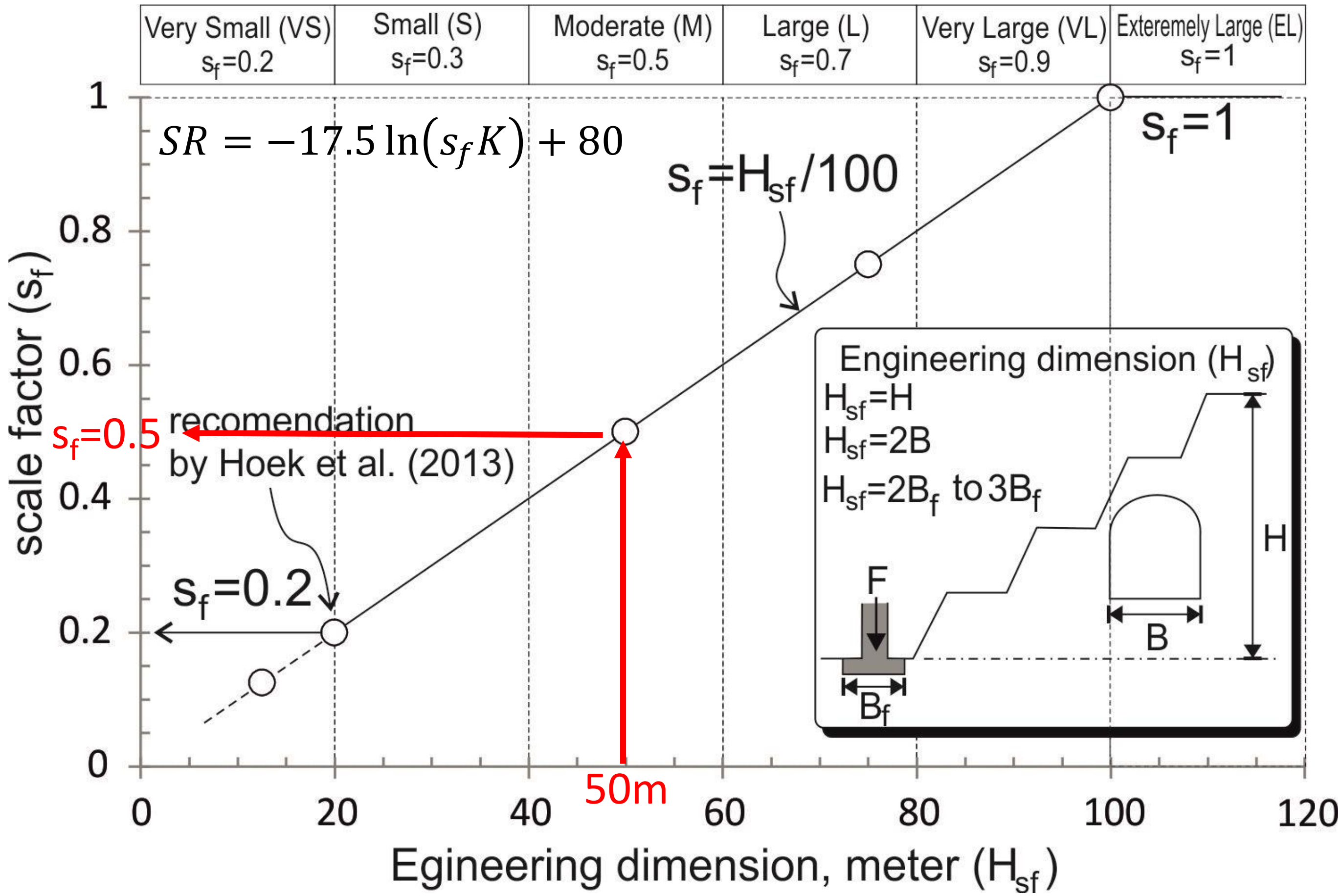


SR=100
$s_f=0.75$

For example:

When average spacing of discontinuity is 7.5 meter and engineering dimension is about 75 m, SR is almost equal to 100, **it means that rock mass structure behaves massive (<u>and/or sparsely blocky in terms of Engineering Dimension</u>)?** I do not recommend the use of intact term as upper rockmass class in GSI ! (as similar recommendation in the study by Schlotfeldt and Carter, 2018)

If we look at this approach in reverse



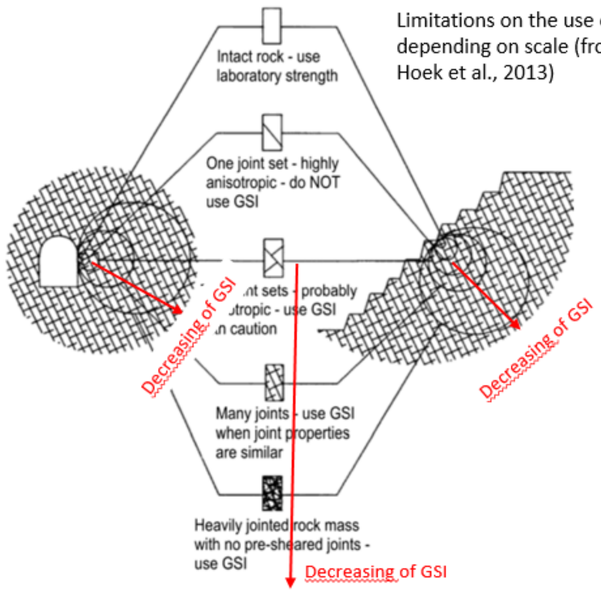
For example:

When the maximum engineering dimension is 50 m (let's say maximum slope height is 50 m), s_f=0.5 will be considered in general scaled SR equation.

Result and Conclusion

i. Almost all known quantification studies of GSI <u>are covered by using generalized scaled SR formulation.</u>

ii. The new scaled equation of SR can satisfy Hoek's scale dependent GSI approach for rating of jointed rock mass as illustrated in Figure.



Limitations on the use of GSI depending on scale (from Hoek et al., 2013)

When engineering dimension increases,
decrease in GSI should be expected !

iii. Average spacing of discontinuity sets (S_{ave}) and number of discontinuity sets (N) are the practical parameters to quantify scaled Structure Rating (SR) for isotropic rock masses. Jv is a geotechnical parameter which includes both S and N together, this is the main reason of the use of Jv in the quantitative chart by Sonmez and Ulusay (1999). <u>Hence, it should be underlined that Hoek and Brown failure can be applied to homogenous and almost isotropic jointed rock masses and also to intact rock.</u>

iv. The value of GSI can be selected from the original quantified GSI chart proposed by Sonmez and Ulusay (2002) by considering **scaled SR** and **SCR scores**. However, when the **scaled SR** is used, s_f should be shown in the GSI notation as a subscript ($GSI_{sf=x.x}$ for example $GSI_{sf=0.6}$) to reflect that it is a scaled GSI based on engineering dimension.

The proposed method by Peck (1969) and the emphasized statement by Müller (1970) as *"The most widely accepted way of dealing with uncertainties in geological materials has come to be known as the "observational method (Peck, 1969). (from http://www.ib.pwr.wroc.pl/wpula/W11.pdf that is available in Oct. 2021)"* and *"Many attempts have been made to handy calculation methods and simple formulations for everyday use to engineer may be provided with simple working tools. I see a danger in this: Complicated things do not become simpler through simplification at all cost. Things in geomechanics are complicated by their very nature (Müller, 1970)."* should be remembered, even today.

Finally, according to my modest experiences gathered from large open pit slope studies, we can clearly indicate that hand calculation (empirical) methods are effective tool in practical approaches that can only be used in combination with experience for the selection of applicable **initial** design parameters. Because of the possible complexity of the geological characteristics for each case, the methods such as proposed by Peck (1969) and the past statements such as emphasized by Müller (1970) which are about the use of empirical tools are still valid today.

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Thank you very much for your attention