The Six-Ways Method – A more robust process of estimating the Geological Strength Index

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There are different methods to estimate the Geological Strength Index (GSI), and each of these require various inputs which are determined differently. For a given rock mass, this can produce conflicting (and sometimes unreliable) results causing uncertainty to geological assessments and subsequent design, which, in turn, affects safety, costs, and time. The consistency of inputs required for GSI estimations can vary due to the experience of field personnel and their understanding of the inputs, unfavourable conditions onsite or human error – and, simply, the difficulty of predicting the strength of a rock mass beneath the surface with relatively limited primary data.

The 'GSI Six-Ways' is an approach that is suggested in order to not rely on any one (or few) methods for estimating the GSI, which could be significantly biased by specific input data or practitioner experience. The method provides the user with a wholistic quantitative and visual output to provide a more thorough grasp of the GSI of the geomechanical unit in question.

As the name suggests, there are six 'ways' or calculations this process utilises to develop the visual output. All are highly established methods; Direct Methods: Hoek et al (2013) - JCond$_{89}$, Hoek et al (2013) - JCond$_{76}$, Cai et al (2007), and Indirect Methods: RMi (Palmstrom 1995), RMR (Bieniawski 1976), Q (Barton et al 1974). For each of these, each input can be determined once an appreciation of the block and defect conditions are known.

Keywords: Six-Ways, Geological Strength Index (GSI), Geomechanics, Rock Mass Rating (RMR)

Introduction

Since the development of the Geological Strength Index (GSI), the process by which the system has been applied has varied significantly by the needs of different workers for different applications. As reviewers of many interpretive reports across the dam and tunnelling industries, it has become apparent that some workers utilise the equations presented in papers to produce precise GSIs, which are then statistically considered to select a GSI for use, whilst others provide an envelope of values by utilising the charts in provided in the original papers [that described the Geological Strength Index], often lacking the precision of other methods by providing an ambiguous range, when estimates of rock mass shear-normal strength require a numerical value as an input.

The basis for GSI selection is generally lost in the process and is not always reported, with the end user or reviewer not understanding the limitations of the inputs or estimated GSI in the process of selection of the value utilised in the ultimate estimate of rock mass strength.

It has also been noted that on large projects, though small projects are not immune, some inputs which are known to be highly variable, such as RQD have a major influence on the estimation of GSI. Pells et al (2017) provided a clear demonstration of the variability of RQD estimation between highly experienced professionals classifying the same rock mass (refer **Figure 1**). Further, different workers have different preferences as to which system they utilise to estimate GSI based on their professional and academic experience. Those from tunnelling and mining backgrounds lean toward Q and RMR, those from dams favour Cai or Palmstrom. Thus the estimated GSI can vary significantly depending on the method adopted. With the rapid growth of digital data acquisition, more and more systems are providing estimates of GSI on a 'point-by-point' basis, providing the user with a massive database that can be overwhelming.

Comparison of various GSI estimation systems is not new and has been previously reported by Vasarhelyi et al. (2016). This paper discusses a new approach to use some of those existing systems, coupled with an innovative visual display presenting the estimated GSI for different rock masses and systems of estimation; rather than only comparing and discussing over/under-estimations or equation revisions.

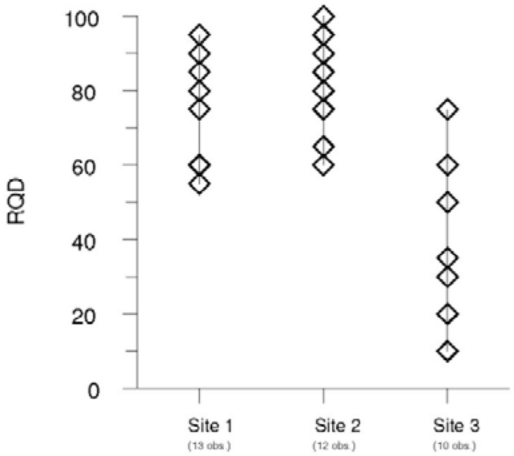


Figure 1 Variability in estimation of RQD between workers for the same outcrop (After Pells et al. 2017).

As suggested in Hoek et al (2013), the use of graphical methods, especially when modern GSI charts are utilised, can provide robust results when undertaken by '*qualified and experienced geologists and engineering geologists'.* In less controlled environments, or when undertaken by less experienced practitioners, these methods can provide broad ranges that do not accurately reflect the conditions of the rock mass and these values can persist through several phases of design before being called into question.

The Six-Ways Method

The Six-Ways method was developed to identify and remove bias due to errors in input data, or the over-ranging of GSI estimation in both directions due to the broad categories of the conventional tables. The process takes the inputs from six different methods of estimation and provides six estimates of GSI. This allows any bias due to data errors (logging errors or oversights) to become readily apparent as the variability in results becomes visually obvious when methods using different inputs are applied.

This method also allows the development of strength envelopes for geomechanical domains, allowing designers to understand the variability within the rock mass based on the envelope between the two shear-normal curves.

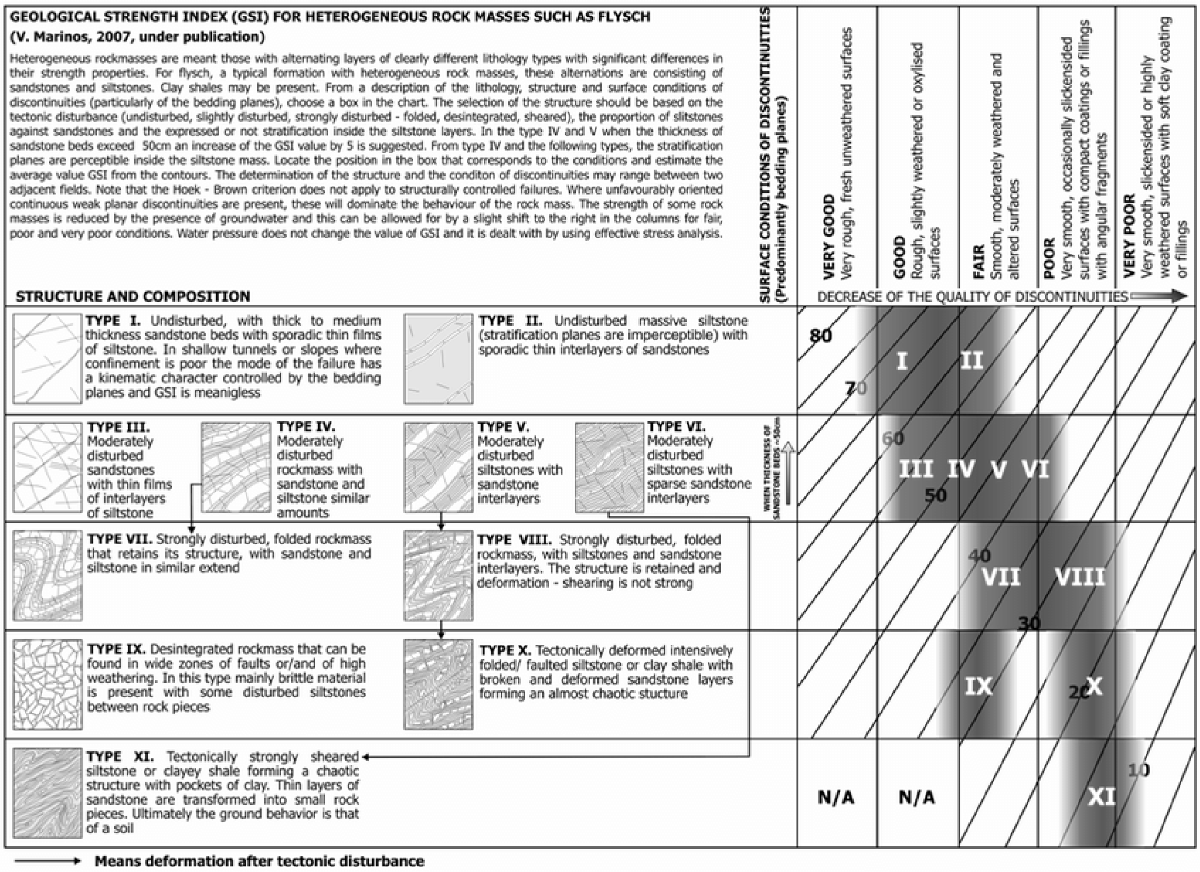
Current Practice

GSIs are commonly presented as per **Figure 2**, or, in the case of anisotropic rock masses, as per Figure 3. This can make it difficult for an engineer/geologist to decide what value to use as the ranges can be ambiguous and not necessarily reflect observed defect conditions or [block] interlocking characteristics. Commonly there is no record of the reasoning behind the selection of the ranges, or why a particular value within the highlighted range has been selected for use.

Figure 2 Example of selection of GSI Ranges using a conventional GSI chart (After Hoek, 1995) and differences as noted in industry as to the method of selection by different practitioners.

The chart, as provided in Figure 2, is noted to be the most commonly utilised across industry, with the flysch option, as shown in Figure 3, far less commonly utilised although a large number of infrastructure projects lie within metamorphic or highly deformed terranes.

Further, there are many different versions of the original chart (Figure 2) being utilised in practice, with guidance for different parameters provided on the different axes of the chart, with some utilising two Y-axes.



GEOLOGICAL STRENGTH INDEX (GSI) FOR HETEROGENEOUS ROCK MASSES SUCH AS FLYSCH

(V. Marinos, 2007, under publication)

Heterogeneous rockmasses are meant those with alternating layers of clearly different lithology types with significant differences in their strength properties. For flysch, a typical formation with heterogeneous rock masses, these alternations are consisting of sandstones and siltstones. Clay shales may be present. From a description of the lithology, structure and surface conditions of discontinuities (particularly of the bedding planes), choose a box in the chart. The selection of the structure should be based on the tectonic disturbance (undisturbed, slightly disturbed, strongly disturbed - folded, desintegrated, sheared), the proportion of siltstones against sandstones and the expressed or not stratification inside the siltstone layers. In the type IV and V when the thickness of sandstone beds exceed 50cm an increase of the GSI value by 5 is suggested. From type IV and the following types, the stratification planes are perceptible inside the siltstone mass. Locate the position in the box that corresponds to the conditions and estimate the average value GSI from the contours. The determination of the structure and the conditon of discontinuities may range between two adjacent fields. Note that the Hoek - Brown criterion does not apply to structurally controlled failures. Where unfavourably oriented continuous weak planar discontinuities are present, these will dominate the behaviour of the rock mass. The strength of some rock masses is reduced by the presence of groundwater and this can be allowed for by a slight shift to the right in the columns for fair, poor and very poor conditions. Water pressure does not change the value of GSI and it is dealt with by using effective stress analysis.

TYPE I. Undisturbed, with thick to medium thickness sandstone beds with sporadic thin films of siltstone. In shallow tunnels or slopes where confinement is poor the mode of the failure has a kinematic character controlled by the bedding planes and GSI is meanigless

TYPE II. Undisturbed massive siltstone (stratification planes are imperceptible) with sporadic thin interlayers of sandstones

TYPE III. Moderately disturbed sandstones with thin films of interlayers of siltstone

TYPE IV. Moderately disturbed rockmass with sandstone and siltstone similar amounts

TYPE V. Moderately disturbed siltstones with sandstone interlayers

TYPE VI. Moderately disturbed siltstones with sparse sandstone interlayers

TYPE VII. Strongly disturbed, folded rockmass that retains its structure, with sandstone and siltstone in similar extend

TYPE VIII. Strongly disturbed, folded rockmass, with siltstones and sandstone interlayers. The structure is retained and deformation - shearing is not strong

TYPE IX. Desintegrated rockmass that can be found in wide zones of faults or/and of high weathering. In this type mainly brittle material is present with some disturbed siltstones between rock pieces

TYPE X. Tectonically deformed intensively folded/ faulted siltstone or clay shale with broken and deformed sandstone layers forming an almost chaotic stucture

TYPE XI. Tectonically strongly sheared siltstone or clayey shale forming a chaotic structure with pockets of clay. Thin layers of sandstone are transformed into small rock pieces. Ultimately the ground behavior is that of a soil

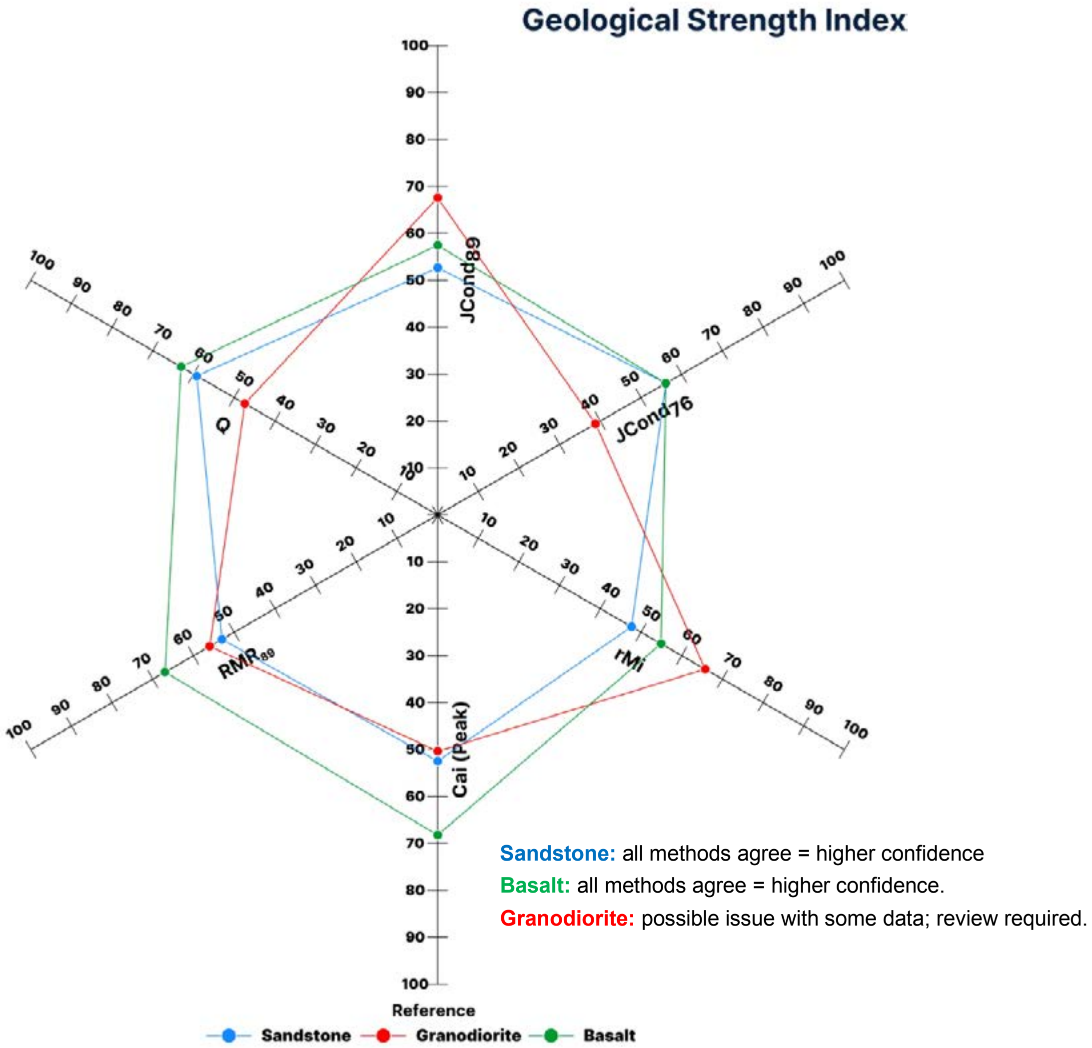
Figure 3 Geological Strength Index for heterogeneous [flysch] rock masses (Marinos et al, 2007)

Process

The plot shown below (Figure 4) is generated by way of a spreadsheet (Excel, Lotus 123, OpenOffice, Numbers, etc), with data then transferred to a graphical display software package (preferably Golden Software's Grapher). Within the data entry and estimation spreadsheet, the user is stepped through each estimation method using a series of dropdown lists for each input parameter. These lists contain the qualitative categories or quantitative ranges used for each of these methods, or in some cases, descriptions understood from field work. Inputs that are used in more than method are only required to be selected once, lowering the chance of data entry errors across the methods. The inputs selected are connected to 'Look Up' tables [sourced from the original publications for each method] in other tabs of the spreadsheet, further reducing errors associated with manual entry. The ease and speed of this step of the process allows changes to be made readily, or at different stages of the project or research, when more information is acquired or understood.

In a perfect situation, the results of all six methods of estimation will produce the same estimate of GSI. The world is, however, not perfect. The six different methods allow the user to rapidly compare the results by way of the numerical output presented as a spoked hexagonal plot. Simply put, the more hexagonal the hexagon is, the more robust the estimated GSI. If the hexagon is deformed, it flags potential issues with the input data, such as errors in estimation [typically] of RQD, strength, or block volume/defect spacing. The user can then make checks of the input data to ensure any logging errors or bias are addressed, resulting in a more robust GSI.

As can be seen in **Figure 3**, GSI has been estimated for three (3) different geological units. The results for the sandstone and the basalt are considered typical for the Six-Ways method with relatively hexagonal plots, though Cai, Q, and RMR are skewed somewhat to the higher side. There is, however, an obvious issue with the data input for the granodiorite, with a significantly deformed hexagon. In most cases, this can be traced back to issues with the field data, commonly RQD or joint spacing, and the hexagon will often be significantly improved following relogging of the core to improve the quality of the input data. It is not uncommon for other logging issues to be identified during these quality improvement phases, resulting in a more robust estimate of GSI.



Sandstone: all methods agree = higher confidence

Basalt: all methods agree = higher confidence.

Granodiorite: possible issue with some data; review required.

Figure 4 Example of a Six-Ways plot for three (3) different rock masses.

A second plot (**Figure 5**) provides the distribution of the GSI results, and the adopted GSI based on the removal of the two, sometimes more, outliers. The statistical distribution of results can be considered by the user when referring to the estimation spreadsheet. The shaded bar shows the range of results, with the width increasing as the range reduces, providing a second visual indication of a tight cluster of results. Each individual result is provided in addition to the recommended GSI for use, which is represented by the mean of the trimmed dataset.

Trimming is completed using the TRIMMEAN function in MS Excel, which excludes a percentage at the top and bottom of the dataset. This is achieved by calculating the percentage represented by two or more points, then excluding that range to narrow the database to the more clustered range. This value is presented on the results plot (Figure 5).

Cai's (2007) residual GSI is also provided on the plot to allow the user to generate an input for the assessment of residual rock mass strength curves for post-earthquake conditions (the small triangle below the GSI ranges (**Figure 5**)).

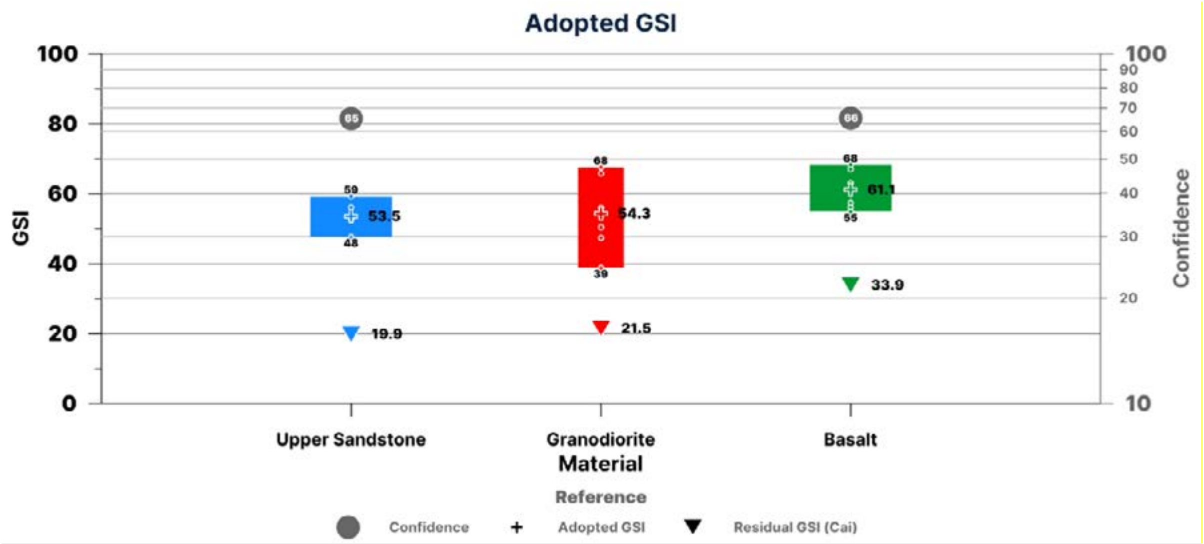


Figure 5 Presentation of the GSI range, range of estimates, and 'adopted' GSI, in addition to the residual GSI (inverted triangle).

In addition to the GSI results, the shape of the hexagon is mathematically assessed by fitting it to an ellipse, with the six points of the hexagon defining the circumference of the ellipse. A perfect hexagon would present points coincident with a perfect circle, whilst a deformed hexagon will provide an ellipse that passes through fewer points and is less circular; thus reduced confidence in the estimated GSI. This is shown by the grey circles on **Figure 5**.

For the convenience of others, we provide the sources and summaries of the six published methods utilised in the Six-Ways plot, with the equations to estimate GSI, in addition to the method to undertake back calculations for some less common methods that rely on block volume and shape. It is of importance to note that the terms 'defect/s' and 'discontinuities' are used interchangeably in the below descriptions to remain consistent with the original authors' terminology.

Isotropic versus Anisotropic

A common issue faced by practitioners is the selection of GSI from the Isotropic (Figure 2) or Anisotropic (Figure 3) Chart. The Six-Ways method was developed to remove the dependency on selecting an appropriate chart by utilising multiple inputs from different classification systems. Using the different rock mass classification systems provides an estimate of GSI through the classification of the rock mass, which considers block size, block shape, the number of defect sets, in addition to the defect wall condition. Further, by applying six different methods, any bias from one method that may specifically favour isotropic conditions should fall as an outlier and be screened from the final database for GSI estimation.

Direct methods

JCond$_{89}$ – Hoek et al. 2013

Using RQD (defined by Deere & Deere (1963)) and Joint Condition rating (defined by Bieniawski (1989)) to estimate GSI, Hoek et al 2013 suggested these as the best descriptors to assist with quantifying the axes of the original GSI estimation chart. A plot of estimated GSI, with the basic GSI chart on y-axis and the sum of Scale A and B values on the x-axis, demonstrates a relationship:

$$GSI = 1.5\, JCond_{89} + (\frac{RQD}{2})$$

eq. (1a)

An alternate method, using a different joint condition scale, is also provide in Hoek et al (2013) as provided below:

$$GSI = \frac{52\, Jr/Ja}{(1 + Jr/Ja)} + (\frac{RQD}{2})$$

eq. (1b)

JCond76 – Hoek et al. 2013

Following a similar process to JCond$_{89}$, this method utilises work by Bieniawski (1976) and the development of the Joint Condition rating (JCond$_{76}$). Hoek et al (2013) re-estimated the relationship, resulting in:

$$GSI = 2JCond_{76} + (\frac{RQD}{2})$$

eq. (2)

Cai et al 2007

A method using block volume and a joint condition factor was developed to produce a numerical result from originally qualitative descriptions. Based on GSI values found and intact rock strength properties, equivalent Mohr-Coulomb strength parameters and elastic modulus of the jointed rock mass are estimated.

- Vb: Block volume
    - Using joint spacing, joint orientation, number of joint sets and joint persistence (Cai et al, 2007), guiding to a block size or volume. Cai et al (2004) provide different equations dependant on the number of joint sets in the rock mass, or if no clear joint sets present, or the degree of discontinuity. The field personnel may also physically measure representative blocks if possible.
- Jc: Joint condition factor, adopting rating values from RMI and Q systems
    - Jw: Large scale waviness
    - Js: Small scale smoothness
    - Ja: Joint alteration factor

The two inputs above are used in tandem with the GSI graph by Hoek et al, where Jc correlates to Joint or Block Wall Condition (X-axis) and Vb correlates to Block Size (Y-axis). A relationship was determined from this graph, still using the variables from RMi and Q systems, to arrive at:

$$GSI = \frac{26.5 + 8.79\ln(Jc) + 0.9\ln(Vb)}{1 + 0.015\ln(Jc) - 0.0253\ln(Vb)}$$

eq. (3)

Where Jc = joint condition factor; and Vb = block volume.

The residual GSI assumes the block volume is set at 10 cm^3 and there is a reduction in defect surface character due to shearing.

Indirect methods

RMi – Palmstrom 1995

The RMi (Rock Mass index) is essentially the degree that joints reduce a rock's strength.

$$RMi = \sigma JP$$

eq. (4)

Where σ = uniaxial compressive strength of intact rock; and JP = jointing parameter.

Palmstrom (1995) discusses that if the intact rock is weak or if defects are discontinuous or have wider spacing, this could play a increased role on the overall strength of the rock mass, and emphasises that the intact rock properties should not be ignored.

The parameter JP represents joint condition factor and block volume. Where joint condition factor (jC), is a relationship in itself;

$$jC = jL(\frac{jR}{jA})$$

eq. (5)

Where jL= joint size and termination factor; jR = joint roughness factor; and jA = joint alteration factor.

It is known the constant ‘s’, a Hoek-Brown failure criterion constant, can be determined using the RMR and Q systems. JP can more accurately determine ‘s’ than RMR and Q in Palmstrom’s (1996) view as this parameter is calculated using more fundamental elements of the rock mass. Therefore, utilising ‘s’, and specifically the inverse of ‘s’, a GSI can be back estimated from RMi parameters, arriving at:

$$GSI = 9\ln(s) + 100$$

eq. (6)

Where

$$s = JP^2$$

eq. (7)

RMR89 – Bieniawski 1989

The Rock Mass Rating (RMR) system developed by Bieniawski (specifically the 1989 revision), assigns numerical ratings from a variety of charts and tables to the classification parameters listed below, with the summation of these providing the RMR (out of 100).

- UCS
- RQD
- Spacing of Discontinuities
- Condition of Discontinuities
- Groundwater Conditions
- Orientation of Discontinuities

Bieniawski applies weightings to each of these, due to their recognised importance on rock mass classification. Hoek and Brown (1997) provide a simple relationship between GSI and RMR, where:

If RMR_{89} >23:

$$GSI = RMR_{89} - 5$$

eq. (8a)

Else:

$$GSI = RMR_{89}$$

eq. (8b)

Q – Barton et al. 1974

The Q system utilises six parameters and ratings to determine a numerical value. The equation relating these parameters is as provided in Barton et al. (1974);

$$Q = (\frac{RQD}{Jn})(\frac{Jr}{Ja})(\frac{Jw}{SRF})$$

eq. (9)

Where;

- Jn = number of joint sets rating
- Jr = least favourable joint set (or filled discontinuity) roughness rating
- Ja = least favourable joint set (or filled discontinuity) degree of alteration or clay filling rating
- Jw = water inflow and pressure effect that could wash out discontinuity infill rating
- SRF = faulting, or hard massive rock strength/stress ratio, or squeezing/swelling in soft rocks rating

Hoek et al. (1995), refined a GSI-Q relationship to arrive at;

$$GSI = 9\ln(\left(\frac{RQD}{Jn}\right)\left(\frac{Jr}{Ja}\right)) + 44$$

eq. (10)

Table 1 compares the inputs required against each method. This is helpful when results are being interrogated allowing the user to focus on certain features or datasets for potential errors.

Table 1 Input parameters for each of the Six-Ways to estimate GSI.

Six-Ways Method	Direct			Indirect		
Parameter	**JCond$_{89}$**	**JCond$_{76}$**	**Cai et al**	**RMR$_{89}$**	**Q**	**RMi**
JCond$_{89}$ (Joint condition 1989)	✓					
JCond$_{76}$ (Joint Condition 1976)		✓				
RQD (Rock Quality Designation)	✓	✓		✓	✓	
UCS (Uniaxial Compressive Strength)				✓		✓
jL (joint size and termination factor)						✓
jR/Jr (joint roughness factor/rating)					✓	✓
jA/Ja (joint alteration factor/rating)			✓		✓	✓
Vb (block volume)			✓			✓
s (Hoek and Brown's criterion)						✓
Jw (Waviness)			✓			
Js (joint surface)			✓			
Jn (number of joint sets rating)					✓	
Discontinuity Spacing				✓		
Discontinuity Length				✓		
Groundwater Conditions				✓		
Discontinuity Orientation				✓		

Conclusions and recommendations

Quantitatively expressing qualitative data is a key and a regular challenge for geologists. As discussed, the topic of this paper it is not a new or additional parameter or piece of information to collect in the field or in research, but rather seizing the opportunity to do more with what is already available in the geological and geotechnical databases to hand, especially electronic datasets in Slate[1] or AGS format. The Six-Ways method utilises already established methods and assists the user to account for the biases in these methods, to improve the understanding of the data collected and to provide greater confidence in the GSI selected for design. The Six-Ways method produces a clear output that visually demonstrates the confidence in the resulting estimate and can also display multiple rock masses in the one plot. The output allows results to be visually selected and each chart has different criteria for guidance.

Further improvements or advancements of this method, currently underway, include the incorporation of other methods of GSI estimation, so the plot could provide more than 'Six-Ways' for greater confidence in the estimated GSI.

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[1] Slate is a Middle Third Geological digital geological and geotechnical logging system.

Managing Suki Kinari Hydropower Project through Covid19 Period

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Suki Kinari Hydropower Plant is an 884MW run-of-river type project located in the Himalayan region of northwest Pakistan. The project featuring 23km long headrace tunnel, underground powerhouse, 7 vertical shafts started its construction in 2017. When the Covid19 pandemic emerged in 2020, the project construction was at its peak. This paper presents a brief summary of the project's journey through the Covid period from the perspective of the Owner's Engineer, the role of Mott MacDonald in a joint venture with MMP and YREC.

1. Introduction

Suki Kinari is an 884MW hydropower project located in Pakistan constructed by China Gezhouba Group Company (CGGC). When the Covid19 pandemic emerged in 2020, the project construction was at the 3rd year of its 6-year construction programme starting in 2017. With main sponsors, skilled workers, construction equipment and some critical construction materials all sourced from China where strict Covid19 prevention and control measures had been in place for a long period, the impact of Covid19 on the project was significant. This paper presents a high-level summary of how Covid19 affected the construction of this technically challenging project and the mitigation measures adopted by the contractor. With pragmatic and collaborative approaches adopted by the project participants, the programme delay due to Covid19 was minimised and the project is now in the completion stage.

2. The Project

As the largest private independent power producer (IPP), the Suki Kinari project takes priority on Pakistan's development agenda. The country has a severe shortage of power supply and relies heavily on imported coal, oil and gas for producing electricity. When completed, the project will generate enough power for over 1 million families in Pakistan and reduce 3.2 million tons of CO^2 emission by replacing fossil fuel power. With most of the project components being underground and zero resettlement, environment and social impact of the project were considered to be low.

The project, located in a stretch of deep, narrow gorges of the Kunhar River in Khyber Pakhtunkhwa Province, Pakistan, is classed as a run-of-river type project. A 50m high rockfill asphalt core dam creates a storage of approximately 10 million m^3, enabling the project to provide some daily regulation for the grid. The role of the project in the power system is primarily peak shaving.

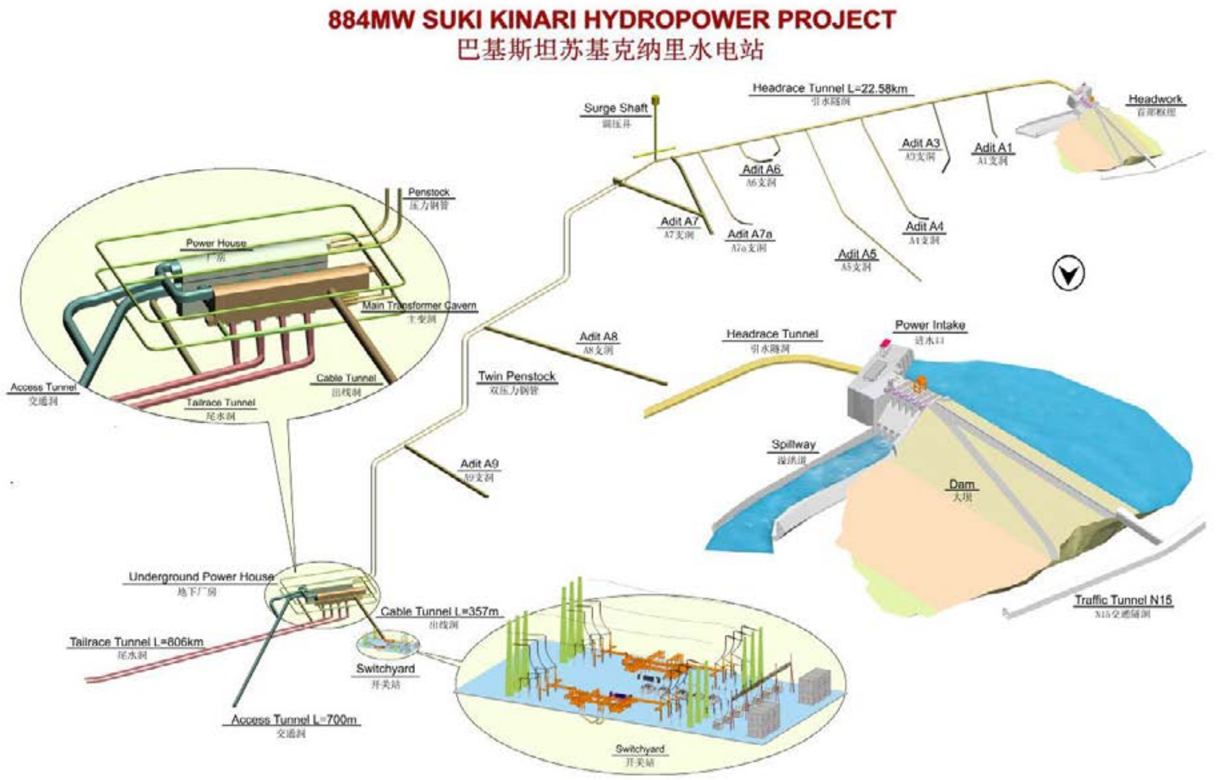
Photo 1 Khunhar Valley in the project area

Photo 2 Construction site at the powerhouse location with steep terrain

The most noticeable feature of the project is its head. At 910m net head, the project is one of few under-construction hydropower projects with over 800MW capacity and 900m net head, if not the only one.

Figure 1 shows the general scheme arrangement. A brief introduction of major components is provided in the following subsections.

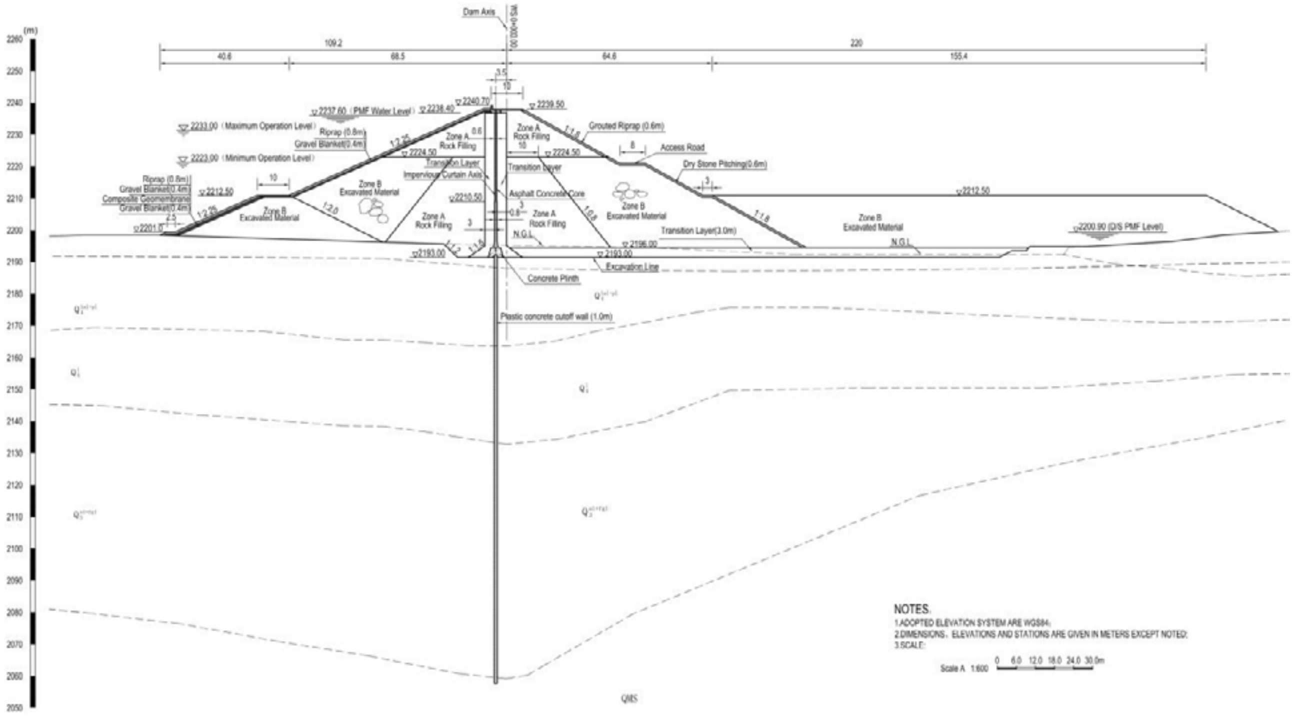
Figure 1 General arrangement of Suki Kinari HPP



2.1 Dam

The asphalt concrete core rockfill dam is 54.5m high, 258m long and 10m wide at the crest. It has a 1V:2.25H upstream slope and 1V:1.8H downstream slope. The upstream coffer dam forms part of the dam body. A 1.0m thick plastic concrete cut-off wall connecting with the asphalt core forms a barrier preventing seepage through the dam body and foundation. The maximum depth of the cut-off wall is 122m. Figure 2 shows the typical cross section of the dam and Photo 3 shows the dam under construction.

Figure 2 Typical dam cross section



NOTES.
1.ADOPTED ELEVATION SYSTEM ARE WGS84;
2.DIMENSIONS、ELEVATIONS AND STATIONS ARE GIVEN IN METERS EXCEPT NOTED;
3.SCALE:

Scale A 1:600 0 6.0 12.0 18.0 24.0 30.0m

Photo 3 Rockfill dam under construction

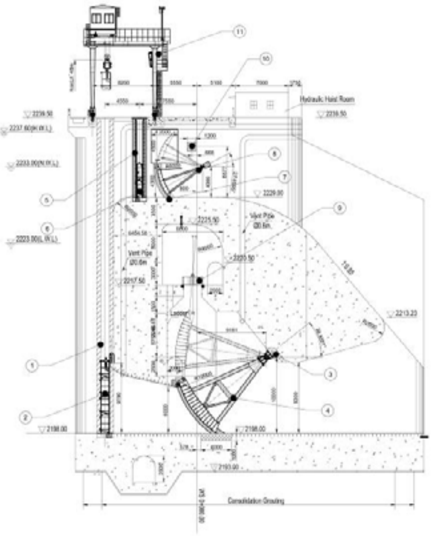
2.2 Spillway and intake

As shown in Photo 4 and Figure 3, the double-layer gated spillway is located at the right abutment of the dam. Both top and bottom layer have 5 bays of spilling chutes to discharge 0.01% AEP flood. The bottom layer also functions as a flushing sluice to remove sediment from the reservoir.

Photo 4 shows the power intake adjacent to the spillway to facilitate flushing sediment. No desander is provided for the project.

Photo 4 Spillway and power intake under construction

Figure 3 Double layer spillway



2.3 Headrace tunnel

Measured from the intake to the surge shaft, the length of the horse-shoe shaped headrace tunnel is 23km. The equivalent diameter of the tunnel is 6m. The headrace tunnel is typically lined with reinforcement concrete except for a short steel lined section where the geological conditions were poor and rock cover was shallow. The headrace tunnel including multiple vertical shafts was the critical path of the project construction schedule.

Photo 5 shows the lined headrace tunnel with minor defects treatment pending.

Photo 5 Reinforcement concrete lined headrace tunnel of horseshoe shape

2.4 Shafts

The 181.9m deep surge shaft is a double chamber type with restricted orifice. There are 6 vertical power shafts to lower the waterway to powerhouse level. A bifurcation at the downstream of the surge shaft connects the headrace tunnel with two high pressure penstocks, each with 3 vertical shafts of 220m~250m deep respectively.

Photo 6 Power shaft under construction

2.5 Powerhouse

The underground powerhouse complex comprises of two large caverns: main powerhouse cavern and transformer cavern. Two caverns are connected by 4 bus bar tunnels and two internal access tunnels. Four tunnels of various functions, i.e. main access tunnel, GIL (Gas Insulated Lines) tunnel and two tailrace tunnels connect the underground structure with the outside world.

The main powerhouse and transformer cavern has a dimension 123.9(L)×25.5(W)×53.0m(H) and 133.0(L)×17.8(W)×33.4m(H) respectively (Figure 4).

Four vertical shaft 6-nozzle Pelton units are installed in the powerhouse with the total installed capacity of 884MW (Photo 7).

Figure 4 3D image of underground powerhouse complex

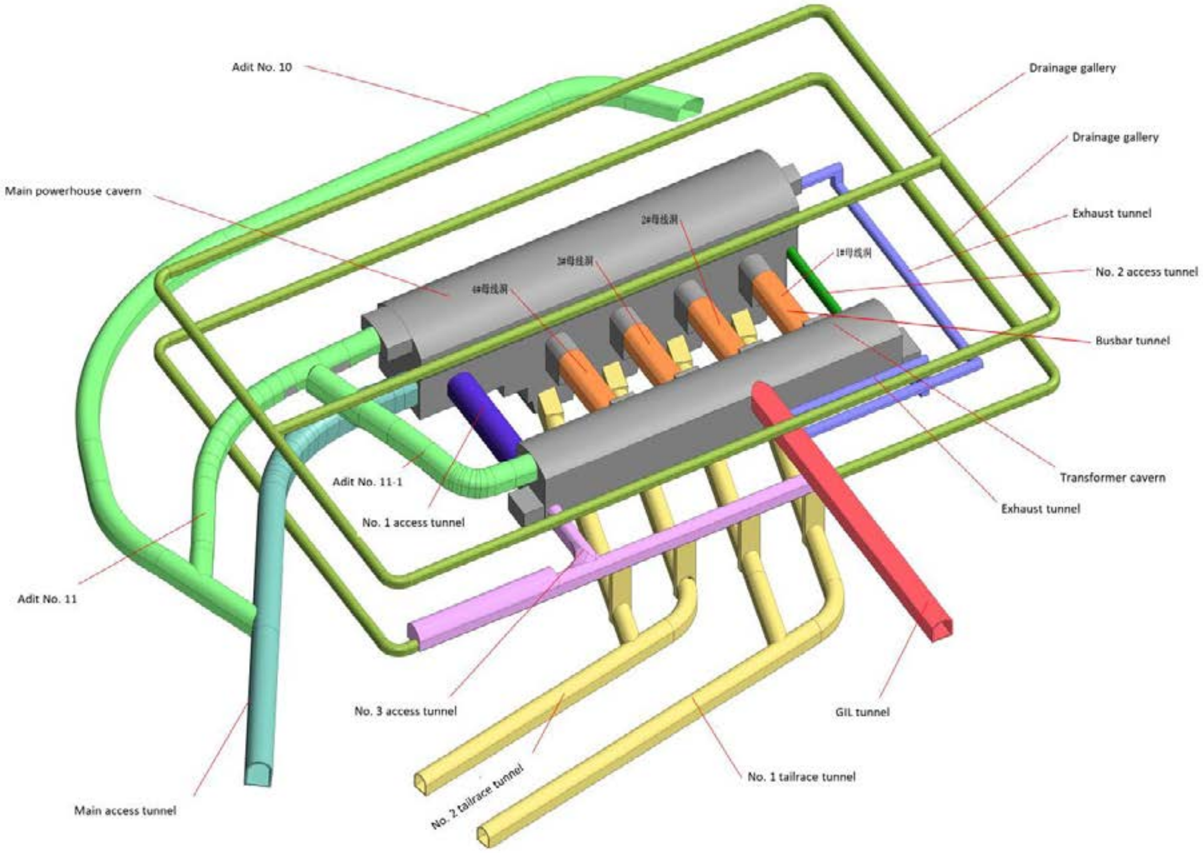


Photo 7 Runner chamber of Pelton turbine

3. Project participants

The project achieved financial closure in 2016 with the main sponsor being China Gezhouba Group Company (CGGC) and Haseeb Khan (Private) Limited as the minor sponsor. The Project is one of the prioritised projects under the strategic China Pakistan Economic Corridor ('CPEC') initiative set up by the Chinese and Pakistan governments to support infrastructure development of Pakistan.

Mott MacDonald was first involved in the project in 2008 to deliver an initial feasibility study which identified an optimal development scheme. With the project proceeding to construction stage, Mott MacDonald worked as the owner's engineer for the project company SK Hydro (Pvt) Limited in a JV with YREC (China) and MMP (Pakistan), a role that supported the client in design review, construction supervision and contract management.

An EPC contract was awarded to subsidiary companies of the CGGC Group with CGGC No.3 Engineering Co. Ltd being selected as the contractor for civil works and CGGC International Co. Ltd as the contractor for E&M supply. OEM of main equipment includes Andritz and Harbin Electric Machinery Company Limited.

Construction supervision was delivered by the OE's site team of 20~30 local engineers and 2~4 from China depending on construction stages. The OE site team resides in a separate enclosed building outside the contractor's village, which greatly facilitate Covid management for the OE site team.

On the EPC contractor side, the management team and most of skilled labour were from Hubei Province of China where Covid19 was firstly reported, making the Suki Kinari feel the impact ahead of any large infrastructure projects in Pakistan.

4. The Pandemic

The novel virus was first identified in the Chinese city of Wuhan in December 2019, where the headquarter of CGGC is located. In order to contain it, the Chinese government imposed a lockdown for Wuhan on 23 January 2020. The World Health Organization (WHO) declared the outbreak a public health emergency of international concern (PHEIC) on 30 January 2020, and began referring to it as a pandemic on 11 March 2020.

Although strict control measures were in place, Covid19 eventually spread across the world. On 26 February 2020, Pakistan confirmed its first two cases of the coronavirus. On 21 March 2020, all international flights were suspended for two weeks. The country was put under a nationwide lockdown from 1 April 2020 which was extended twice until 9 May 2020. However, due to various lockdowns imposed by the regional governments, the goods transport system came to a halt in late March 2020.

By imposing strict movement control measures, China successfully kept the case numbers low until 2022 when the country started easing restriction on international flights.

In Pakistan, the provincial governments began phase-wise lifting of the national lockdown on May 9, 2020. In June 2020, Pakistan adopted the strategy of 'smart lockdown', which involved identifying hotspots of infection through testing and contact tracing and imposing a localized lockdown in focused areas with high disease spread.

5. Management of Covid-19 at the site

The construction sites of the project extend over an area stretching some 35km along the Khunhar Velley. To prevent the spread of Covid19 at the site, the EPC contractor adopted a strategy centred on two concepts: grid-based management and prevention-oriented control. Grid-based management aimed to limit the impact of any Covid19 infection to a small area by isolating any grid unit from other units while the prevention-oriented approach minimised the probability of Covid19 infection at the site.

In total the EPC construction setup at the site was divided into 28 grid units for Covid19 management. Each unit was responsible for the management of its own personnel in the unit. A special taskforce of 179 personnel in total was established to be in charge of Covid19 management for all the grid units. Interaction among units and with the public was limited to the minimum. Stringent measures for example wearing full-body Covid19 PPE, thorough disinfection upon entering a grid unit, quarantine in an isolated facility within the grid unit upon returning from outside, etc were implemented when interaction with outside personnel was inevitable.

The EPC contractor published a Standard Operation Procedure (SOP) for Covid19 control soon after Covid19 emerged, which was then reviewed and updated regularly in accordance with the development of Covid19 and actual conditions at the site. Main objective of SOP include:

- Strictly control physical interactions among different grid units and other parties. Meetings were undertaken online.
- Isolate the construction site from the public with the focus on external suppliers. Personnel entering any grid unit was subject to thorough checks including PPE compliance, temperature measurement, symptom check, etc. Vehicles entering a construction site managed by any grid unit must be sterilized (Photo 8). Working staff returning to the site from leave were required to be self-quarantined in a designated facility.
- Reduce the chance of infection at the working place by regular disinfection in the construction camp.
- Identify Covid19 infection early by regular temperature taking at checking points and working place (Photo 9).

Photo 8 Vehicle disinfection

Photo 9 Temperature taking at the site

6. Covid19 impact and mitigation

In the project EPC contract, a Force Majeure Event (FME) was defined as *"any event or circumstances or combination of events or circumstances that is beyond the reasonable control of a Party and that on or after the Commencement Date, materially and adversely affects the performance by such material and adverse effect could not have been prevented, overcome or remedied in whole or in part by the affected Party…".* The contract then listed a number of events that may be classified as Force Majeure events, among which "Epidemic or plague" is included. In addressing the impact by Covid19 on the project, all project participants treated it on FME basis.

It is understandable that Covid19 shocked the contractor with no preparation or contingency plan in place when it emerged. There was also a great level of uncertainty about how it would develop. The impact of Covid19 on the contractor side was significant, including:

- At the initial stage of Covid19, the EPC contractor took strict measures to prevent and control the epidemic situation including mobilising manpower to enforce movement control, setting up quarantine facilities and supplying materials such as masks, sanitizer, etc. OE was supportive to the control measures and provided guidance to the contractor for the compliance of the relevant T&Cs of the contract.
- Disruption of human resources plan implementation. Although the majority of labor resources were recruited in Pakistan, skilled works were mainly mobilised from China. Strick travel restriction enforced by Chinese and Pakistan government make it very difficult and costly to mobilise personnel to work on the site. On the other hand, the contractor must pay extra allowance to retain Chinese workers stranded in Pakistan.

- Disruption of work procedures. To minimise the impact of Covid19 on the project construction, the contractor imposed mini lockdown at the site by putting anyone who tested positive and those who work together with him into quarantine for certain period until all tested negative. This inevitably disrupted the work plan.
- Disruption of supply chain. Importing materials from China took longer time due to delay by the manufacturer, broken logistics chain in China and Pakistan, etc. There was also a shortage of construction materials in Pakistan mainly due to Covid19. Extra efforts were made by the contractor to secure material supply by expanding the list of suppliers and sourcing materials from other construction sites.
- Labor grievance. Comparing with the Covid 19 control measures imposed for the public in Pakistan, the prevention and control measures adopted by the EPC contractor were generally more stringent. There were some grievances from local labors.
- Cost escalation. Costs of most construction materials in Pakistan increased significantly during the Covid19 period, which affected cash flow of the contractor to such an extent that payment terms needed to be adjusted to mitigate the impact. The solution proposed by OE included two major adjustments: i) splitting large payment milestone into several smaller milestones, ii) earlier take-over of some completed works by the Owner. These measures facilitated more constant cash flow to the contractor and greatly relieved their financial pressures without materially breaching the contract.

7. Lessons Learnt

The scale and duration of Covid19's impact on the project was unprecedented. Looking back at the actions taken by the project participants for the Suki Kinari project, there are some important experiences which contributed to the successful management of Covid19 for the project:

- Extraordinary situations require extraordinary solutions. This means all project participants should understand that it is the EPC contractor at the frontier facing the direct impact of Covid19 on the project and facilitate the implementation of EPC contractor's mitigation plan on a fair and transparent basis.
- Prepared for the worst-case scenario. Since its emergence there was a great uncertainty about how Covid19 would develop with time, for good or for bad. It is prudent the Contractor should prepare for scenarios, in which situation may get worse before getting better.
- Collaborative approach by all parties. Covid19 will inevitably have negative impacts on most project participants, if not all of them. Collaborative approaches enabling minimisation of Covid19 impact on project construction generally serves the interests of all project participants.