Application of block tectonic model and interblock tectonics at Koteshwar Dam project

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***Abstract*—The concept of evolving a block tectonic model for a high concrete gravity dam located in a dynamically evolving Himalayan terrain has been attempted for the first time in the Indian context. Precise delineation of the lithounits, demarcation and ordering of discontinuities and mega shear zones at the site and demarcation of tectonic blocks form the basis of model. The physical and geo-mechanical characters of rock masses in each of the tectonic block is defined and their likely response during and after the construction of the structures over them is assessed beforehand and necessary design modifications are suggested. It has immensely helped in anticipating/understanding the problems at the foundations of the structures and those on the abutment slopes. The necessary corrective measures were suggested in time.**

Keywords—tectonic model; geomechnics; lithounits

I. Introduction

The Koteshwar dam site located in Devprayag tehsil of Tehri Garhwal district of Uttarakhand and it is approximately 22 Km downstream of the famous Tehri dam. The dam site is located at the location of erstwhile Pindars village and it is well connected by a metal road with the district headquarter i.e. New Tehri.

The dam site is located approximately 170km from the state capital Dehradun. The nearest rail head is Rishikesh which is about110km away whereas the nearest airport is at Jolly Grant, at a distance of roughly 130km. The dam site is located between Lat N 30° 15’ 40” and Longitude E 78° 30’ 20” and it falls in the Survey of India toposheet no. 53J/7.

II. Regional Geological Framework

The Koteshwar dam project area lies within the Main Himalayan Belt (MHB), in the midlands of Lesser Himalaya. A generalised stratigraphy of the Main Himalayan Belt in Garhwal-Kumaun region indicates that the rocks of Lesser Himalaya exposed around Koteshwar dam area are divisible into two major tectono-stratigraphic units- i.e. i) the Krol Super Group (Proterozoic III to Eocene) and ii) the Garhwal Group (Proterozoic II). The rocks of the Garhwal Group (Sedimentary cycle-II of, directly come in contact with the rocks of relatively younger Krol Super Group, which also includes Jaunsar Group of rocks (Chandpur phyllites and Nagthat quartzites) along a major high angle reverse fault known as Srinagar Thrust. In between these two major groups of rocks, a narrow linear wedge exposes the rocks of Simla Group (Proterozoic-III), at few locales.

The dam site is located in Zone IV of the Seismic Zoning Map of India wherein seismic shaking may result in damage reaching intensity rating of VIII on MM scale.

III. Salient Features of Project

The project consists of an array of different surface and subsurface structures (Fig.1). Apart from the concrete gravity dam consisting of 14 blocks, a 575m long and 8m diameter diversion tunnel on the left bank having a design discharge of 670 Cumecs, four vertical penstock shafts (7.5m dia; 48m deep at El± 576m), four lower horizontal penstocks (7.5m dia, 60m long, El± 523m), a surface powerhouse on the right bank (124.60m long and 48.50m wide at El± 517m), a main access tunnel (8m dia, 376m long) on the right bank having an approach at El± 576m and getting down to the service bay level at El± 546m, a freight shaft (8m dia, 30m deep), on the right bank, three numbers of drainage cum inspection galleries (8m dia, 30m long), on either bank, a107m long and 96m wide stilling basin at the toe of the dam and a 215.50m long and 136m wide switchyard of 400KV,at El± 630m/ El± 635m, on the right bank, have also been constructed.

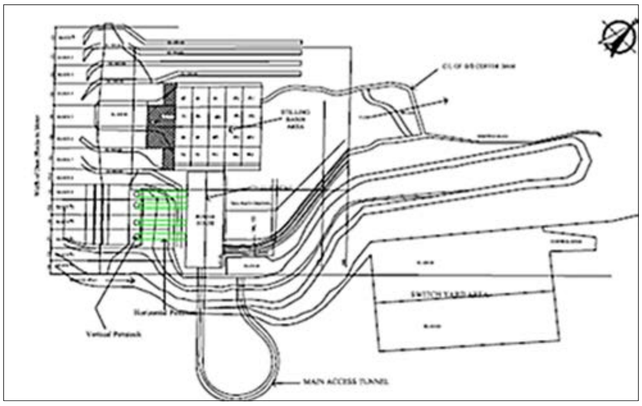

Fig.1. General Layout of Koteshwar HEP

IV. Block Tectonic Modeling

The concept of block tectonic modeling for rock masses at any project site was introduced in India by Dr. A. Varga, Russian Geologist from HPI, Moscow who was associated with the design and early phase of construction at Tehri dam project. The first such model in India was prepared Nawani for Tehri dam Project and applied for the evaluation of the project components [1]. A maiden attempt in India has been made by the author in this paper for evolving the Block Tectonic Model for a high concrete gravity dam located in Himalayas with an aim to assess the rock masses at Koteshwar dam site.

A. Geology at Site

The gorge of Bhagirathi at the dam site has the asymmetric configuration with flatter slopes on the right bank and steeper slopes (40° -70°) oriented sub parallel to the strike of the rocks [2].

The width of the valley at the dam site at FRL (El ±612.5 m) was about 150m which continues for about a distance of 120m towards downstream after which the valley widens up to 200 - 220m which was largely attributable to the presence of the broad alluvial terraces of river-borne-material (RBM) on the right bank. The ground elevations at the site vary from El ±545m (edge of water Bhagirathi) to about El ±750m above the crown of diversion tunnel.

Phyllites belonging to Chandpur formation of Upper Proterozoic (Pt3) were exposed at the foundation of main dam and other important structures like stilling basin, power dam, pressure shafts, power house and tail race channel [3–9]. Based on their lithological, petrographical and mineralogical characteristics these metamorphic rocks are divisible into four main sub units such as i) Phyllitic Quartzites (PQ) which are metamorphosed fine grained rich in arenaceous content, ii) Phyllites Thinly Bedded (PT) which are metamorphosed argillites), iii) Quartzitic Phyllite (QP) which are Phyllites rich in free silica content and iv) Sheared Phyllite (SP) representing the sheared and tectonized variants of PQ and PT.

The rythmicity and compositional banding in different sub units distinguished above, alternates forming complete and incomplete rhythms varying from a few millimeters to about 100 cm. All these rocks show development of foliation and have been folded to various extent during different phases of deformation [3–9].The zones of phyllitic quartzite consist of 90-95% of strong arenaceous phyllites, which were light grey, dark gray and purplish in colour, with thin interbeds (1-3 cm) of greenish-grey phyllite or clayey phyllite (5 -10%). The total thickness of these predominantly a PQ bands were up to 50m. The bands of predominantly PT phyllites were formed by the relatively strong phyllites (up to 90%) of grey and greenish-grey colour, with thin interbands of puckered phyllites, along with some boudins of PQ. The total thickness of such bands was about 70m. The bands of PT alternating with PQ consist of 50-60% of the former and 40-50% of latter. The total thickness of such bands was up to 100-110m. The bands consisting of interbedded sequence of PT and QP were totaling to a thickness of about 180 to 220m. The bands representing thin rhythmical interbedding of PQ (20-25%), PT (60-70%) and QP (5-20%) form the remaining part of the area and their total thickness reached up to 300 m. Such zones often exhibited fine folding/puckering and signs of crumpling under strong compression. Bands solely consisting of SP were negligible and were limited to the close proximity of shear zones or the areas where the crumpling is of intense nature.

According to the engineering-geological importance, characteristics of jointing and lithological composition the above zones of different bands can be grouped in three main types of engineering geological zones

1) Predominantly PQ with thin interbands of PT
2) Predominantly PT with thin interbands of PQ
3) Interbedded sequence of PQ/PT with lenses of QP

B. Weathering Pattern

The physical conditions and properties of rocks are largely influenced by the exogenous processes of which weathering and de-stressing are two important factors. The effects of de-stressing are discernible through the opening along the joint planes which reduces with the depth or inside the hill slope as it goes deeper. The effects of weathering also have a direct bearing on some of the other characters of the rock mass such as the RQD, strength, velocity of elastic waves, permeability and deformation modulus. Three zones were clearly distinguished at site.

1. Zone A

This is the uppermost zone which showed signatures of intensive weathering and de-stressing, where the physical and chemical weathering causes considerable alteration of rocks. The rock surfaces often exhibited yellow - brownish to reddish appearance. The joints were altered and show ferruginous content along them. In many cases the joint traces were not well preserved in these zones. These zones were equivalent of the W3 and W4 grades of weathering.

The typical properties for rocks in this zone were: Velocity of longitudinal waves – Vp = 1200-1400 m/sec;Deformation modulus – E = 1000 MPa;Density – d = 2.50-2.70 t/ cum.Compressive strength – σc= 15 MPa; RQD – 10 – 15 %.

2. Zone B

This zone had been distinguished below Zone A and it was characterized by less signatures of weathering, de-stressing and less alteration of the rock mass. The rock surfaces, sometimes, exhibited yellow - brownish to reddish appearance. The joints were slightly altered and showed ferruginous content along them, however the joint traces were well preserved in these zones. The joints exhibited some opening along them and often were filled with products of alteration. This zone was comparable to the W2-W1 grade of weathering.

The rocks of zone B were characterized by the following propertiesVelocity of longitudinal waves – Vp = 1700-3600 m/sec;Deformation modulus – E = 3000-4000 MPa;Density – Pd = 2.74 – 2079 t/cu.m. ;Compression strength – σc = 25-30 MPa ;RQD – 25 – 45 %;Coefficient of filtration – 0.15-0.60 m /day.

3. Zone C

This was the bottommost zone and was represented by relatively unaltered, fresh and intact rocks. The rocks of this zonewere un-weathered, however, at times the joints showed iron staining along them. The joints were tight to very tight. The rocks in this zone were generally impermeable. This zone corresponds to the W1-W0 grade of weathering. The following parameters were typical for this zone.Velocity of longitudinal waves – Vp = 3400-5400 m/sec; Deformation modulus – E = 6000 – 8000 MPa; Density – 2.78-2.80 t / cu.m. ; Compression strength – σc = 35 – 40 MPa;RQD - > 50 %;Coefficient of filtration – 0.06 m/day.

C. Structural Discontinuities

The site of Koteshwar dam lies in the Lesser Himalayas of Main Himalayan Belt (MHB) which is characterized by different phases of deformation. The structural evolution of the project site conforms to the regional pattern as it shows definite signatures of three or more phases of deformation. The model of structural discontinuities has been developed taking into account the disposition of all kinds of discontinuities viz. bedding, foliation, joints, and shear zones and also their characteristic features.

D. Folding Patterns

The open warps and open folds of first generation are clearly discernible in the area between the inlet of diversion tunnel and out let of diversion tunnel. The flexures of these folds are represented by parallel overturned antiforms and synforms. The axial planes of these folds are dipping at about 30º towards N090 – N100º and the plunge of the fold axis is varying at 20º - 40º towards NE.

The folds of second and third generation are also represented as seen through the relation between the different sets of joints which are axial planar to a particular phase of folding. The folds of third generation are tight isoclinals and at places root less, as was seen on the right bank.The major structure at the sites of dam, stilling basin and powerhouse is an antiform one limb of which i.e. the right limb is overturned and it is plunging towards the NE i.e. downstream.

E. Bedding or S0 Plane/Joint

The bedding joint is clearly distinguishable by the colour and compositional contrast. The bedding planes are dipping at 500 - 850 towards N 1400 – N 1600 at the lower elevation on either bank whereas they dip at 350 - 800 towards N 3300 – N 3500. The change in the trend is due to the overturning of the south-eastern limb. This joint is being referred as J1 for all the analysis purpose. The poles of this joint were plotted on the stereonet as shown in Fig. 2 and Fig. 3.

The above plots indicate that the maxima for the bedding joint below El 590m is in the southeastern (SE) quadrant whereas for the areas above El 590m the maxima points towards the north - west to north – north - west (NW – NNW). The above change in the azimuth of beds clearly indicates an antiform at the dam site.

F. Schistosity Foliation S1

The schistosity foliation is well developed as the axial plane to the folds of bedding joint thus clearly establishing their genetic relation. The intersection of the cleavage (schistosity) planes with the bedding forms a well-marked lineation. The attitude of schistocity the S1 planes varies from 250 - 400 towards N 0300 – N 0600 with their strike falling in the NW – SE direction. These joints have been referred as J2 for all the practical purpose of classification and analysis. The stereoplots of these joints for lower and higher level are depicted in Fig.4 and Fig.5 below.

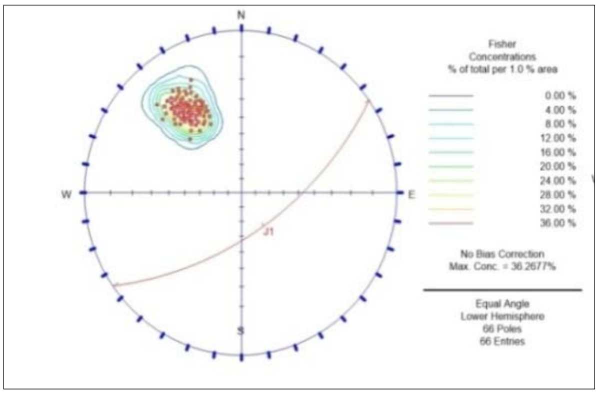

Fig. 2. Plot of Bedding Joint J1 (Below El 590m)

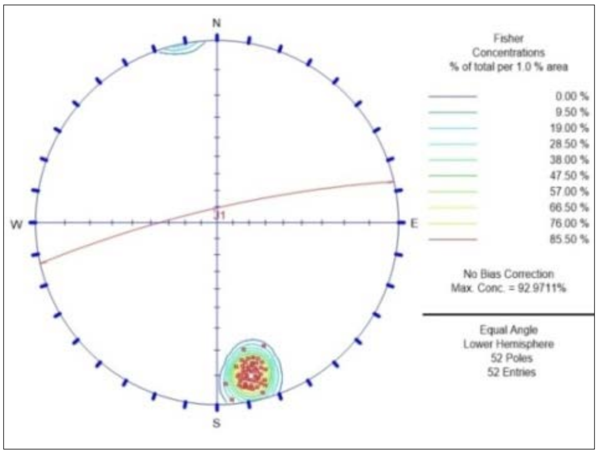

Fig. 3. Plot of Bedding Joint J1 (Above El 590m)

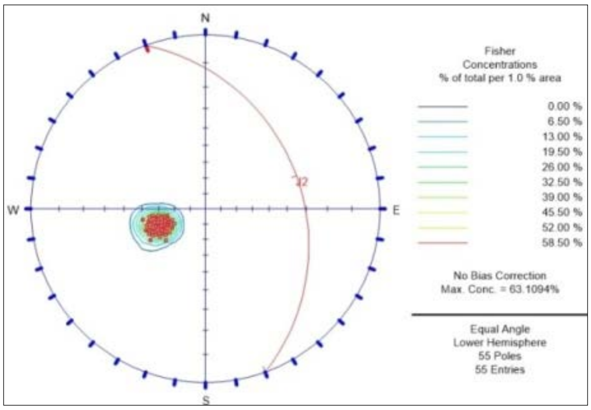

Fig. 4. Stereoplot of J2 joint below El 590m

The dip of the foliation joints was low (180 -250) on the right bank limbs whereas they were dipping slightly with more inclination (300 - 400) on the left bank (Fig. 4 and Fig.5)which also supports the inference drawn about the overturned antiformal closure at the dam site with its Northern limb (Left bank) being the normal limb and the Southeastern limb (Right Bank) being the overturned limb.

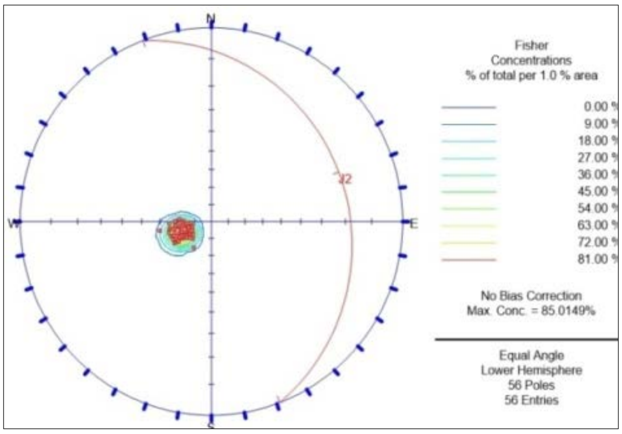

Fig. 5. Stereoplot of J2 joint above El 590m

G. Joints

At the project site a total number of five sets of joints have been delineated including the bedding and foliation joints. The joints J1 and J2 have been defined and discussed above and they represent the bedding and foliations respectively. The other joints have been numbered as J3, J4 and J5 respectively as they represent the later phases of deformation. The attitude of different sets of joints/discontinuities is given in table -.

H. Mega Shear Zones

A number of shear zones have been identified in the project area during the course of geological mapping and they can be grouped under four main categories viz. i) Longitudinal Shear Zones (LSZ), ii) Foliation Shear Zones (FSZ), iii) Cross Shear Zones (CSZ) and iv) Diagonal Shear Zones (DSZ) as shown in the Block Tectonic Model evolved for the Koteshwar dam site.

1. Longitudinal Shear Zones (LSZ)

The shear zones which are aligned nearly parallel to the bedding of the rocks have been classified as Longitudinal shear zones or L-shears and they exhibit strike ranging from N 550E - S 550W to N 700E - S 700W and dip in the northwest as well as in south-easterly directions. The amount of dip varies from 450 to 800. Four mega longitudinal shear zones namely LSZ-1 to LSZ-4 have been delineated at the dam site and they are aligned nearly parallel to the flow direction of Bhagirathi river. Of these the LSZ-3 fall right in middle portion of the channel and nearly matches with the trace of the suspected river bed fault/shear zone of GSI [10–12]. These shear zones have strike continuity ranging between 1 and 3km and were characterised by clay gouge thickness of 10cm to 70cm and the affected zone of 0.50m – 2m. The shearing effect along them was pronounced and they had obliterated the trace of bedding at places.

2. Foliation Shear Zones (FSZ)

The shear zones which are nearly parallel to the axial planar foliation joints have been grouped as foliation shear zones (FSZ). These shear zones are having the general strike of N 300W - S300E with 200 to 400 dip in the north-easterly direction.

As such two mega FSZ have identified which have been named as FSZ-1 and FSZ-2 (Fig. 6). These shear zones were seen continuing from one bank to the other crossing the valley at an acute angle. The strike continuity for these shear zones varied from 200m to more than 1km. They were characterized by infilling of clay gouge and crushed rock material of 10cm – 50cm thickness whereas the affected zone was limited to 50cm – 70cm.

A number of minor shear seams parallel to their traces having clay gouge <2 – 10cm thickness were expected in the foundations of dam and appurtenant structures.

3. Cross Shear Zones (CSZ)

The shear zones that are having their attitude eskew to those of bedding and foliation joints have been classified as cross shear zones (CSZ) and at times they have dips steeper than foliation joints. The cross shears are most frequent at the dam site. Two prominent mega cross shear zones have been identified between the upstream end of dam and the terminal part of stilling basin and they have been named as CSZI and CSZ2, they are of special significance to the project. The CSZ2 shear zone seems to have slightly displaced the shear zones LSZ-1 and LSZ-2 towards the left bank to the river Bhagirathi. These shear zones have their strike continuity between 300m and more than 1km and they were seen crossing the valley nearly at right angle. They were characterized by the infilling of clay gouge, crushed rock flour and crushed quartz veins of 10cm – 70cm thickness and the affected zones of 50cm – 2m.

4. Diagonal Shear Zones (DSZ)

The shear zones which have their dips towards upstream side that is opposite to the bedding and foliation shears have been termed as diagonal shear zones. These shear zones were not frequent and as such only one mega shear DSZ was identified that passes through the locations of dam block nos. 1, 2 and 3 beyond which it crossed the dam axis and continued towards Sain nala. The strike continuity of this shear zone was between 200m and 1km and it showed clay gouge thickness ranging from 5cm – 15cm and affected zone 30cm – 50cm.

I. Ordering of Discontinuities

The major discontinuities of Ist , IInd, IIIrd and IVth order are represented by the regional faults and thrust identified around the project area, such as MCT/MBT, Srinagar thrust and mega shears etc (Table-II). The other sets of discontinuities have been ordered as Vth, VIth and VIIth order as described below.The characteristic features of the mega shear zones at Koteshwar dam site have been given in Table-I.

1. V th Order Discontinuities

The bedding and foliation joints having strike continuity varying between 200m to more than 1000m have been categorized as Vth order discontinuity. The spatial disposition of these discontinuities gives rise to block sizes of 50 sq. m - 200 sq.m. At the foundation levels of the major structures these were tight in nature, however, climbing on the abutment slopes they showed opening and filling of secondary material. The shear zones along the bedding and foliation had filling of crushed rock and clay to the orders of 20cm – 50cm.

2. VI th Order Discontinuities

The discontinuities of the VI-th order are the joints that have strike continuity varying from 10m to more than 100m. They were represented by the diagonal and cross shears at the site and joints of other sets. These joints often have the filling of clay, crushed rock and crushed quartz veins that were up to 30cm. The intersection of these joints resulted in the formation of blocks of smaller dimension 20sq.m to 100 sq.m.

3.VII th Order Discontinuities

These are represented by the joints of limited strike continuity that is largely limited to either bank that to in the zones of puckered and crumpled rock mass. The strike continuity of these discontinuities varied from 3m to about 30m. These have zones of crushed rock and filling of clay gouge and crushed quartz veins.

TABLEI. CHARACTERISTIC FEATURES OF MEGA SHEARS AT KOTESHWAR DAM SITE

Shear Type/No.	Relation with bedding (S_0)	Dip amount/ azimuth	Strike continuity observed/ inferred (Km)	Filler type/ thickness (m)	Affected zone (m)	Remarks
Cross Shear Zones CSZ-1 and CSz-2	Cutting across, obliquely	45º-70º/ N060º -080º (in D/S direction)	0.5 - +2.0/ 1.0	Crushed rock, clay gouge, crushed quartz vein/ 0.10 - .70	0.50 -2	Truncation of beds, intense shearing, silicification, tensional features, slicken-sides clay gouge are the associated features.
Longitudinal Shear Zones LSZ-1 to LSZ-4	Parallel/ subparallel	45º-75º/ N130º -160º	0.5-1.0/ 3.0	Clay gouge and crushed rock/ 0.10 - 0.70	0.5 - 2.0	Intense crumpling, silicification dragging effects, puckering are the associated features.
Foliation shear Zones FSZ-1 and FSZ-2	Oblique to Bedding	20º-35º/ N030º -060º	0.20 – 2.0	Clay gouge and crushed rock/ 0.10 - 0.50	0.50 – 0.70	Puckering
Diagonal DSZ	Opposite	40º-65º/ N220º -260º	0.20 – 1.0	Clay gouge and crushed rock/ 0.05 - 0.15	0.30 – 0.50	

TABLEII. MAJOR DISLOCATIONS AT DAM SITE

Order	Description	Continuity (Km)	Thickness of the Zone (m)	Disposition	Examples
I	Fault/thrust large, deep seismogenic (?)	>1000	1000	Trending NW-SE dipping northearly	MCT/MBT
II	Fault/thrust seismogenic (?)	>100	50-100	Trending NW-SE, dipping at high angle northerly/ southerly	Srinagar Thrust
III	Fault/tear	>10	10-50	Trending NW-SE, E-W, NE-SW, NNE-SSW; steep dipping	Dewal tear, Chamba fault, Rishikesh Lineament, Mussoorie Lineament
IV	Fault/shear/tear	>1	1-10	Trending NW-SE, NNW-SSE, dipping southerly/northerly	Mega shears at the dam site.

TABLE III. ORDERING OF DISCONTINUITIES AT DAM SITE

Sl. No.	Joint set	Orientation of Joints		Order V		Order VI		Order VII	
		Angle of dip	Azimuth of dip	Spacing (m)	Length (m)	Spacing (m)	Length (m)	Spacing (m)	Length (m)
1.	1	35º-80ºAbove El 590m	N330-350	5-20	100-300	1-5	30-100	0.5-10	5-30
		35º-65ºBelow El 590m	N130-160						
2.	2	18º-40º	N030-060	5-20	100-200	1-5	50-100	1.0-2.0	5-10
3.	3	50º-65º	N060-080	5-20	100-200	1-5	50-100	1.0-2.0	5-10
4.	3a	45º-75º	N070-110	5-15	100-300	1-5	30-100	0.5-1.0	5-30
5.	4	40º-65º	N220-260	5-10	100-200	1-5	50-100	0.5-2.0	5-10
6.	4a	35º-60º	N180-210	5-10	100-200	1-5	30-100	0.5-1.0	5-10
7.	5	40º-70º	N290-310	5-10	100-200	1-5	30-100	0.5-2.0	5-30

J. Rock Mass Classification

The value of the first parameter i.e. UCS was available from the results of tests carried out at site and lab and it was 42 MPa. As such no difference was obtained for the two most prevalent units of phyllite viz PQ and PT. The values for SP will be much lower but they are limited to the vicinity of shear zones. The logging of drill cores, from 12 drill holes, and the analysis thereof revealed the following mean values RQD.

TABLE IV. RQD VALUES FOR DIFFERENT WEATHERING ZONES AT KOTESHWAR DAM SITE

Sl. No.	Zone	Mean Value of RQD	Assigned Rating
1	A (Intensely weathered	16%	3
2	B Moderately Weathered	42%	8
3	Slightly or Un Weathered	58 – 60%	13

For rock mass classification the bedding and foliation joints of VIth and VIIth orders were considered as representative of the joints of the rock mass. On the right bank the bedding joints are dipping into the hill and hence they are oriented favorably vis-à-vis stability of slopes or foundation of the main structures. The rating adjustment for such relation of joints in RMR was accorded by subtracting 2 from the total rating.The beds on the left bank, for a major part, are dipping towards valley side which is not favorable considering the stability of slopes and in this case the rating adjustment is done by subtracting 7 from the total rating. The RMR values as obtained above were also used in some empirical equations and the value of modulus of deformation was worked out. Seraphim and Pereira equation is commonly used for determining E through RMR as given below

$$E = RMR-10/40 \qquad (1)$$

Taking the value of RMR from above Table V (RMR values has to be substituted without the adjustment for orientation of main joints in relation to the structure)

$$E= 50 – 10/40 = 10 \text{ GPa} \qquad (2)$$

TABLE V. THE RMR VALUES OF THE ROCK MASS

Right bank			Left bank		
Zone of Intense Weathering	Zone of Moderate Weathering	Zone of Slight or No Weathering	Zone of Intense Weathering	Zone of Moderate Weathering	Zone of Slight or No Weathering
20 - 25	40 - 45	45 - 50	18 - 20	35 - 40	40 - 45

TABLE VI. MODULUS VALUES AS DETERMINED BY EQ. -1 FOR DIFFERENT ZONES AT KOTESHWAR

Rock mass zone	A	B	C
E, MPa	2400	6400-8500	8500-11300

The values E given in the above Table for moderately and un weathered zones coincides with the values obtained through geophysical surveys but they are slightly higher than those obtained through jack testing. It is not uncommon to happen considering the special conditions of testing (water saturation of tested rock mass) as well as the complicated structure of this rock mass.

The RMR values, without the rating adjustment for orientation of joints, as determined for intensely weathered, moderately weathered and un-weathered zones are 50, 45 and 25 respectively. These values were used for determination of Hoek and Brown parameters m and s as per the equation 9 and 10 above and they are given in Table VII below.

TABLE VII. HOEK AND BROWN PARAMETERS FOR DIFFERENT ZONES AT KOTESHWAR DAM SITE

Sl. No.	Hoek & Brown Parameter	Intensely Weathered Zone	Moderately Weathered Zone	Un Weathered Zone
1	m	0.687	1.403	1.677
2	s	0.00024	0.00222	0.00387

These obtained values of m and s are substituted in the equations to get the values of shear parameters as given in the Table below. These values are corresponding to the normal stress (σ) value of 1 MPa.

TABLE VIII. SHEAR PARAMETERS FOR DIFFERENT ZONES AT KOTESHWAR DAM SITE

Sl. No.	Shear Parameter	Intensely Weathered Zone	Moderately Weathered Zone	Un Weathered Zone
1	tan φ	0.90	1.12	1.17
2	C (MPa)	0.405	0.56	0.63
3	σ cm (MPa)	1.8	2.9	3.4
4	σ tm (MPa)	0.015	0.07	0.10

It is evident from the above Table that the mean values of tan φ and C are close to the values obtained through the testing of cores i.e. tan φ - 1.54 and C - 0.65 MPa which corroborates the observed data and tested data.

V. BLOCK TECTONIC MODEL AND INTER BLOCK TECTONICS

An attempt has been made to decipher the possible bearing of the major shears on the geomechanical behaviour of the rock mass at the dam site, to prepare a conjectural tectonic block model of the evolution of present-day morphotectonic expression. This is the maiden attempt by the author in India to develop the block tectonic model for a high concrete gravity dam located in Himalayan terrain.

The geometry, orientation, frequency and interplay of major (IV order) LSZ, CSZ, FSZ and DSZ shears (Fig.6 Plate-1) have considerably affected the geomechanical characteristics of the rock mass and provided a scope of dividing the dam site into three different tectonic blocks (Fig. 6). The boundaries of these tectonic blocks (1, 2, and 3) are defined by CSZ-1 and CSZ-2 shears (Plate-1). The upstream coffer dam and inlet of diversion tunnel lie in tectonic block no.1 i.e upstream of CSZ-1. All the fourteen dam blocks including the spillway and power intake lie mainly in tectonic block no. 2 which is further dissected by four LSZ shears (LSZ-1 – LSZ-4), two foliation shears FSZ-1 and FSZ-2 and the diagonal shear DSZ. The upstream part of stilling basin, vertical and horizontal penstocks and all the six inspection galleries also fall in tectonic block no.2. Part of stilling basin, major part of powerhouse, tail race channel, main access tunnel and outlet of diversion tunnel lie in tectonic block no. 3 (Fig. 6,and Fig. 7,).

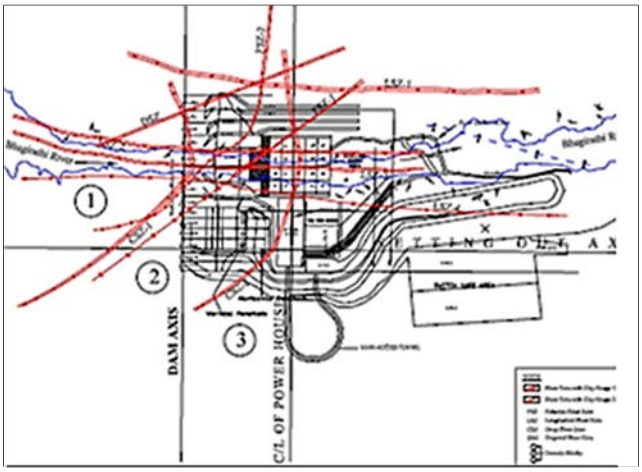

Fig. 6. Block tectonic model for Koteshwar dam

These major tectonic blocks are also dissected by a number of V order dislocations, thus further dividing them into different smaller blocks of sizes varying from 5 m x 30m to 20 m x 100 m. Frequency of joint sets of V, VI, VII orders is responsible for blocky structure and degree of jointing is the most essential factor determining the strength and deformation properties of rock mass. The shear strength of filling materials of shear zones and open joints was the key factor for the stability of rock mass. The intersection points of mega shears/faults were highly deformed and de-stressed. The observation has also been validated in underground structures when these zones proved to be detrimental causing instability and water seepage.

Identification of these tectonic blocks and evaluation of sense of movement along mega shears in conjunction with regional tectonic frame work, was of immense help in understanding the likely behaviour of rock mass.

Fig. 7.Position of mega shears and tectonic blocks at koteshwar dam site

TABLE IX. MODEL OF THE ROCK MASSES IN DIFFERENT TECTONIC BLOCKS VIS-À-VIS PROPOSED ENGINEERING STRUCTURES, AT KOTESHWAR DAM SITE.

Tectonic block	Rock type/ Rock mass group/grade	Joints/blocks	Weathering/ destressing	Permeability (K) (of rock mass)m/day	Geomechanical properties (of fresh rock mass) MPa	Constructed engineering structures
Block 1 (Beyond CSZ-1)	PT, interbedded PQ and PT, PT and QP. (Group 1 and 2, Gr. I and II)	Highly to moderately jointed; RQD %= 35-50, Jv=15-25 or more	W_2-W_3 10m thick zone, W_1-W_2 15m thick zone (on higher slopes)	Less than 0.3 – 0.9.	E= 4000 - 6000 Vp= 3.2-4.2 km/sec	Inlet of diversion tunnel, u/s coffer dam, heel portion of dam blocks 3,4,5&6
Block 2 (between CSZ-1 and CSZ-2 shears)	PQ, PT and interbedded PQ and PT and PT and PQ(Group 1 and 2, Gr. I and II)	Highly to moderately jointed; RQD %= 40 - 65, Jv=10-20	W_2-W_3 10m thick zone, W_1-W_2 20m thick zone	0.02 – 0.06 Higher values of 0.4 in de-stressed zone	E= 6000 - 8000 Vp= 4.2-4.7 km/sec	Dam blocks,spillway, power intakes, penstocks, part of stilling basin
Block 3 (Downstream of CSZ-2)	PQ, PT, interbedded sequence of PTand PQ, Limonitised and Puckered PT Group 1 and 2, Gr. I) Mega shears (Group 3 & 4, Gr. III)	Highly jointed; RQD %= 30-, Jv=8-16	W_2-W3 20m thick zone (on higher slopes)	0.2 – 0.6 Higher values of 1.2 – 1.5 in Sheared rock mass zones	E= 4000 – 6000 Lower values 1000 - 2000 in the slump mass zone on left bank and SP zones on the right bank Vp=3.2- 4.2 km/sec	Stilling Basin Blocks, MAT, Switchyard and Outlet portal of Diversion Tunnel

As per the block tectonic model part of diversion tunnel, part of dam blocks 1, 2, 3, 4 and 5 and a minor part of power dam lie in block no. 1, dam block nos. 4 – 14, all the stilling basin blocks, entire powerhouse, main access tunnel, horizontal and vertical penstock shafts and tail race channel fall in block no.2 whereas part of tail race channel, downstream coffer dam and outlet of diversion tunnel fall in tectonic block no.3.

VI. CONCLUSIONS

Block tectonic model is a useful and important tool to assess the nature of foundation rocks and their response during and after the construction of structures. The exact nature of rock mass in terms of physical and geomechanical parameters including the permeability charactersat the respective tectonic block is well known to the geologist and engineer vis-à-vis the location of structure.

At Koteshwar dam site the likely failures from the abutment slopes were properly anticipated and design modifications were incorporated during construction stage. The instability on the right bank slopes, between dam and powerhouse areas was induced along the major shear CSZ-2. Similarly the instability on the slopes above the stilling basin area was due to the weaker and highly sheared rock mass owing to the intersection of multiple shear zones viz LSZ-1, DSZ, FSZ-2 and CSZ-2.The most important outcome of this model at Koteshwar has been towards confirming the disproval of any river bed fault at the dam foundation in the overflow section. The earlier investigations by GSI had suspected such a fault in the river bed based on the poor to very poor core recovery and highly fractured rock mass along with clay gouge from the cores of the hole drilled near the toe end of the dam. The model (Fig-6 and Plate-1) illustrated that the reason for poor core recovery and clay gouge could be that the hole encountered the intersectional zone of mega shears LSZ-2, LSZ-3 and CSZ-2. The same was corroborated during the geological mapping of the foundation of dam and stilling basin.

The foundation treatments at dam, stilling basin and powerhouse, support measures at underground penstocks and shafts and stabilization measures of the abutment slopes were modified which helped in successful commissioning of the project in 2011.

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