GEOLOGICAL AND GEOTECHNICAL INVESTIGATIONS AND INTERPRETATIONS THEREOF FOR STATUE OF UNITY FOUNDATION

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Abstract. The statue of Unity, tallest statue of Late Sardar Vallabhaiji Patel, is constructed at around 3.50 km downstream of the Sardar Sarvoar Dam. The statue is located on Sadhu hill, one hill islanded in Narmada river waterway. The Sadhu hill is around 250m inside the Narmada waterway and the top of the hill was at RL 72.0m.

Sardar Vallabhaiji Patel was a great Statesman and played a leading role in struggle for independence and guided into a united, independent nation. He forged a united India from British colonial premises and more than five hundred self-governing princely states. He was first deputy Prime Minister and first Home Minister of the country. To pay the respect to this great leader, Gujarat Government decided to build a tallest statue of this leader in the world and the same is constructed at Sadhu hill. The statue is 182m tall and is of Bronze panels fixed on steel cladding which are fitted to concrete cores.

This paper covers in detail the geological and geotechnical features of the statue site and surrounding area. It will be also detailing the difficulties faced during the design, the foundation and the basic structural design for such a tall structure. The statue is having two RCC cores and cladding around to support bronze sheets which are moulded to the statue shape. Considering the iconic importance of the structure, extensive geological and geotechnical investigations were carried out along with field tests.

Keywords: Brecciated, Sandstone, Shale.

1 Site Location and Topography

The proposed statue of unity is located on a rock promontory known locally as Sadhu hill on the north side of the Narmada River bed. During periods of high river flow, this promontory is an island within the river channel. The top of the rocky promontory was at an elevation of R.L. 70.90M above the mean sea level.

The Narmada River is the fifth largest river in India and drains a large area of central India to the west. River flow is very seasonal, reflecting the monsoon climate of the sub-continent. This has been reduced since the construction of the Sardar Sarovar Dam upstream of the proposed location for the Statue of Unity has taken place.

2 Regional Geology

The Narmada River flows along the ENE-WSW trending Narmada-Son Fault (NSF), a well-known seismo-tectonic feature. A major part of the course of the Narmada River fall within the rocky area comprising basaltic lava flow belonging to the Deccan Trap Formation. The river follows a constricted course in this reach characterized by waterfalls, rapids and gorges. The true alluvial reach of the Narmada is encountered in its lower part within the state of Gujarat. This reach is about 90km in length and forms the southern margin of the N-S extending Gujarat alluvial plains.

The Narmada-Son Fault (NSF) divides the Indian plate into two halves and has a long tectonic history dating back to the Archaean times. This fault trends in ENE-WSW direction and is laterally traceable for more than 1000km. It demarcates the Peninsular India into two geologically distinct provinces: the Vindhyan-Bundelkhand province(VBP) to the north and the Deccan province to the south regards the Narmada-Son Fault as a part of the composite tectonically controlled zone in the middle of the Indian plate and termed it as the SONATA zone (abbreviated form of Son-Narmada-Tapti Lineament zone). The Narmada and Tapti Rivers all throughout their course follow these tectonic trends. Geophysical studies in the central part of this zone reveal this to be a zone of intense deep-seated faulting.

The Narmada Basin has become reactivated in response to the collision of India with the Asian continent with uplift and subsidence taking place in a zone including the Son Narmada fault and along the pre-existing structures to the south of the Son-Narmada fault.

3 Geology of Sadhu Hill Area (Statue Location)

As mentioned above, the site chosen for the construction of the monument was an isolated hill mass in the Narmada river bed as shown in Fig 1. The hillock is close to the right bank of the river. It comprises sedimentary rocks of Bagh Bed belonging to Cretaceous age. Main rock type is Quartzitic Sandstone. Minor shale beds are also present (Ref 3). The area occupied by this hillock measures about 0.6 km2 as could be assessed from the SOI contour map. The maximum height attained by the hillock is 70.90 m. The Hillock is an inlier as it is surrounded by the younger Deccan trap basalt on all sides. The inlier may be formed due to tectonic activities during different geological periods. The hillock is in the form of a 'horst structure' wherein the central block has come up relative to the adjacent block. The horst structure is formed due to 'reverse faults' (Pancholi, 2010).

Fig1: Sadhu Hill in Original Condition

Due to tectonic activities at the end of Deccan Trap volcanism in the region, the sandstone beds have developed numerous joints as shown in Fig 2.

Fig2: Mosaic Texture in Quartzitic Sandstone

The second abundant sedimentary rock type is medium- to dark-grey shale that apparently appears to be bituminous in nature (Fig.3). Many of the shale contain considerable amount of fine-grained sand particles and detrital muscovite mica Argillaceous content has recrystallised into fine particles of sericite mica, leading to the development of an incipient phyllitic cleavage. The intrusive rocks are mainly dolerites and finer grained basalts.

Fig 3: Grey Coloured Shale

The site falls in zone III of the seismic zoning map of India (BIS) where maximum expected magnitude of an earthquake is 6.0. Most of the area is covered by the Deccan traps and is along the Narmada-Son Lineament, which is now inactive. Other faults nearby the study area are Piplod fault, Rajpardi fault, Borkhadi fault and Barwani-Sukta fault. The SSNNL is running a network of 9 seismological stations comprising of short period sensors since 1990 and recorded considerable amount of local seismicity.

Sadhu Hill abruptly rises with a vertical cliff. At the base of the hill lies the shale beds and shale beds are encountered further in boreholes but they are not exposed on the surface of the Sadhu Hill. The youngest formations are exposed only in the north-western dwarf hillock, indicating that it forms the down thrown block.

The Sandstone rock, with low dips of 15°-22° westerly have very rough uneven surface, intersected by two prominent vertical joint sets. These joints formed large rectangular blocks of hard Sandstone rock with crushed infillings within joints opening. Some of these blocks have been detached fully from their in-situ positions on the bedding planes, whereas, majority of them are still intact, but bit unstable with wider open gaps around them. It was necessary to assess correctly the engineering characteristics of rock mass through boreholes identification.

Sadhu hillock is the isolated conical hill formed by erosional effect of Narmada River and can be defined as island in the river having flow of water on its all sides during flood season. Beautiful sections of this hillock have been exposed on its north eastern & south western side by virtue of erosional effect by the Narmada River in the past. Thus, a complete sub-surface rocks can be seen in these exposed sections which increase reliability of the borehole data drilled in the Sadhu Hill. Moreover, subsurface geology is clearer in these sections than in the borehole section.

In the case of drilling results of project area, a great variation in RQD values have been found.

A borehole, if drilled along the joint plane, will obviously intersect crushed infilling material and poor RQD values are obtained. Whereas another borehole, drilled just a meter away, will interact hard sandstone rock throughout its drilled depth with 100% RQD values.

Generally, the hard sandstone rock has been known for their excellent competency having uniaxial compressive strength generally more than 80 MPa along with high bearing capacity. Here also, these rocks appear to be very favourable to withstand the induced load of proposed statue with least variability in shear strength and bearing capacity through all zones of influence below the foundation.

4 Geotechnical Investigation at Sadhu hill

The geotechnical investigation comprised 18 rotary cored boreholes to depths of 30m to 90m. The hydraulic rigs with triple tube core barrels were used to drill these deep boreholes. Three of the boreholes were inclined (45^0) to investigate the rock mass immediately below the statue foundation. Five of the boreholes were surveyed using a down the hole televiewer to provide rock mass information and discontinuity orientations.

As already explained above, Geophysical survey and surface geological rock outcrop mappings were performed to delineate major discontinuities, shear zones, geological setting for preliminary geological & geotechnical assessment of rock condition. The rock mass rating was calculated to know the response of rock mass and foresee the unexpected problematic zones as well as assessment of slope stabilization, foundation treatment if any etc.

5 Geotechnical Assessment/Finding of Investigations

The main objective of geological and geotechnical survey was to summarize surface geological, subsurface geotechnical studies to work out with the following important attributes:

i. Lithology
ii. Joints
iii. Discontinuities
iv. Permeability
v. Stratigraphy
vi. Geological setting

The effect of the same was studied on the statue foundation and the global stability of Sadhu hill. The additional objectives of the geotechnical investigation are to characterize the contact between overburden and in-situ rock condition. To understand the porosity, permeability of rock and over burden materials which provide geotechnical inputs to the design mechanism of support system, rock excavation system for the foundation of 182 m high statue, slope stability analysis, blasting geometry, establishment of appropriate powder factor of blasts (PF) and road foundation, required for construction phase in appear Statue of Unity at Sadhu hill site were carried out. The further objectives were assigned to provide comprehensive, graphic, geological, geotechnical, hydrological, geophysical and conceal surprises if any, weak zones, water in rushes information about the site conditions for technical purpose based on bore hole data to evolve an explicit, safe and economic design operation and selection of appropriate rock friendly machinery.

6 Additional testing at Sadhu hill and interpretation Thereof

Following testing was carried out at Statue location to understand the various properties of the rocks.

i. Borehole logging
ii. Packer permeability test
iii. High Pressure dilatometer
iv. Cross hole shear test
v. Electrical Resistivity test

6.1 Interpretation of Borehole Logging

A feature of the strata noted from the borehole core is a degree of tectonic disturbance in places. This results in brecciation of the rock mass which in places has recemented but in some horizons, a very weak reddish brown siltstone matrix is present between the breccia clasts. The degree of breccation is variable with the more disturbed zones being described as fault breccia. The four main shale units are present in most boreholes. These thin (<2 cm) shale bands are intermittent and indurated.

6.2 Packer Permeability Test

It is measured with Lugeon testing. The reported Luegeon values are generally in the range of 1-5 which indicates tight discontinuities with a few higher values suggesting some of the discontinuities are open/partly open. The very low permeability recorded by the Lugeon data implies that the rock is better than the number of discontinuities and fractures observed in the cores suggest.

6.3 High Pressure Dilatometer

Young’s modulus are found to be in range of 4 GPa average.

6.4 Cross Hole Shear Test

The general observation from the cross hole seismic investigation indicates that the velocities of P and S waves vary from 2490 – 3132 m/sec and 1215 - 1628 m/sec respectively. The value of Poisson ratio varies from 0.28 to 0.34.

6.5 Electrical Resistivity Test

Measured values of resistance of the ground to passage of electrical current are 1450 to 7440 ohm.m which are less than typical values of the sandstone.

7 Engineering Parameters of the Rock

i. Strength: The permeability of sandstone is recorded less than 1.50 Lugeon indicating high quality of Sandstone.
ii. Strength (in terms of UCS): The lower bound strength is taken at the 20th percentile of the combined UCS data giving a strength of 49 MPa.
iii. Following parameters are worked out based on Hoek-Brown criterion (Rock mass assessment)
UCS= 48 MPa; GSI= 40; D = 0.1; m = 17; E = 12 GPa
iv. The joint roughness factor of approximately 8 is considered.
v. From cross hole seismic test, the S-wave velocity is approximately 1250 m/s to 1500m /s at 30m. Similarly, P wave velocity varies from 2500m/s to 3000 m/s at 30m which is consistent with fractured sandstone.
vi. The E_i value of 42 GPa is indicated as a mean value which shows the stiffness of the rock.

8 Statue Foundation and the Challenges

The statue foundation is a raft foundation on quartzitic Sandstone at RL 52.50m on Sadhu hill as shown in Fig 5. The foundation for such a tall structure (tallest in the world) is designed with stringent design criterion and due weightage to geology, geotechnical assessments of the rock, structural aspects of the statue, seismic parameters, wind speed and other design considerations.

Fig 5: Foundation Construction

The foundation for Statue is 3m thick raft with wide base of 44m x 34m. The bearing capacity of 1500 KPa was computed for the founding strata of Sandstone. The wide base combined with high safe bearing capacity has provided a good base to the statue which is stable against overturning and sliding effects. The entire raft has been cast in a single pour to avoid joints.

The design of statue foundation was a tough job considering following points: -

i. Stability of rock mass – Overall stability (considering the complex geology)
ii. Local Stability
iii. Sandwiched Shale rock in between Quartzitic Sandstone layers
iv. Seismic parameters pertaining to Seismic zone V (although the area falls in zone IV)
v. Basic wind speed of 50 m/s
vi. Scouring of the hill due to river water.

9 Solution to the Challenges

Looking at the complex geology and issues as elaborated above, the foundation design was going to be a challenge. Due to big variation in values of several parameters, the consideration of all these parameters into design was also a complicated job.

9.1 Stability of Rock Mass - Overall stability (considering the complex geology)

The available borehole information and 3 D conceptual ground model shows the rock to be highly affected by tectonic action which has resulted in non-planar bedding and impersistent discontinuities due to the effects of local faulting. Locally, shale was observed in the boreholes above the highest shale band but these are also impersistent. Furthermore, the brecciated zones within the rock mass have been found to be the results of local faulting and are found to be localized in the nature. There was no evidence of a plane of weakness within the rock mass that would give rise to global instability.

Numbers of checks have been given for confirming the global stability including worst recorded bedding plane orientation in the area and the effects of a 15m tension crack full of water the head of the wedge.

9.2 Local Stability

Where the erosion of shale by flood waters has results in overhanging sandstone, the shale shall be protected from further erosion by the use of shotcreting. The rock terracing is being done with slopes that may have unfavourable orientation in respect to the minor faults.

9.3 Sandwiched Shale Rock in between Quartzitic Sandstone Layers

Although, shale layers sandwiched between sandstone layers are very thin(<1000mm), those are felt to be major plane of weakness. However, considering the depth of shale layers (>17m) below the formation level, the major pressure will be getting dissipated before reaching to those layers.

The foundation of the statue was ensured to be resting on sandstone.

9.4 Seismic Parameters pertaining to Seismic Zone IV

Although, the site comes under zone III, the consideration for foundation design is taken as zone IV and the zone factor is taken as 0.24 g. The seismicity of the area is having a deep impact on the foundation design.

9.5 Basic Wind Speed of 50 m/s

The wind load for the statue structure has been estimated using a basic wind speed of 50 m/s and by carrying out a detailed wind tunnel studies. The wind effects are very high and due to which, the foundation design has become very complicated. The very high anticipated sways in the structure have made the structural stability complicated. To reduce the effects of wind and excessive deflections of the structure, 2 numbers of Tuned Mass Dampers have been provided to increase overall damping of structure.

9.6 Scouring of the Hill due to River Water

Due to very high water currents during the flood discharges from the dam and even in the normal time, the banks and the other earth structures are subject to scouring action. The shale layers below the water are susceptible to water erosion more due to which the hill may get weakened in submerged portions. The proper treatment for this is still underway and will be firmed up once the inspection will be completed for submerged portions.

10 General Idea about Statue Structure

The Statue is unique, not only in terms of its height and scale, but more significantly because it is a true (or near to as possible) representation of a man; Sardar Vallabhbai Patel. As such, due to the primarily geometrical challenges that a human form creates, conventional solutions are generally inappropriate. Instead, bespoke solutions have been found, developed and implemented.

Devising an efficient structure for the Statue raised several challenges, from both a design and construction perspective. The 'spine' of the Statue is formed by the reinforced concrete core and this not only has to withstand and safely transfer significant wind and seismic forces to the foundations, it also has to provide support to the 'skeletal frame' that creates the shape of the Statue figure. The skeletal frame not only has to respond to the complex geometrical shape of the figure, but at its extremities it has to provide fixture and support to the relatively heavy bronze 'skin', that ultimately creates the form of Sardar Vallabhbhai Patel. These complex design issues were similarly manifest as complex construction challenges. It was therefore essential that the design be developed with pro-active input from L&T and its key sub-contractors and suppliers and, the bronze cladding contractor.

The Statue has been modelled using 3D finite element analysis as shown in Fig 6. For schematic design, the core has been modelled using a grillage of 1D elements connected using 'stiff arms'. This approach allowed for control of in plane and out of plane bending stiffness of walls and captured the effects of warping stiffness and shear stiffness. The output forces of the 1D analysis elements has been used to design the core wall sections. Only door and large service penetrations have been modelled.

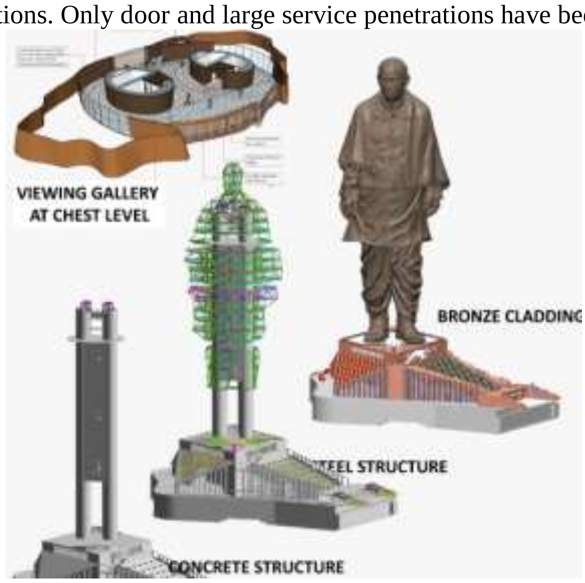

Fig5: Modelling of Statue Structure

The 182 m tall statue is made up of a 25 m high base and 157 m tall statue. The base has high roofs with steel trusses and RCC slabs. The statue is divided into 5 parts – the lower & upper legs, lower & upper body and the shoulder & head.

The steel in the statue is in 3 layers: Primary, Secondary and Tertiary. The Primary frames are vertical trusses that interconnected with infill steel members and in turn connected to the RCC cores. These transfer all the load from the statue skin onto RCC cores. The Secondary steel that is part of the primary layer, are trusses that carry the load from the bronze cladding connected through the tertiary steel frames. These two layers form the basic skeleton of Statue. The Tertiary layer is set of steel trusses connected between secondary steel and bronze cladding that bridges the gap between the skin and the skeleton of the statue. Each tertiary steel frame is unique as each bronze panel is unique. Viewing galley at a height of 135m from podium level has been provided as a unique experience for the visitors.

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