2. Geological Set Up

2.1 General Geology of the area

Regional geological survey in the Lower Narmada valley (Malwa tract) between Vadodara (Baroda) in Gujarat and Bagh in M.P was originally done by Blanford (1869). He established the detailed geological sequence and described the Deccan trap lava flows and the underlying Bagh sedimentaries resting on the basement metamorphics. Other workers worked out additional geological details (Krishnan 1968) (Table 18). Numerous basic dykes impregnate the host rocks in the area (Fig. 2).

Table 18: Stratigraphic succession in the lower Narmada valley of Gujarat

Age	Formation	Description
Sub Recent to Recent		Calc tuffa, soil, alluvium and gravel
Upper Cretaceous to Eocene	Deccan trap	Basalt flows intruded by dykes and sill
------------------------------------	Unconformity--------------------	------------------------------------
Middle to Upper Cretaceous	Bagh beds (Infra Trappeans)	Sandstone, Shale and Limestone.

2.2 Geotectonic setting

Both Narmada and Karjan projects are located in the Lower Narmada Valley, which is considered as a rift zone (graben) bounded by faults (Crookshand 1936, Auden 1949, Krishnan 1961, West 1962, Ahmed 1964 and Mathur et. al. 1968). These faults are aligned parallel to the Narmada-Son lineament (NSL) zone in ENE-WSW direction. The NSL zone is also known as 'SONATA' (Sone-Narmada-Tapti-Lineament) (Fig. 1). It is 1600-km long and 150-200 km wide, between Long 72^{o} and 88^{o}E. This zone transacts the shield area of peninsular India into northern and southern blocks. The NSL zone represents a intracratonic rift system which was reactivated several times in the geological past (West 1962); block faulting as well as horst and graben tectonics have been suggested for its origin by many workers (Choubey 1971; Roy and Bandhopadhyay 1988). There are two major boundary fault systems within the NSL zone, a northerly dipping Narmada North Fault (NNF) and southerly dipping Narmada South Fault (NSF). These are mantle reaching faults as confirmed by Deep Seismic Soundings (DSS) (Kaila 1988) and gravity study (Mishra 1992, Verma and Banerjee 1992, Agarwal et. al. 1995). It is characterized by the high gravity, positive isostatic, anomalous geothermal regime with relatively high temperature gradient and high heat flow, shallowing of magmatic crust, elevated 'Curie Point' and solidus of basalt geoisotherms and recurrent seismicity. It was reactivated several times in the geological past (Raju et al. 1970, Das and Ray 1973, Ravishankar 1993). Tectonic imprints of both the Narmada (ENE-WSW) and West Coast (N-S to N10°E- S10°W) lineament trends are seen in this area (Mehta and Prakash 1982).

2.3 Post Deccan trap activity in the area

Distinct phases of post Deccan trap tensional and compressional deformations are seen in the 'SONATA' zone and adjoining region. These are evident from the occurrence of dyke swarms, displacement of dykes, dipping of the basalt flows and emergence of the Bagh beds from underneath the Deccan traps in juxtaposition with basalt. A number of reverse faults have been observed in the area including Nramada Main River channel fault indicating compressive post Deccan trap activity (Fig. 3). The area is still under compression due to northward movement of the Indian plate (Appendix-I). It is evident from the recent seismic activity in the NSL zone (Prakash and Srikarni 1998, Acharya et al. 1998).

2.4 Neotectonism

Holocene sediment exposed in the area between Broach and Gora on Narmada River is involved in neotectonic activity as indicated by off setting of northerly flowing tributaries, the two terrace levels and their tilting and local convexities in thalweg of Narmada river. Increase in the thickness of post trappean marine sediments towards Ankleshwar is another evidence. The longitudinal profile of Narmada between Gora to Ankleshwar indicate the up warping between Rudh (21° 57'- 73° 28') and Rajpardi (20°46'-73°15'). Quaternary deposits of Tilakwada (21°57'30"; 73°36') appear to be disturbed by Neotectonic activity (Srinivasan et. al. 1981).

2.5 Seismicity of the area

The project area falls in the zone III of the seismic zoning map of India (IS 1893). Movement of the Indian Plate towards north has resulted in the formation of deep-seated lineaments. The Narmada-Son lineament is the most significant fault, which has divided the Indian plate into two main tectonic blocks. These have been further divided into rifts and grabens with central massif. Investigations indicated that the margins of the peninsular India have shown sub-Recent movements (Kailasam 1979). The study of Kaila and Rao (1979) show that the west coasts is a zone of moderately high seismicity. The NSL and Tapti Lineament (TL) zone are seismically active. The largest seismic event experienced in the area is the Broach earthquake with magnitude 5.4 observed in 1970. In the recent past the area experienced several times seismic events of fairly high intensity. A few significant earthquakes have occurred in these zones e.g. Broach earthquake of 1970 (M 5.4), Koyna earthquake of 1967 (M 6.5), Satpura earthquake of 1938 (M 6.3), and Rewa earthquake of 1927(M 6.5). The Narmada and Karjan projects lie in a "mobile" belt of about 20km width in SONATA zone, bounded by ENE-WSW trending fault towards North and Piplod fault towards South (Jai Krishna et. al. 1976). The Son- Narmada -Tapti rift zone is considered to be seismically active (Acharya et al. 1998).

2.6 Geology of Narmada dam site

The project site is occupied by the "Aa" type Deccan basalt flows underlain by sedimentary rocks of Bagh beds (infra-trappeans). A typical "Aa" flow of Hawaii type is tripartite with a basal clinkery zone, thick and massive middle part exhibiting columnar joints, and upper tuff or agglomerate or clinkery fragment zone. In this area the basal zone is almost absent and top of the flows are marked by agglomerate or tuff (Plate 4). In the left bank 8 flows of dense and porphyritic basalt varieties and on the Right Bank 5 flows of dense, porphyritic and amygdaloidal varieties have been delineated in the foundation area above riverbed level. Thickness of the individual lava flows varies from 7 to 56m. The attitude of basalt flows varies from near horizontal to low dips (upto 25°). Basalt flows are displaced along steeply dipping fault (Plate 4). A red bole layer separating amygdaloidal basalt flows was exposed in the riverbed on the left bank and in the foundation of left divide wall between lower chute and stilling basin. Continuity of red bole layer towards Right Bank is cut by a River Channel (bed) Fault. The River Channel Fault (RCF) has brought sedimentary rocks (Bagh beds) in juxtaposition with basalt flows at the dam base (Fig. 3). Bagh beds are exposed in the upstream and downstream of the dam either by erosion of overlying basalt as inliers or by faulting. The sedimentary rocks (Bagh beds) comprising of quartzitic sandstone, argillaceous sandstone, shale, pebbly sandstone and limestone are sub-horizontally disposed (Plate 5 and 6). The lower part of the Bagh beds is arenaceous and upper part of the beds is mainly calcareous (Krishnan 1968).

Plate 4: Agglomerate and columnar jointed basalt (basal clinkery zone is absent) in the foundation of right training wall displaced by a fault, Sardar Sarovar (Narmada)Project

Plate 5: Sub-horizontal disposition of the infra-trappean sedimentaries (Bagh beds) and basalt flows in the Right Bank of the dam, Sardar Sarovar (Narmada) Project

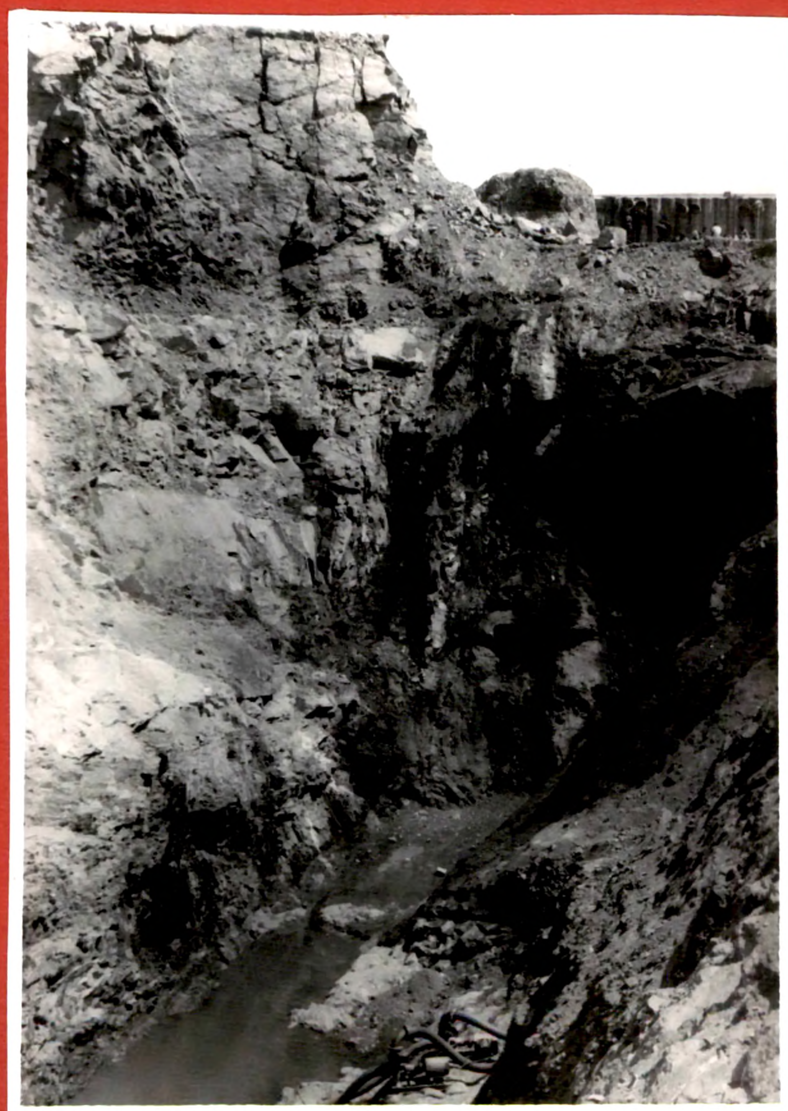


Plate 6: Excavated trench along river channel fault, Sardar Sarovar (Narmada) Project

2.6.1 River Channel fault

The River Channel Fault is aligned in N80°E-S80°W direction, dipping 60° towards N10°W is obliquely traversing the foundations of four spillway blocks (41 to 44). Width of the fault zone is about 10 to 12m (Fig. 4). The Fault is associated with 5 to 15 cm thick gougey material and rock mass adjacent to fault zone is sheared and fractured. It is an en echelon type reverse fault having displacement of the order of 210m with up throw side towards north i.e. towards Right Bank. The RCF is offset by Mokhadi and Akkalbar faults, located about 450 and 600m upstream and downstream of the dam, respectively (Fig. 2).

2.6.2 Dykes

There are a number of ENE-WSW trending basic dykes intruding the basalt flows and sedimentary rocks in the area (Fig. 2). Thickness of the dykes varies from 1-2m to 20-25m. These dykes in the foundation area are displaced along low dipping shears/ faults.

2.7 Geology of the Narmada Underground Powerhouse Site

The area is hilly, covered with thin mantle of soil. It consists of lava flows of basalt, separated by hard agglomerate and intruded by ENE-WSW trending dolerite dykes and sill. Four basalt flows have been identified from the ground level to 30m below the turbine level i.e. between El.132 and (-) 42m. The powerhouse is located in between two 40 to 45m thick dolerite dykes and sill. The dyke close to the river dips 60°-65° towards SE direction i.e. towards left bank while the second located near the northern end of the machine hall is near vertical. Major part of the turbo- generator units is located in the dolerite sill. Weathered zones extend 7 to 23m deep in dolerite and 0.5 to 5m in basalt. These two dykes would provide seepage barriers from pond No.1 located in the North and Narmada River in the South of the powerhouse. The rock mass permeability varies within large ranges (0-30 lugeons). Oozing and water dripping have been noticed at and near shear zones. Major part of the exit tunnels, draft tube tunnels and foundations of turbo-generator units including bottom sides of the machine hall are located in the dolerite rock dissected by chlorite coated joints, shears and slaked zones.

2.8 Geology of the Karjan dam site

The Karjan dam is located on the Deccan basalt flows of "Aa" and "Pahoehoe" type. The "Aa" flows characterised by fine grained or porphyritic dense basalt towards the base becoming amygdular or tuffaceous at the top are exposed on the abutments at higher levels. In the river section, "Pahoehoe" type basalt characterised by wrinkled (ropy) (Plate 7) and vesicular top, and pipe amygdales at the base is exposed. Thickness of the individual flow unit varies from 4 to 40m. Exposures of the Bagh beds and dolerite dykes are not seen in the foundation area. A characteristic feature of the rocks in this area is the presence of weathered rock seams at the interfaces of many flows.

2.8.1 Nature of Weathered rock seams

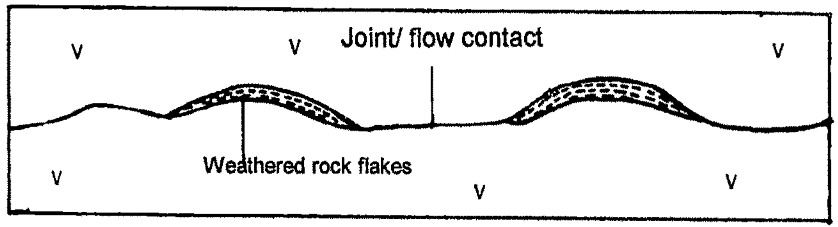
Weathered rock seams consist of a zone of highly to completely weathered basalt associated with thin film of clayey material at places (Plate 8 and Fig. 6). These are of wavy, branching and of pinching and swelling nature. Thickness of seam varies from a few mm to a meter. Zeolite/ calcite infilling has been noticed along some of the weathered seams. These seams were developed along flow contacts and also along sub-horizontal open joints due to percolation of seepage water. Conspicuous seepage was noticed through these seams in the foundation of riverbed blocks during the excavation of treatment shafts and drifts.

Plate 7: Exposure of ropy lava at the Karjan dam site

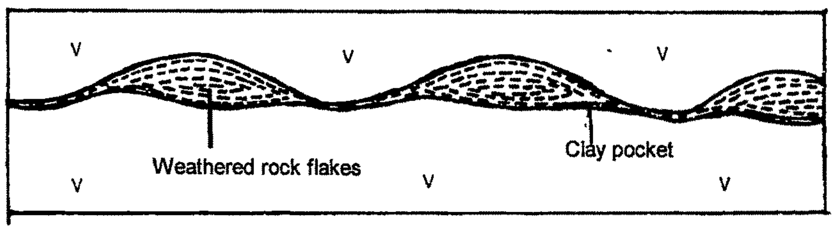
(a) Disposition of weathered rock seam in the foundation of dam block

(b) Preparation of in-situ shear test blocks on weathered rock seam

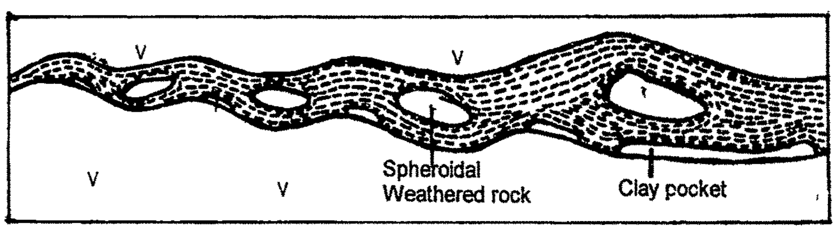
Plate 8:: Disposition of weathered rock seam in the foundation of spillway block and preparation of in-situ shear test blocks, Karjan dam (a & b)



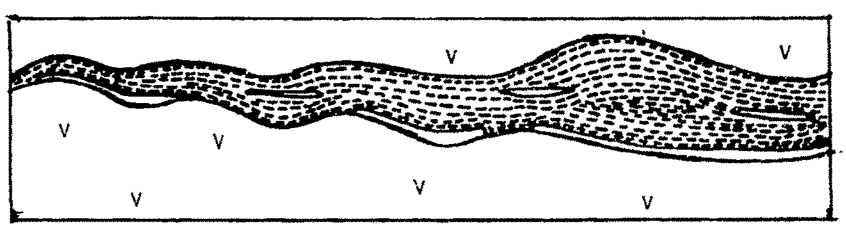
Type-I: Partly developed seam along joint



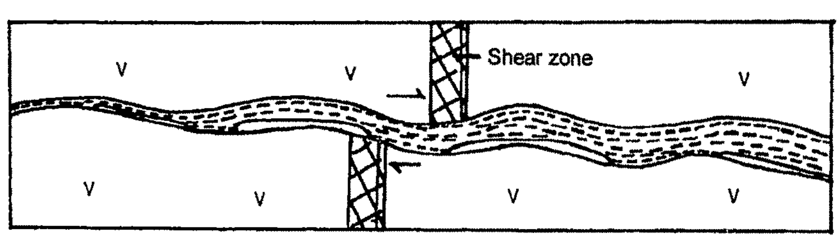
Type-II: Pinching and swelling seam



Type-III: Seam with spheroidal weathered rock



Type-IV: Thick seam without spheroidal weathered rock



Type-V: Seam associated with slickensided surface due to movement

Fig. 6: Different types of weathered rock seams in the foundation of Karjan dam

Plate 9: Foundation preparation of the river channel fault exposed at the dam base (view from upstream), Karjan dam

Slickensided surfaces were observed at few places along weathered seams indicating movement. A few vertical shear zones were observed displaced about 1 to 2m laterally along these seams (Fig. 6). Therefore, these seams were considered potential weak planes for sliding of dam blocks.

2.8.2 River channel fault

Karjan River flows from south to north in a straight channel along a fault at and adjacent to the dam base (Plate 9 and Fig. 2). In the absence of marker horizon actual displacement of basalt flows is not known. This fault cuts through the foundation of three riverbed blocks. Width of the fault zone is about 12m. Fault zone material consists of hard sheared basalt, reinforced by calcite zeolite veins and associated with thin discontinuous gougey material.