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Geological investigations at Sardar Sarovar (Narmada) Project, Gujarat, India

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Abstract

The 128.5 m high and 1226 m long concrete gravity dam across river Narmada is in advance stage of construction. Total nine sites were considered, out of which, three alternative sites were investigated and the dam site No. 3 (21°50'N, 73°45'E) was finally selected, as it was most favourable from geological and engineering considerations. The detailed geological investigations including surface geological mapping, diamond core drilling, test and trial pits, calyx holes, shafts and adits, laboratory tests, in-situ tests and isotope tracer studies were taken up during pre-construction and construction stages.

The paper gives the brief account of investigations for selection of the dam site and the details of geological investigations carried out. These geological investigations helped in deciding the final foundation grade and in identification of weak features and their remedial measures.

Introduction

The construction of multipurpose Sardar Sarovar (Narmada) Project is in progress. The dam would be 128.5 m high and 1226 m long. The proposed Full Reservoir Level is 138.68 m, Maximum Water Level is 140.21 m and Minimum Draw Down Level is 110.64 m. This project will generate 1450 MW electricity and has irrigation potential of 1.79 Mha in Gujarat. It will also provide water for domestic and industrial use to about 8215 villages and 135 urban centres.

The first geological reconnaissance for dam site in lower Narmada valley was carried out in 1947 by Geological Survey of India (GSI). Total nine alternative dam sites have been considered from Mokhadi rapids down to the area where the Narmada leaves the hills. After examining all these sites, three of them (viz. Dam site No. 1, Dam site No. 2 and Dam site No. 3) were investigated in detail. The Dam site No. 3 is found more suitable from engineering and geological considerations.

In view of rocky surroundings, devoid of any alluvial deposits in the riverbed, relatively narrow valley and the expectancy of very high floods, a concrete gravity dam with an overflow section extending the entire river bed is considered as basic layout. A mild curve of radius 7600 m is provided to mobilise the shear resistance of all monoliths together to ensure greater safety against sliding. The vertical steps in the foundation have been eased out in the form of suitable uniform slopes in order to achieve better arch effect.

Considering the close proximity of the riverbed fault to the Narmada tectonic lineament which is considered as seismogenic, the dam has been designed accordingly. The matter was discussed at length with various eminent Experts and Consultants in India and abroad. The earthquake of 6.5 magnitude on Richter's Scale has been considered for design of the dam. To withstand the vibrations of seismic event, design has been done for agreed seismic coefficient of 0.125 g.

The GSI has also carried out the Rim

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Stability Survey in the states of Gujarat, Maharashtra and Madhya Pradesh. It has been inferred that by and large, no weak features cross the reservoir periphery and the river Narmada is effluent in nature and its basin is tight.

The project consists of main concrete gravity dam, stilling basin with sloping apron, four rock fill dams and three connecting channels in the head reach of Narmada Main Canal, the surface canal bed power house (250 MW) and underground river bed power house (1250 MW). Due to hilly terrain in the right bank, the Narmada Main Canal starts from about 8 km distance from the Main Dam. The 460 km long main canal is having capacity of 1133 cumecs (40000 cusecs) at its head and 71 cumecs (2500 cusecs) at its tail near Gujarat-Rajasthan border.

Regional Geology

The area surrounding the Sardar Sarovar (Narmada) Project is occupied by the sedimentary rocks of Cretaceous age (Bagh beds). The rock types comprise quartzitic sandstone, sandstone, shale and limestone. These rocks are overlain by Deccan Trap basalts (igneous rocks) of Cretaceous-Eocene age. The Deccan Trap flows consist primarily of amygdaloidal, porphyritic, dense and vesicular basalts. The sedimentary beds and basalt flows are intruded by dykes and sills of dolerite and basalt. The Bagh beds are folded as broad anticlines and synclines (on the regional basis) while the overlying Deccan Traps have a near horizontal attitude, except at places where low dips are noted. The Bagh beds occur as inliers surrounded by the Deccan Traps. However, at places, the contacts of Bagh beds and Deccan Trap are faulted ones. Many faults have been demarcated during the course of investigations of various dam sites.

Geological Investigations For Alternative Dam Sites

Geological investigations for dam site in lower Narmada valley were taken up by GSI in 1947. The geologists of the Government of Gujarat were also associated in the investigations. In 1961, the Broach Irrigation Project was approved. Ever since, nine sites (sites I to IX) viz three at Navagam village, two near Limdi village, one near Baharphalia village, two d/s of Mokhadi fall and one u/s of Mokhadi fall, were considered for preliminary investigations (Fig - 1).

Navagam Dam Site No. 1 : Three alternative dam alignments (site No. I, II and III) near Navagam village and one site (site No. IV) near Limdi village were considered for Navagam dam site No. 1. The height of the dam was to be 320' (97.53 m). The surface studies indicated that the foundation of main dam in river gorge and saddle dykes on the right bank would be in the Deccan traps, and on the left bank, the main dam and saddle dykes would be on fault, traps, quartzites and shales. The contact of traps and Bagh beds is marked by the E-W running fault on the left bank. The subsurface exploration was conducted by 156 drill holes (aggregating to 6877 m of drilling length). The length of the structure was 2250m.

The scope of the project was revised and it was proposed to construct a dam with greater height than envisaged in Broach Irrigation Project, to take maximum advantage and full benefits, as this being the terminal project on the river. The attempts were initiated to locate more suitable site in the upstream reach of the Narmada gorge portion.

At site No. V near Limdi village, the quartzite and quartzitic sandstone with several dolerite dykes and sills are exposed in the riverbed. The right bank is unstable as its slope is steeper than the dip of quartzites along the slope. The fault boundary between trap and quartzite is also close to the d/s toe of the dam. Two open fissures were also found running across the

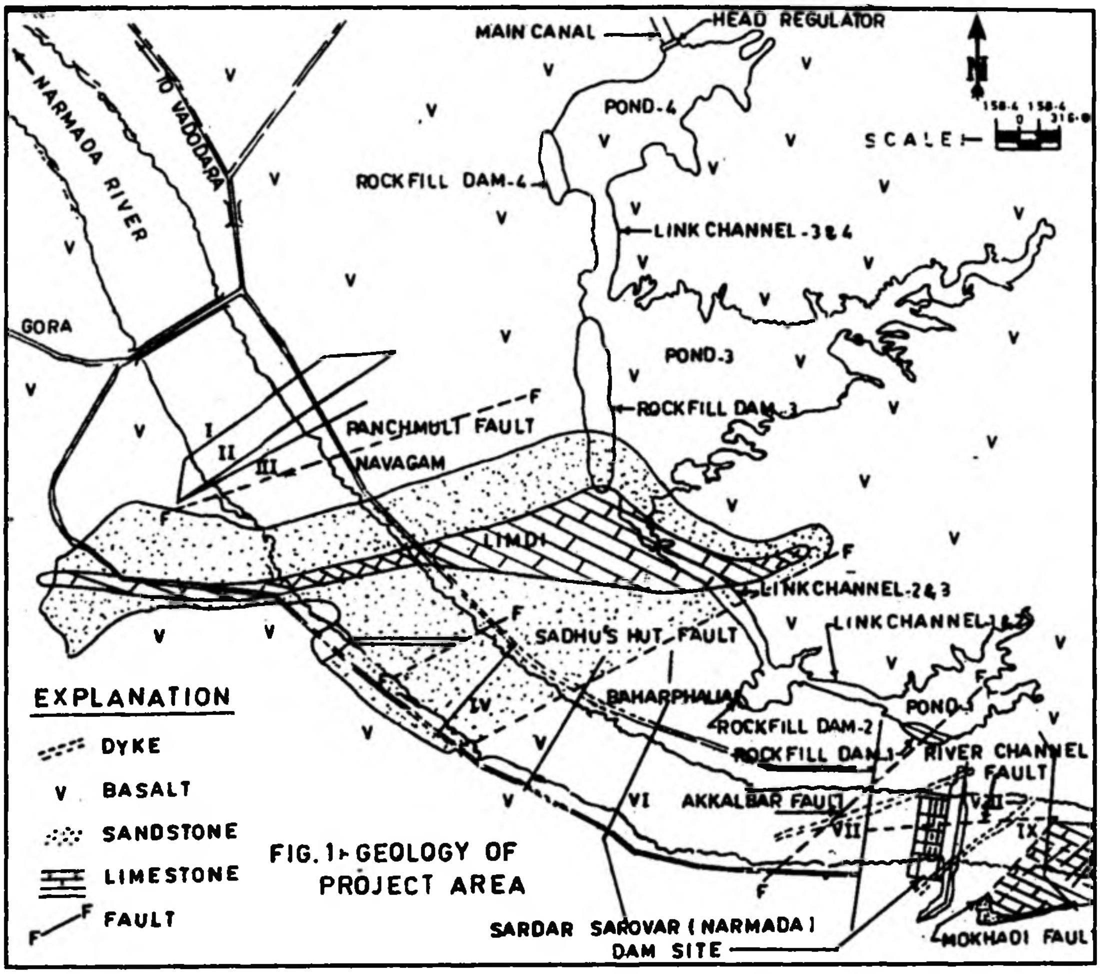

Fig. 1 General geological plan encompasing different dam axes.

river. Further field studies were not taken up. The site near Baharphalia village (site No. VI), is about 500 m u/s of site No. V near Limdi village. This site is intercepted by two faults viz. (i) the Akalbar fault (N65° E-S65° W) at ch 253 m on the left abutment and (ii) the fault boundary of trap and quartzite (Sadhu's hut fault - ENE-WSW) on the right bank at ch 1700 m. About 10 m wide shear zone (ENE-WSW) is on the right bank. There are two deep gullies near ch 600 and 700 m. These gullies have been formed by fracture or fault. Due to these adverse features, this site was not considered suitable (Balasundram, 1982).

Two sites considered in the d/s of Mokhadi fall are (i) Navagam dam site No. 2 (site No. VII) and Navagam dam site No. 3 (site No. VIII).

Navagam dam site No. 2: This site is near Akalbar village and about 5 km u/s of site No. 1. The investigations were taken up in April 1963. Here, the length of the dam was 1524 m. The Deccan Trap and dykes of dolerite were to form the foundation. The river bed is dissected by two faults viz. (i) Akalbar fault on the right bank (trend - N65° E-S65° W direction with vertical dip) and (ii) fault along the river channel, trending almost in E-W direction with dip of 60° towards right bank. These faults have lifted up the portion between them resulting in a horst. Total 22 drill holes (1425 m drilling length) were executed. In the fault zones, the depth of plug was to be evaluated taking into account the width of the fault (Balasundaram, 1982).

However, it was found that by shifting the alignment further u/s, it was possible to eliminate the Akalbar fault, as it goes far beyond the right abutment. The dam site No. 3 was therefore considered in November 1963.

Navagam dam site No. 3 : This alignment is 610 m u/s of dam site No. 2. Only one fault viz. river channel fault, remains in the foundation. The length of the dam is 1226.62 m and height is R.L. 146.5 m.

Ali and shenoi, (1969) of GSI observed that: "This alignment is shorter by 700 feet (213.76 m). Besides, it avoids a 150 feet (45 m) wide shear zone encountered close to the right bank along site No. 2. It is therefore, considered that site No. 3 is more suitable from geological and economic point of view."

At the site in u/s of Mokhadi falls (site No. IX), investigations were taken up in 1960 by drilling 3 holes (93 m drilling length). The foundations of the left bank would be on sedimentary rocks of Bagh beds and the right bank foundation would be on Deccan Traps. Two faults, (i) Mokhadi fault near left bank and (ii) deep river channel fault would cross the foundation in the river bed. Because of these unfavourable features, the site was not investigated further.

The preliminary investigations of the nine sites indicated that none of these sites is free from fault and other foundation defects. Only at the dam site No. 3, there is only one fault and least foundation defects present. Hence the further detailed investigations were taken up along the Navagam Dam Site No. 3 in 1963 and continued till the commencement of the work in 1978-79.

Geological Investigations at Narmada Dam Site No. 3 (Final site)

Pre-construction stage (1963-1977) : The pre-construction stage geological investigations were performed to assess the suitability of the site, to identify foundation defects and to provide data for design. The surface geological mapping on 1:100 scale covering an area 210 m upstream and 210 m downstream of the dam alignment was taken up in 1967-68. Total 129 core holes aggregating to 8225.27 m depth were drilled. The drilling was performed (i) to determine the depth of suitable foundation grade, (ii) to delineate fault and shear zones, (iii) to determine rock mass permeability and (iv) to determine succession of litho units. 30 exploratory holes of which 19 vertical and 11 inclined, revealed the discontinuity of lava flows and sedimentary rocks from one bank to the other and presence of crushed, calcined and weathered trap. This established the existence of a fault along the fair weather river channel. A 335 m deep drill hole (No. 145 A) at 60° inclination towards left bank piercing the river channel fault was drilled to determine the displacement of rock due to river channel fault. A 34.13 m deep, 90 cm dia calyx hole on the right edge of river channel was drilled in 1966-67 for visual inspection of the river channel fault zone. The sonic logging of this hole was done by Central Water & Power Research Station (CWPRS), Pune in April 1968. The core samples were tested in laboratory to study their physical properties. The petrographic examination of rocks was also carried out.

Construction stage (1978 onwards): The construction work started after the declaration of the Narmada Water Disputes Tribunal Award in August 1978. Foundation excavations, river diversion works and treatment to river channel fault were taken up. The foundations for the dam seat were excavated from the ground surface to the depths of 5 to 33 m. This helped in identifying foundation defects, studying their characteristics and evaluating their porperties for the design of the structure as well as for the foundation treatment. The construction stage geological investigations were directed mainly to collect further data on weak features.

The construction stage investigations include core drilling, calyx holes, exploratory shafts, adits, in-situ tests, laboratory tests for physical properties of rocks, petrographic examination of rocks and natural aggregates and isotope tracer studies of limestone.

Core drilling : In all, 284 NX size core holes aggregating to 11,179.67 m depth were drilled to obtain additional foundation data for the design of dam as well as appurtenant structures viz. end training walls, auxiliary spillway, energy dissipation device, irrigation by pass tunnel etc (Table-1). Some of the exploratory drilling was done to study the weak features such as fault zone, red bole and sedimentaries (Table - 2). The triple tube core barrel and M-series double tube core barrels (Table-3) were used to recover more intact cores.

Three - 13 to 20 m deep probe holes in each monolith were drilled to ensure that there is no weak feature immediately below the final grade foundation and to assess the continuity of competent rock mass. At ch 1275 and 1320 m, NX size holes at 5 to 10 m interval were drilled in the foundation trench between 30 m u/s and 90 m d/s, to study the nature of limestone.

All these holes are water pressure tested to determine the rock mass permeability in lugeon. The geological logging of all the holes was done. The interpretation of core data and drilling information was recorded as per the IS:4464-1967. The core boxes are preserved as per IS:4078-1980. The succession of litho units, their core recovery, Rock Quality Designation (RQD) and permeability values in lugeon are given in Table-4.

In addition to this, subsurface explorations were carried out by 144 core holes at Rockfill dams 1 to 4, and 13 core holes at three link channels. Total 312 core holes aggregating to 15,285.57 m have been drilled for subsurface explorations of hydro power structures, viz. Canal Head Power House (CHPH) and River Bed Power House (RBPH). One 300 m long (along longer axis) and 3X3.5 m in size, exploratory adit was excavated in the right bank hill for RBPH location and to study the nature of rocks and their physico-engineering properties. However, these details fall out side the scope of this paper.

Calyx holes : Two, 90 cm dia and 18 & 18.6 m deep calyx holes on left bank were drilled to assess the nature of basalt flow contacts below the known layer of red bole.

Exploratory shafts : Two, 23.25 and 20.55 m deep and 4 to 5.5 m dia shafts were excavated to assess the nature of basalt flow contacts below the existing red bole layer.

Adits : Total 10 adits were excavated out of which two adits of 2.4X2.6 m size and 20.5 m and 24.3 m in length, were driven on right abutment and one 16 m long adit was driven on left abutment to examine the nature of lava flow contacts. For the in-situ tests on sedimentary rocks, red bole and lava flow contacts, five adits on the right side of the river channel fault zone trench and two adits near the left end of service spillway were excavated. The abjective to perform these tests inside the adits was to eliminate (1) the effects of release of stresses in the open and (2) deterioration of foundation rock due to exposure.

In-situ tests : To assess the nature of settlement of different rock units under varying load conditions, tests were carried out to determine the modulus of deformation. The tests were conducted inside drifts, taking precaution to reduce the rebound effects. In-situ deformability tests were conducted on river channel fault zone material and various rock types. The in-situ shear tests were conducted on weȧk rocks such as argillaceous sandstone, pebbly sandstone and also contacts of various sedimentary rocks, basalt flow contacts and red bole etc. Uniaxial jacking tests were done on the left

Table - 1 : Details of exploratory drilling

Structure	Total drill holes	Total metres	Pre-construction stage		Construction stage	
			Holes	metres	Holes	metres
Left NOF Blocks						
Left key to 20	56	1253.63	9	350.36	47	903.27
Auxiliary Spillway						
Blocks 21 to 27	38	800.59	5	222.55	33	578.04
Service Spillway						
Blocks 28 to 51	122	6724.96	55	3582.4	67	3142.56
Right NOF						
Blocks 52 to 54 & 61 to right key	18	674.7	1	88.39	17	586.31
Power Dam Blocks						
55 to 60	15	470.67	2	60.96	13	409.71
D/S of Left NOF Blocks						
Left key to 20	21	1257.29	18	1210.04	3	47.25
Left end Training wall						
D/S of Block 21	11	327.07	--	--	11	327.07
Chute floor Blocks						
21 to 27	8	227.37	2	73.76	6	153.61
Left Divide wall						
D/S of Block 28	3	158.52	--	--	3	158.52
Stilling Basin						
Blocks 28 to 51	53	3068.79	25	1663.58	28	1405.21
Right Training wall						
D/S of Block 51	7	381.3	1	60.96	6	320.34
Area u/s of dam	19	1539.71	11	912.27	8	627.44
Area d/s of endsill	18	927.01	--	--	18	927.01
Irrigation By Pass Tunnel (I.B.P.T.)						
Alternative I	9	477.72	--	--	9	477.72
Alternative II	10	781.19	--	--	10	781.19
Alternative III	5	334.42	--	--	5	334.42
TOTAL	**413**	**19404.94**	**129**	**8225.27**	**284**	**11179.67**

Rockfill Dam No.1	15	468.16
Link Channel 1-2	3	108.21
Rockfill Dam No.2	18	354.24
Link Channel 2-3	6	353.57
Rockfill Dam No. 3A	16	392.92
Rockfill Dam No. 3	50	1246.1
Spillway for ponds	15	286.33
Link Channel 3-4	4	96.31
Rockfill Dam No. 4	30	598.28
TOTAL	**157**	**3904.12**
Canal Head Power House	78	2715.54
River Bed Power House	169	10539.32
Garudeshwar Weir	65	2030.71
TOTAL	**312**	**15285.57**
Canal Head Regulator	3	67.06
GRAND TOTAL	**885**	**38661.69**

ABSTRACT

Structure	Holes	metres
Main Dam	389	17811.61
I.B.P.T.	24	1593.33
Rockfill Dams	144	3346.03
Link Channels	13	558.09
Hydro Power	312	15285.57
Canal Head Regulator	3	67.06
TOTAL	**885**	**38661.69**

Table - 2 : Summary of exploration carried out for various features

Feature	Auxilliary spillway		Service Spillway		Stilling basin		Beyond endsill		U/S of dam		Mokhadi	
	No.of holes	metreage	No.of holes	metreage	No.of holes	metreage	No.of holes	metreage	No.of holes	metreage	No.of holes	metreage
Preconstruction stage												
Fault	--	--	21	1628.77	7	588.26	--	--	3	200.99	--	--
Construction stage												
Red bole	2	71.11	10	181.46	11	474.79	--	--	1	33.53	--	--
Sandstone and Limestone	--	--	16	1397.94	3	248.42	--	--	--	--	--	--
Sandstone	--	--	6	265.87	1	50.8	--	--	2	213.32	--	--
Limestone	--	--	2	215.43	--	--	4	220.06	--	--	3	253.56
Contract of rock/colcrete in red bole drift	--	--	4	59.93	--	--	--	--	--	--	--	--

Table - 3 : Summary of Explorations carried out on Various Appurtenant Structures

Sr. No.	Structure	Explorations by Drilling Operation										90 cm dia Calyx hole		Shaft	Adit	
		Total		Single Tube		Double Tube		Triple Tube		M-Type Double						
		Holes	metres	Holes	metres	Holes	metres	Holes	metres	Tube Holes	metres	Holes	metres	No.	metres	No.
1	Left N.O.F.Blocks Left key to 20	56	1253.6	16	455.27	17	281.32	10	209.92	13	307.12	---	---	---	---	---
2	Auxilliary Spillway Blocks 21 to 27	38	800.59	14	338.34	17	271.31	2	61	5	129.94	---	---	---	---	-
3	Service Spillway Blocks 28 to 51	122	6725	55	3582.4	60	2969.8	3	77.16	4	95.77	---	---	---	---	5
4	Right N.O.F. Blocks 52 to 54 & 61 to right key	16	674.7	1	88.39	10	356.96	5	133.75	2	93.6	---	---	---	---	1
5	Power Dam Blocks 55 to 60	15	470.67	2	60.96	6	178.74	3	109.37	2	121.6	---	---	---	---	1
6	D/S of Left N.O.F. Bls. Left key to 20	21	1257.3	18	1210	1	19.81	---	---	2	27.44	--	--	--	---	---
7	Left Training Wall d/s of Block 21	11	327.07	---	---	3	92.31	3	112.9	5	121.86	---	---	---	---	---
8	Chute floor Blocks 21 to 27	8	227.37	2	73.76	6	153.61	---	---	---	---	---	---	---	---	---
9	Left Divide Wall d/s of Block 28	3	158.52	---	---	---	---	---	---	3	158.52	---	---	---	---	3
10	Stilling Basin Blocks 28 to 51	53	3088.8	24	1663.8	24	1257.2	2	87.77	3	80.28	3	70.73	2	43.8	---
11	Right Training Wall d/s of Block 51	7	381.3	1	60,96		9.13	3	142.98	3	168.23	---	---	---	---	---
12	Area U/S of Dam	19	1539.7	11	912.27	8	627.44	---	---	---	---	---	---	---	---	---
13	Area D/S of Endsill	16	927.01	---	---	13	694.27	---	---	5	232.74	---	---	---	---	--
14	Irrigation Bypass Tunnel	24	1593.3	---	---	7	413.9	2	84.22	15	1095.2					
	TOTAL	357	19405	144	8446	174	7327.6	33	999.07	62	2632.3	3	70.73	2	43.8	10

abutment to evaluate the modulus of deformation of closely spaced vertical joints. These tests were conducted by CWPRS, Pune and Gujarat Engineering Research Institute (GERI), Vadodara. The results are given in Tables 5,6 &7.

Laboratory tests : The physical properties such as specific gravity, compressive strength, static modulus, Poission's ratio, etc of various rock types were determined (Tables - 5 & 6). The triaxial shear tests were also conducted on sedimentary rocks.

Microscopic examination of rocks : The petrographic examination of all the foundation rocks was done to know the essential constituents, texture, grain size, cementing material etc. The petrographic examination was carried out by GERI, Vadodara. A few samples have also been studied at the University of Roorkee.

About 148 core samples as well as rock lumps collected from dam site were examined under microscope. The rocks identified are basalt (amygdaloidal, porphyritic, glomeroporphyritic and glassy), dolerite, palagonite, argillaceous sandstone, quartzitic sandstone, calcareous sandstone, calcareous shale and limestone.

Petrographic examination of natural aggregates : The representative samples of coarse and fine aggregates from shoals located along Narmada river were collected for petrographic examination. The petrographic examination of aggregates revealed that 90 to 95% of the constituents

Table - 4 : Details of litho units encountered at SS(N)P

Flow No.	Litho unit	Permeability in lugeon	Average core recovery %	Rock Quality Designation (RQD %)
	Dolerite	1 to 5	95	89
Left bank	Blocks Left key to 41			
XII	Amygdaloidal basalt	10	65	48
	Red bole			
XI	Amygdaloidal basalt	13	65	41
X	Amygdaloidal basalt	7.5	84	54
IX	Amygdaloidal basalt	7	80	61
VIII	Massive basalt	<1 to 2	81	25
VII	Amygdaloidal basalt	2 to 4	82	36
	Red bole			
VI	Porphyritic			
	Amygdaloidal basalt	<1 to 8	72	32
V	Porphyritic basalt	< 1 to 12	89	38
Right bank	Blocks 44 to 56			
IV	Massive basalt	20	85	29
	Glomero porphyritic basalt			
III	Porphyritic basalt	<1 to 6	86	50
II	Massive basalt	<1 to 8	97	69
I	Amygdaloidal basalt			
	Palegonite tuff	17	69	34
Sedimentary rocks				
	Upper Argillaceous sandstone	25	57	22
	Upper Quartzitic sandstone	26	68	35
	Lower Argillaceous sandstone	20	59	24
	Lower Quartzitic sandstone	22	71	41
	Pebbly sandstone	22	68	52
	Shale	20	86	47
	Limestone	8	75	47
Dolerite sill		6	73	29
Right bank	Blocks 57 to right key			
	Massive basalt	6 to 17	50	11
	Porphyritic basalt	3 to 10	82	40
	Amygdaloidal basalt	<1 to 3	95	64
	Porphyritic basalt	<1	100	75
	Porphyritic basalt	<1 to 3	83	44

are derived from Deccan Traps comprising particles of variants of basalt, secondary quartz, cryptocrystalline silica, calcite and zeolite. The remaining 5 to 10% are of granite, quartzitic sandstone and limestone. The average deleterious constituents in both, fine and coarse aggregates are 3.31 and 2.12% respectively. These are within the limit of 5% prescribed by the IS:383-1970. The average percentage of physically poor constituents are 0.8% in coarse aggregates and 4.64% in fine aggregates.

Alkali Aggregate Reactivity : The Narmada river aggregates were evaluated from alkali-aggregate reactivity considerations by National Council of Cement and Building Materials (NCB), New Delhi. The samples of fine and coarse aggregates were collected in different size fractions from (1) Concrete Mixing and Batching plant at dam site, (2) Akteshwar shoal and (3) Tilakwada shoal. 10 core samples of concrete from fault zone treatment area (Block 41) were also studied using optical microscope. The studies carried out at NCB include (1) Petrographic analysis, (2) Mortar bar tests, (3) Concrete prism tests, (4) Rapid chemical test, (5) SEM studies and (6) Petrography of concrete cores. The results of petrographic analysis, mortar bar tests, concrete prism test and rapid chemical test indicated that the aggregates are non-reactive or innocuous. Megascopically, 10 core samples of 5 to 10 year old concrete showed no signs of alkali silica reaction such as gel or rim formation. Thin section studies of concrete cores under optical microscope and under Scanning Electron Microscope (SEM) also revealed no signs of reaction at the contact point with mortar and the original texture of the aggregates is not disturbed.

Tracer studies : The limestone forms the part of the sedimentary rocks on the right bank. The drilling explorations have indicated the thickness of limestone between 62 m in u/s to 33 m in d/s. The presence of cavities could not be confirmed but heavy water losses and poor core recovery indicated presence of open joints.

The isotope tracer studies were carried out by CWPRS, Pune. The tests were conducted in three sections viz. (1) upstream and downstream of Mokhadi fault, (2) below dam seat and (3) 225 m downstream of dam toe. The results of the microscopic examination of core samples indicated that the limestone are siliceous in nature. The isotope trace studies indicated that the limestone have no solution channels / cavities.

Discussion

The study of regional geologic and tectonic set up by surface mapping and aerial photo interpretation, subsurface explorations and the foundation excavations revealed that different flows of Deccan basalt unconformably overlie the Bagh sediments, between R.L. (-)237 and 140 m. In this 377 m vertical section, various basalt flows of varying thickness (7 to 56 m) consist of dense porphyritic varieties turning amygdular, pink amygdular or tuffaceous / agglomeratic towards top. The subsurface exploration also revealed discontinuity of these flows from one bank to another bank. A fault has vertically displaced the Bagh sediments and overlying Deccan basalt flows by 210 m (Fig 2). The fault has brought basalt flow I (right bank) and VI (left bank) in juxtaposition.

The core holes, calyx holes and shafts confirmed that the contacts of basalt flows are generally tight and there are no weak features below known red bole layer on the left bank.

The subsurface exploration, foundation excavations, in-situ shear tests and laboratory tests revealed the river channel fault, red bole layer between two successive basalt flows beneath the foundations of blocks 28 to 42, the horizontal weak layers of sedimentary rocks at shallow depths beneath blocks 44 to 51, tuff layer at the contact of basalt and sedimentaries, limestone with open joints at depth and sheared contacts of dolerite as major foundation defects which required special treatment.

River channel fault:

The 12 m wide fault zone, skew to the dam alignment (trend-N80°E with dip of 60° towards NW i.e. right bank), cuts across the foundation of spillway blocks 41 to 44. The fault zone material consists of highly fractured, sheared and weathered basalt, associated with clay gouge (Anon.,1986).

The values of deformation for the fault zone material, fractured basalt and sedimentary breccia are low (0.04 to 0.09X10^5 kg/cm^2); these are high for sedimentaries and fresh amygdaloidal basalt, as compared to fault material. The modulus ratio of the basalt and

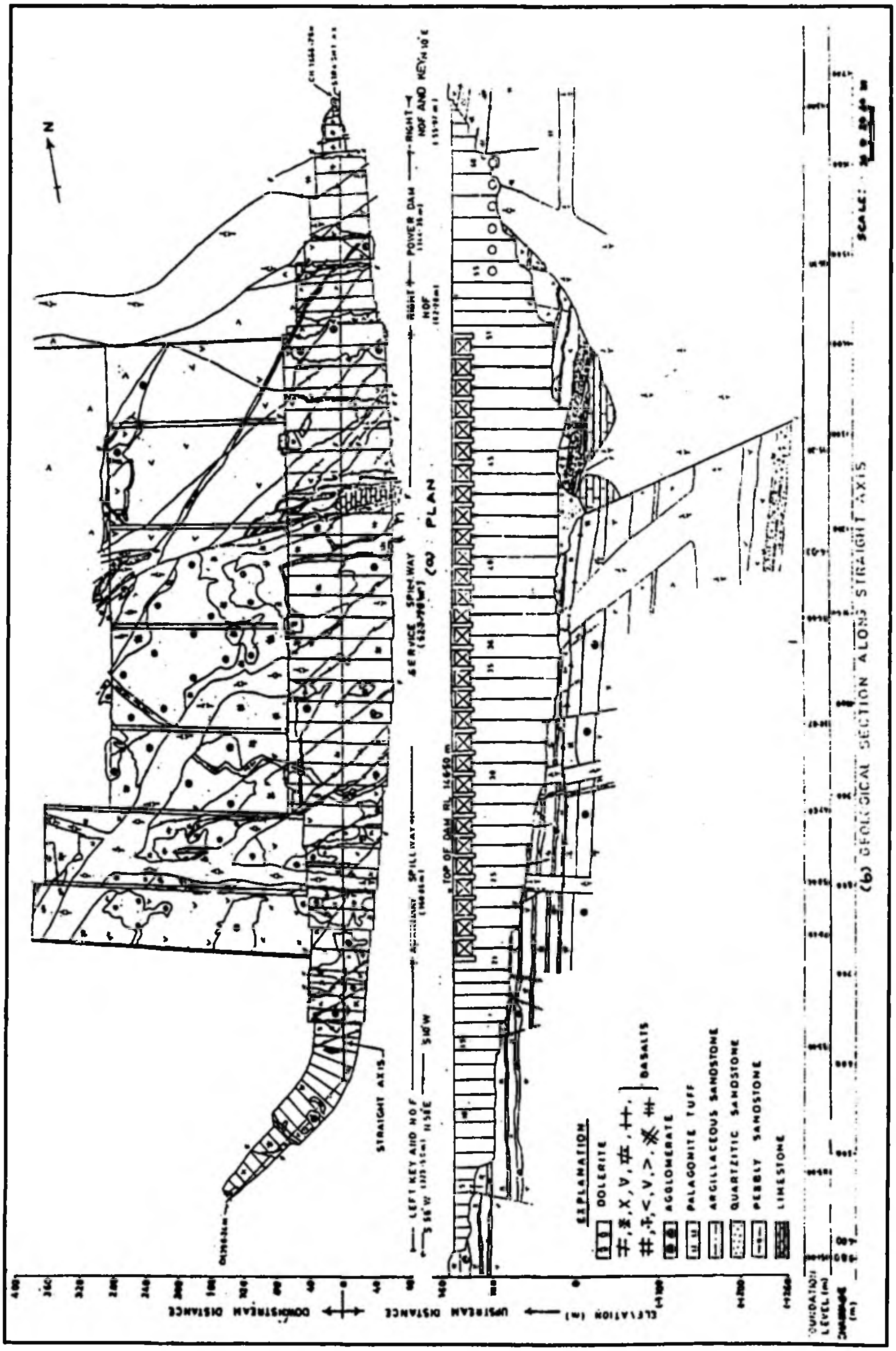

Fig. 2. Geological map and L-section of the dam foundation.

Table 5 : Geomechanical Properties of Foundation Rocks

Sl. No.	Rock type	No.of samples tested	Density			Absorption (72 hours)			Static modulus X 10^5 kg/cm^2					
									Dry			Wet		
			min	max	mean	min	max	mean	min	max	mean	min	max	mean
1	Massive basalt	12	2.67	3.07	2.89	0.2	1.18	0.52	2.5	14.6	5.65	2.16	10.43	4.43
2	Dolerite	6	2.75	3.30	2.99	0.1	1.01	0.39	6.1	14.2	9.4	5.9	13.3	8.8
3	Agglomerate	11	2.87	2.58	2.70	0.77	5.07	2.05	1.06	3.65	2.16	0.38	3.58	1.78
4	Amygdaloidal basalt	9	2.7	3.00	2.78	0.35	1.36	0.68	1.6	5.20	3.23	1.3	4.7	2.90
5	Porphyritic basalt	9	2.7	3.11	2.88	0.17	0.74	0.40	4	7.40	2.88	4.7	7.2	6.05
6	Limestone	12	2.66	2.89	2.78	0.1	1.40	0.69	3.47	8.24	6.28	2.36	6.0	4.45
7	Quartzitic sandstone	12	2.49	2.64	2.56	0.13	2.73	1.44	0.23	4.10	1.65	0.2	3.5	1.4
8	Pebbly sandstone	10	2.54	2.64	2.60	0.71	2.50	1.55	0.26	5.9	2.61	0.33	5.58	1.5

Table 6 : Geomechanical Properties of Foundation Rocks

Sl. No.	Rock type	No. of samples tested	Specific gravity		Compressive strength(dry) kg/cm^2		Percent water absorption (72 hrs)	
			min	max	min	max	min	max
1	Massive basalt	13	2.64	2.93	430	1075(6)	0.12	1.77
2	Dolerite	12	2.75	3.3	527	953(5)	0.12	1.4
3	Agglomerate	30	2.55	2.73	222	684(5)	0.39	4.07
4	Amygdaloidal basalt	12	2.63	2.75	389	925(4)	0.42	1.82
5	Porphyritic basalt	15	2.57	2.89	583	1285	0.1	1.08
6	Limestone	12	2.7	2.89	806	1451(2)	0.21	0.73
7	Quartzitic sandstone	13	2.49	2.59	470	1183	0.67	1.55
8	Pebbly sandstone	16	2.5	2.7	138	834	0.12	8.00
9	Argillaceous sandstone	9	2.75	2.78	---	---	1.34	2.47

(The figures in brackets indicate number of samples tested)

sedimentary rocks is high (Table - 7). This indicated problem of differential settlement in the foundation of riverbed blocks 41 to 44. High percentage of water absorption for pebbly sandstone and argillaceous sandstone made them unfavourable for shouldering the concrete plug. The two dimensional photo-elastic studies indicated that the plug depth of about 1.5 times the width of the fault zone would be adequate for the treatment of the fault zone.

A 24.5 to 34.5 m deep trench down to R.L. (-) 16.5 m near heel and R.L. (-) 6.5 m from dam axis to the toe, from average riverbed level of R.L. 18.0 m, was excavated. Hammock reinforcement consisting of two layers (1 m apart) of 36 mm dia high yield deformed steel bars was provided in the fault plug. The purpose of this reinforcement is to avoid local concentration of stresses, to distribute load uniformly, to safeguard against any local weak pockets and to prevent differential settlement within the plug. 36 mm dia, 8 m long high yield anchor bars were provided in a grid of 3 x 3 m. Consolidation grouting with holes in grid of 3 x 3 m, was done down to 15 m depth below foundation. Two additional vertical grout curtains have been provided at u/s and d/s end of the fault zone plug with holes spaced at 1.5 m.

Red bole layer and argillaceous sandstone beds :

For a 5 to 40 cm thick red bole layer occurring below the foundations of spillway blocks 28 to 42, the angle of internal friction is 17° with no cohesion. For contacts of argillaceous sandstone layers below the foundations of spillway blocks 44 to 51, the same varies

Table - 7 : Abstract of Recommended Parameters

Report Sr. No.	Rock type	Recommended Parameters				
		C in t/m²	Φ in degree	Deformation Fd kg/cm²	Elastic Modulus kg/cm²	Ratio of the two modulli
I	(I) Intertrappean beds Ch 1460 to 1630 m	15	15	---	---	---
	(ii) on Red bole	0	17	---	---	---
II	(I) Intertrappean beds ch 1420m	0	29	---	---	---
III	(I) Intertrappean beds ch 637m	0	39	---	---	---
iv	Basalt Ch 859 m	---	---	$0.1x10^5$	$0.24x10^5$	2.4
V	(i) Through Quartzitic sandstone	0	44	---	---	---
	(ii) Through Argillaceous sandstone	0	17	---	---	---
	(iii) Argillaceous S.S.	---	---	$0.03x10^5$	$0.06x10^5$	2
	(iv) Quartzitic S.S.	---	---	$0.05x10^5$	$0.2x10^5$	4
VI	(i) Through Argillaceous S.S.	20	28	---	---	---
	(ii) Through contact of quartzitic S.S. & argillaceous sandstone	0	11	---	---	---
	(iii) Argillaceous s.s & quartzitic S.S.	0	26	---	---	---
	(iv) Through contact of massive trap & agglomerate	0	18	---	---	---
	(v) Through Pebbly sandstone	0	45	---	---	---
	(vi) Through red bole	10	18	---	---	---
	(vii) Through contact of massive trap & amygdaloidal basalt	0	47	---	---	---
	(viii) Agglomerate	0	0	Test will have to be repeated		---
VIII	(i) Jointed basalt with pockets of agglomerate	---	---	$0.04x10^5$	$0.075x10^5$	1.87

from 11° to 26° with no cohesion (Table-7). This posed a problem of sliding along weak layers. The sedimentaries have gentle dip of 8° towards right bank with apparent dip of 7° towards d/s. This also posed problem of relative stability and sliding. The low values of modulus of elasticity of argillaceous sandstone (Table-7) posed problem of vertical settlement. The low values of modulus of deformation of argillaceous sandstone, compared to that of basalt and quartzitic sandstone, posed problem of differential settlement.

The treatment to these weak layers of red bole and argillaceous sandstone along with tuff layer was provided by underground shear keys to improve shear resistance. This was done by excavating 3 m wide drifts in grid pattern, leaving rock pillars of 4.5 x 8.5 m in red bole area and 8.5 x 8.5 m in argillaceous sandstone treatment. The sheared tuff layer and its contact with basalt was also removed. The drifts was backfilled with concrete / calcrete. Crown of the drifts were designed to provide arch for mobilising better shear resistance after backfilling with concrete.

Grouting : The results of percolation tests (Table - 4), test grouting done in basalts and study of rock mass discontinuities indicated necessity of grouting. *In situ* jacking tests results showed rather low values of the modulus of elasticity for basalt, indicating weathered and jointed nature of rock. Intensive and extensive grouting was done covering entire dam seat area. In the blocks 8 to 42 resting over red bole layer, and blocks 44 to 51 resting over sedimentary rocks, the depth of grout holes was extended down to the bottom of the shear keys.

The curtain grouting has been carried out through drainage (heel) gallery and from the drifts in the right bank abutment. The grout curtain is inclined at an angle of about 13° to 15° towards u/s. The holes are spaced at 3 m. The minimum depth of the grout curtain is 50% of the reservoir head with respect to foundation rock level at given location or 30 m, whichever is less.

Limestone :

Heavy water loss was noticed through limestone. To reduce it, consolidation grouting was extended two meters in the limestone bed. The depth of curtain grouting was extended below the limestone bed.

Contacts of dolerite :

Three major dolerite dykes cross the foundations of blocks 28 to 32, 34 to 38 and 56 to 60. The contacts of these dykes with basalt are sheared. These contacts were provided dental treatment by excavating 0.7 to 3.5 m deep trenches, backfilled with concrete.

Conclusions

The first ever survey for about 97.6 m high dam in lower Narmada valley was taken up in 1947. The scope of the project was increased and nine alternative sites were geologically investigated. The Dam site No. 3 was finally considered suitable from engineering and geological considerations.

The surface and subsurface explorations and various field and laboratory tests helped in identifying the foundation defects like river channel fault, red bole layer, argillaceous sandstone and tuff layers, limestone, and contacts of dolerite dykes etc. These weak features were provided proper treatment. The investigations also helped in deciding the requirement and pattern of grouting.

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References

Ali, Hamja, Shenoi, R.S. (1963-64) : Progress Report on Geological Investigations of Navagam Dam Site, Geol. Surv. Ind. Unpub. Rep.

Anon.(1986): Geological Investigations for Concrete Dam, Vol. I submitted to the World Bank Review Mission, May 1986. Unpub.

Anon.(1990): Evaluation of concrete aggregates for alkali-aggregate reactivity. Unpub. Rep. No. CDI-SP-421, National Council for Cement and Building Materials.

Balasundaram, M.S., (1982): "A Geotechnical Report on Sardar Sarovar Narmada Project", published by Irrigation Department, Government of Gujarat.