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Geotechnical Forensic Investigations of a Gravity Dam: Addressing Seepage and Sliding Problems in the Basalt Foundations of Karjan Dam, Gujarat, India

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Abstract: Geotechnical forensic engineering plays a crucial role in identifying and mitigating potential issues in large gravity dams. The Karjan Dam in Gujarat, India, a 100-meter-high gravity dam built 38 years ago on Deccan basalt, encountered significant geotechnical challenges during construction due to early investigation oversights. These oversights failed to detect sub-horizontal weathered rock seams within the basalt during the pre-construction investigations, which could have posed significant seepage and sliding risks during the dam's operation. Subsequent detailed investigations during the construction phase revealed that these seams extended throughout the foundations of the dam blocks.

In-situ shear tests were conducted to determine the shear parameters, namely cohesion (C) and the angle of internal friction (ϕ) of the seams. The test results indicated low shear strength parameters, necessitating a re-evaluation of the dam's safety. Stability analysis revealed that the spillway and certain non-overflow blocks were at risk of sliding and seepage after reservoir filling. To address these geotechnical challenges, a combination of treatments—including concrete shear keys, grouting, and design enhancements—was implemented to prevent sliding and control seepage. The timely forensic investigation and treatment during the construction stage ensured the dam's safety, which has operated without issues since 1986.

This study underscores the critical importance of integrating engineering and geological assessments at various stages of dam construction. Re-evaluating and addressing evolving foundation conditions, particularly during construction, is essential for applying effective treatments to prevent dam failure during operation. The findings from this case study provide valuable geotechnical insights required for enhancing the safety and resilience of dam infrastructure globally.

Keywords: Geotechnical forensic study, Weathered Rock seams, Concrete Shear keys, Basalt foundation, Seepage and sliding, Dam failure prevention.

1. Introduction

Dams are vital for water storage, flood control, irrigation, and hydroelectric power. Ensuring their safety requires comprehensive geotechnical investigations during design, construction and post construction phases. Geotechnical studies are essential at various stages of dam projects to ensure stability, safety, and longevity. During the Investigation Stage, comprehensive site investigations are crucial. These include geological mapping, drilling boreholes, and collecting soil and rock samples for laboratory testing to determine physical and mechanical properties [1]. Geophysical surveys such as seismic refraction and electrical resistivity are also conducted to assess subsurface conditions [2]. Hydrogeological studies to understand groundwater flow and its potential impact on the dam structure are equally important [3]. During the Construction Stage, continuous geotechnical monitoring is vital. This involves progressive examination and evaluation of foundations, in-situ testing of excavated rocks and associated weak features to detect any deviations from the initial investigations [4]. Instrumentation like piezometers, inclinometers, and settlement gauges are to be installed to monitor pore water pressure, deformation, and settlement during construction [5]. In the Post-Construction Stage, continuous geotechnical monitoring and maintenance are imperative to detect and address any emerging issues. This includes periodic inspections, continued evaluation of installed instrumentation to monitor changes over time, and reassessment of structural stability and foundation conditions [3]. Post-construction studies also involve evaluating performance of the dam during and after major events like earthquakes or floods to ensure that the structure remains safe and functional [2]. Regular updating of geotechnical data and revising safety measures based on new findings and technological advancements is also recommended [1].

Gravity dam failures can result from a combination of structural, hydrological, geological, operational, environmental, and human factors. Structural issues may include weak foundations, poor material quality, design flaws, and construction errors, all of which can compromise the dam's integrity [2]. Hydrological causes such as overtopping, extreme flooding, and inadequate spillway capacity can lead to severe stress on the structure [3]. Geological instability, including seismic activity and erosion, can further weaken the dam foundation ad structure [1]. Operational failures often stem from poor maintenance, improper handling of dam controls, and insufficient monitoring [4]. Environmental factors, such as extreme weather events and sedimentation, can exacerbate these issues [5]. Additionally, human activities, including vandalism, sabotage, and improper land use, can directly or indirectly contribute to dam failure [3]. Recognizing and addressing these potential causes are essential for ensuring the safety and longevity of concrete dams.

The failure of a dam can result in catastrophic consequences, including loss of life, environmental damage, and economic loss. Geotechnical forensic studies are essential for understanding the underlying causes of dam failures and for developing strategies to prevent future incidents. The case study of 100m high masonry-cum-concrete gravity Karjan Dam, Gujarat, India provides insights into potential challenges posed by basalt rocks and associated features such as sub-horizontal weathered rock seams in the safety of structures and their adequate solutions. The timely geotechnical forensic investigation at the Karjan Dam site during-construction stage of the dam ensured safety of the dam, which has been operating without issues since 1986 [6]. The main objective of this forensic study is to review the geological and geotechnical conditions of foundations in light of sub-horizontal concealed weak geological features likely to be overlooked during initial investigations, as in the case of the Karjan Dam, in order to provide timely treatment and ensure the safety of the structure.

2. Study Area

The Karjan Dam (21.7834° N, 73.5329° E) is situated near Jitgadh village in Nanded Taluka, Narmada District, Gujarat. It spans the Karjan River, a left-bank tributary of the Narmada River, which joins the Narmada downstream of the Sardar Sarovar Project. The Karjan Dam is located approximately 25 km downstream of the Sardar Sarovar Dam, in the Lower Narmada Valley, a rift zone (graben) defined by faults aligned parallel to the Narmada-Son lineament (NSL) zone in the ENE-WSW direction (Fig. 1).

2.1. Salient Features of the Dam

The Karjan Dam, completed in 1986, is a masonry-cum-concrete gravity structure stretching 911 meters in total length, with its crest level at 101.23 meters and a full reservoir level (FRL) reaching 115.25 meters. The dam's top stands at an elevation of 119.70 meters, and it reaches a maximum height of 100 meters from the deepest foundation level. The spillway, a concrete structure spanning 171.61 meters, features a gated, ogee-shaped crest equipped with nine radial gates, each measuring 15.55 meters by 14.20 meters, and includes a stilling basin with a horizontal apron and a flip bucket for efficient energy dissipation [6] (Fig. 2). The dam also incorporates non-overflow sections on both the left and right banks, constructed of masonry, along with spillway blocks made of concrete. Work of right and left bank main canals was completed in 1991 and 2000, respectively. A small powerhouse with a 2 MW capacity is situated on the left bank of the Karjan Dam.

2.2. Geology of the Dam Site

Karjan Dam is situated in the Lower Narmada Valley on Deccan basalt flows within a rift zone (graben) delineated by faults aligned in the ENE-WSW direction [6,7]. The basalt flows at the dam site are classified into two types: "Aa" and "Pahoehoe". Aa flows, found at higher levels on the abutments, exhibit a transition from fine-grained or porphyritic dense basalt at the base to an amygdaloidal or tuffaceous composition at the top, with individual flow thicknesses varying from 4 to 10 meters. Pahoehoe flows in the river section are characterized by a wrinkled (ropy) and vesicular top, containing pipe amygdales at the base, with each flow unit typically measuring between 3 to 5 meters in thickness. A notable geological feature in the area is the presence of weathered rock seams at the interfaces of these flows, which have contributed to challenges related to seepage and sliding of dam blocks [8].

2.3. Weathering of Basalt and Development of Weathered Rock Seams:

Weathering is a multifaceted process involving the breakdown and decomposition of rocks within their natural environment [9]. In basalt formations, this process alters both mineral composition and chemistry, influenced significantly by the rock's inherent mineralogy, joints, and fractures. Certain minerals found in basalt, such as olivine and pyroxene, are particularly susceptible to weathering, which can weaken the overall strength and durability of the rock. Weathered rock seams develop between basaltic flows after they cool, primarily along the contact zones of layered basalts [8]. These seams form as water percolates through open or sheared contacts within the rock. Unlike red or green bole layers, weathered rock seams do not indicate breaks in deposition over time; instead, they signify zones of intense weathering and alteration.

Characteristically, weathered rock seams consist mainly of highly to completely weathered basalt, often accompanied by a thin layer of clayey material. These seams exhibit a distinct morphology with a wavy, branching pattern that includes areas of pinching and swelling (Fig. 4). Their thickness varies significantly, ranging from a few millimeters to 1.5 meters. In some cases, infillings of minerals like zeolite or calcite are observed within these seams. Slickensided surfaces along these seams suggest localized movements and displacement, identifying them as potential weak planes vulnerable to structural instability, such as sliding in dam blocks. Understanding the intricate processes of basalt weathering and the formation of weathered rock seams is crucial for assessing the geotechnical challenges posed by such formations in civil engineering and construction projects [10].

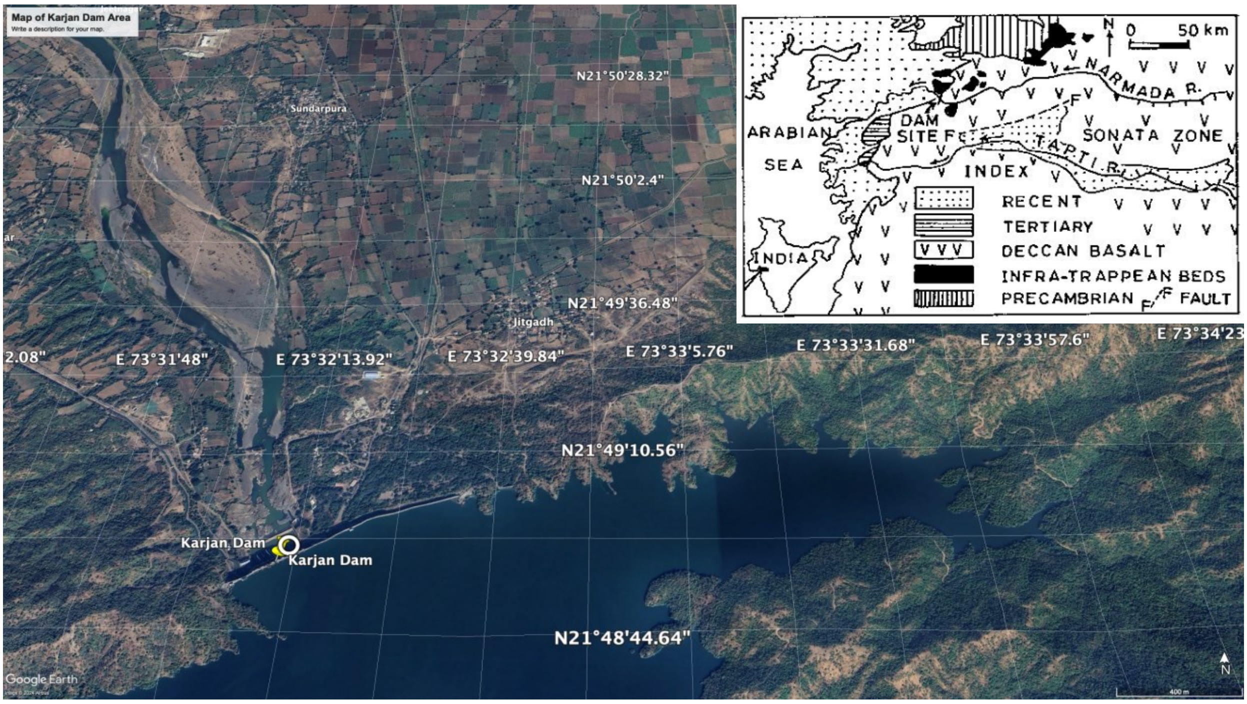


Fig. 1. Location Map of the Karjan Dam

Fig. 2. Spillway of Karjan Dam under operation

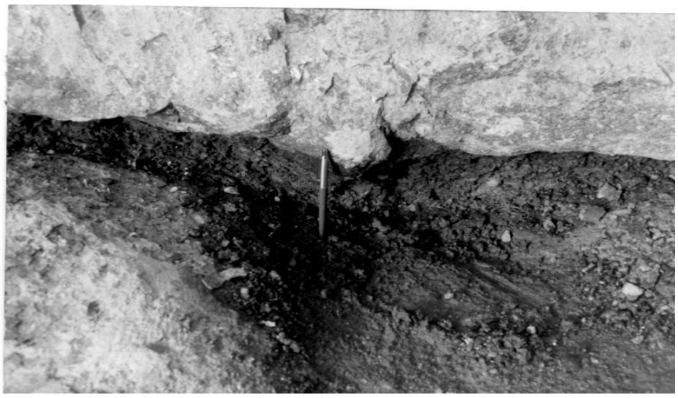
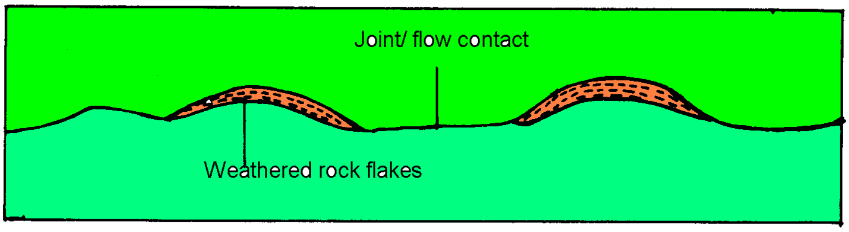


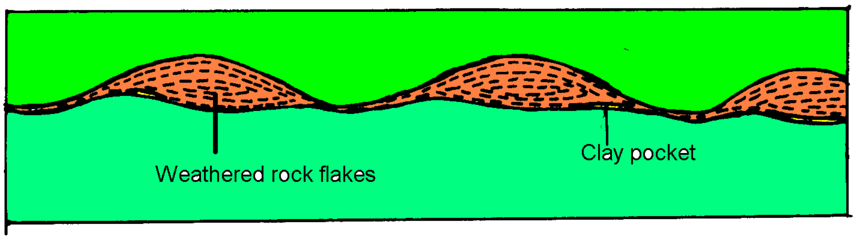
Fig. 3. Weathered Rock Seam developed along the contact of two flows (Adopted from [10])

2.4. Physico-engineering properties of the foundation rocks

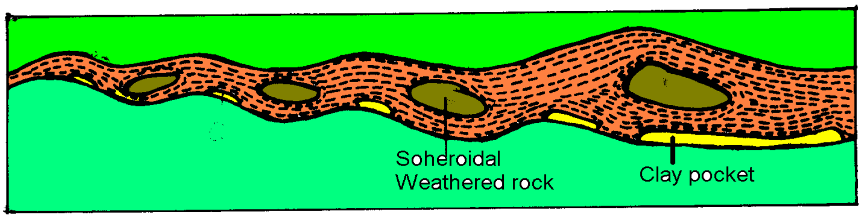
The physico-engineering properties of the foundation rocks including specific gravity, water absorption, porosity, permeability, unconfined compressive strength and tensile strength were determined. The average values of water absorption percentage vary from 1.60 to 2.20, porosity 4.20 to 5.15, specific gravity 2.58 to 2.70, unconfined compressive strength 62 to 79 MPa, tensile strength 10 to 12.50MPa and permeability 0 to 2.73×10^{-9}cm/sec. These values are within the normal limit of fresh, moderate to good values of basalt [11] (Fig. 4).



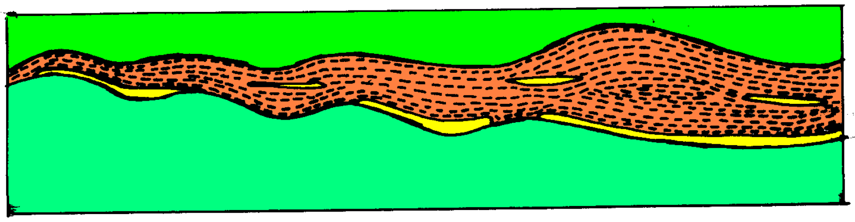
Type-I: Partly developed seam along joint/ flow contact



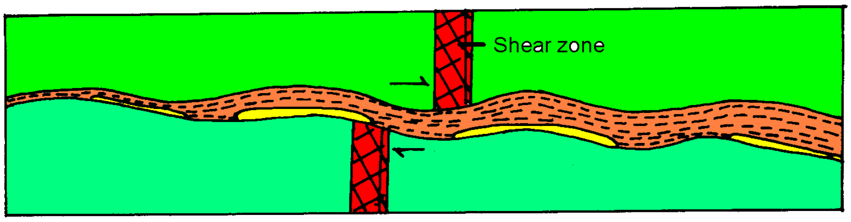
Type-II: Pinching and swelling seam



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. 4. Varied Characteristics of Weathered Rock Seams in Basalt Foundation

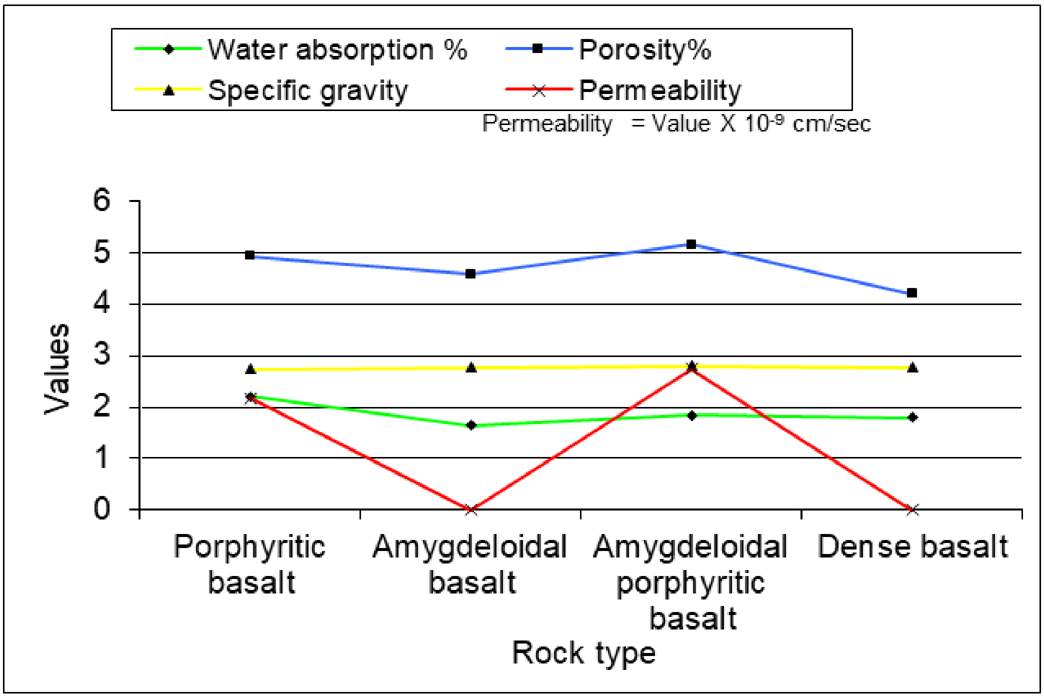


Fig. 5. Physical Properties of Basalt Rocks at dam site (Adopted from [10])

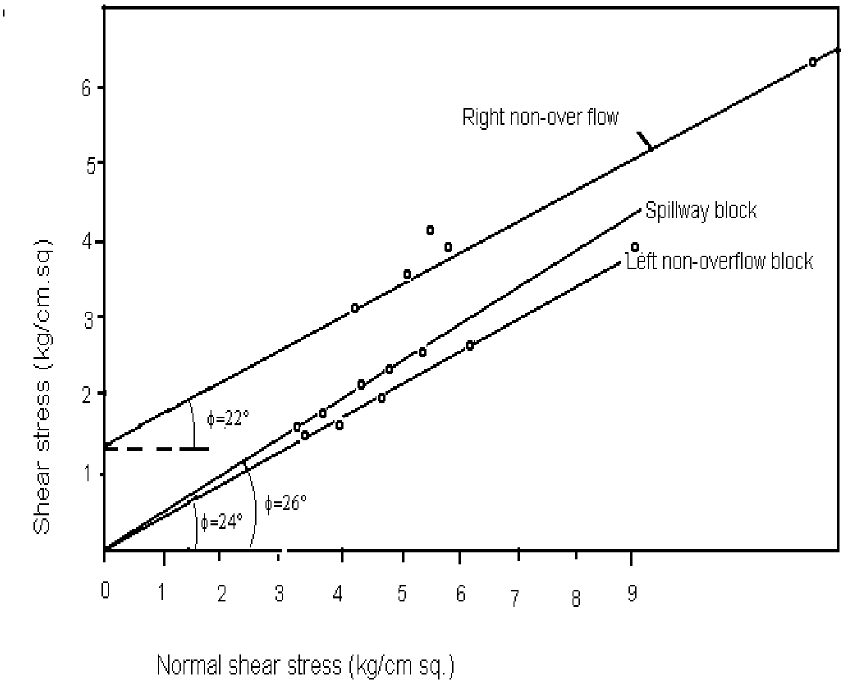


Fig. 6. In-situ shear tests plot of Normal shear stress vs. shear stress of weathered rock seam (Adopted from [6]).

In-situ shear tests were conducted to determine shear parameters of weathered rock seams. Seven test blocks were prepared in the spillway Block No. 5, over weathered seam. To facilitate the tests these rock blocks were encased in concrete. Test results showed the C value of 0 Kg/cm² and an ϕ value 22° to 26° (Fig. 6). Due to low shear parameters, concrete shear keys were provided along and across the weak layers in the dam foundation to resist sliding forces [12]. A higher value of 26 degrees was used in the design of this treatment. This decision was based on expert judgment, considering the wavy nature of the seams, which would increase resistance against sliding.

3. Methodology

The methodology employed in this study integrates intensive fieldwork and rigorous geotechnical testing to evaluate the behavior of foundation materials under varied conditions at the Karjan Dam. This approach aims to address challenges related to seepage and sliding, ensuring the stability and optimal performance of the structure. The study begins with a thorough literature review to gather geological, seismological, and engineering geological data from diverse sources. Geological investigations include detailed mapping and documentation of surface and subsurface features such as rock types and discontinuities using methods like test pits, trenches, and rock cores. Concurrently, the engineering geological study involves the creation of geological maps, characterization of geological materials based on their engineering properties, sampling through boreholes and excavations, and conducting laboratory and field tests to determine the engineering properties and deformation characteristics of the rock mass [6]. In-situ testing is crucial for capturing realistic design parameters, accounting for the heterogeneity induced by discontinuities within the rock mass. Based on the determined shear parameters sliding stability analysis of the dam was conducted to achieve required factor of safety against sliding.

Sliding factor: The sliding factor may be defined as the ratio of the sum of all horizontal forces and components of loading that tend to cause sliding of the dam on its foundation to the sum of all vertical forces and components of loading [13]. This ratio should lie within the range of 0.65 and 0.75 for normal loading with a higher value up to, say, 0.85 under extreme loading combinations, i.e.,

$\sum H/\sum V = 0.65$ to 0.75 for normal loading

≥ 0.85 for extreme loading.

The actual value permissible at a particular site will depend upon the soundness of the rock, the slope of the foundation and the keying effect provided.

Shear Friction Factor: The Shear Friction Factor (SFF) may be defined as the ratio of the total resistance to shear failure within the dam, at its contact with the foundation or within the foundation to the total horizontal load. This can be represented by the formula:

$SFF = (V \tan\phi + CA)/H$

Where SFF= the Shear Friction Factor

V= the sum of the vertical loads (or loads normal to the plane)

A= the area of the plane of contact

H= the some of the horizontal loads (or loads parallel to the plane)

ϕ= the angle of internal friction

C= the ultimate shear resistance of concrete or rock.

In general $\tan\phi$ will lie in the range of 0.6 to 0.75 but may be lower along joints, shears, faults or seams in the foundation [13]. If such features are present, in situ tests are performed to know the shear characteristics of the infilling material of discontinuities.

The shear friction factor should not be less than 5 for normal loading and may be acceptable as low as 4 for the extreme combinations of loading. However, some countries specify values of 4 and 3, respectively for SFF but each site should be considered as unique, and investigation should be conducted appropriate to the size and importance of the dam [13].

The factor of safety (FOS) of dam is defined as the ratio of the sum of the resisting forces tending to prevent sliding divided by the sum of the active forces tending to produce sliding. Thus, the Shear Friction Factor (SFF) of Safety has a certain critical value beyond which a structure is considered safe**.** The minimum values of factor of safety laid down in the Indian standard (IS: 6512 (1984)), for the different load conditions: B- FRL without EQ and with drains operative are: 4.0, 3.0 and 1.5 for condition B, E and F, respectively (Table 1)

4. Geotechnical Problems of Karjan Dam and

Stability Analysis

Main geotechnical problems of Karjan Dam included sliding and seepage along sub-horizontally disposed weathered rock seams in the foundation of overflow and non-overflow blocks [8].

4.1. Sliding Problem

4.1.1. Stability Analysis

Stability analysis of the overflow (spillway) blocks and non-overflow blocks was conducted based on the presence of weathered rock seams at different levels in each block. In some blocks, where the rock cover was shallow (1 to 2m), part of the overlying jointed rocks and seam material was removed during foundation preparation. The analysis considered the foundation areas where seam was removed from the foundation in part and where seam is present in the entire dam block foundation. In the analysis waviness, dip, and depth of the weathered rock seams were considered as per site condition. Initially stability analysis was performed without shear keys under three loading conditions to know need or otherwise of foundation treatment from sliding consideration:

B: Full Reservoir Level (FRL) without Earthquake (EQ.) and with drains operative.

C: FRL with EQ. and drains operative.

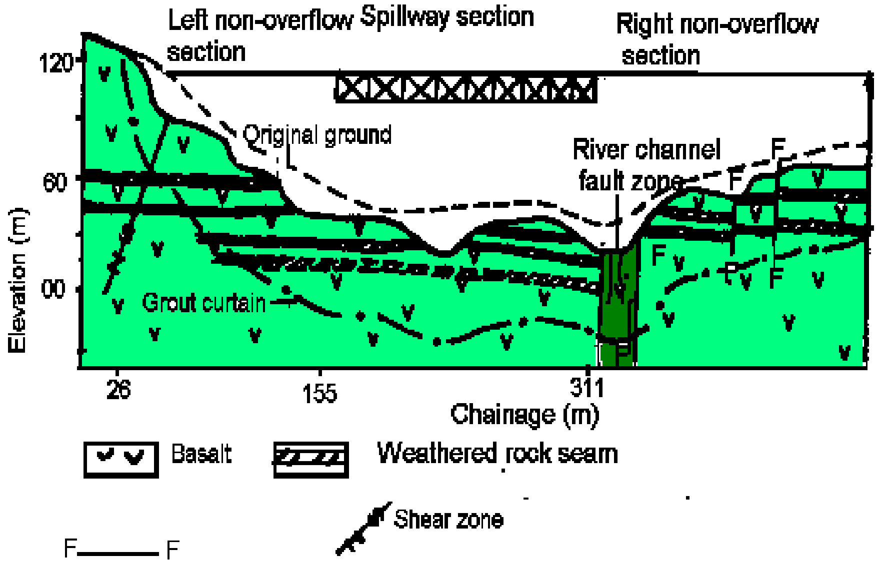
D: FRL with EQ. and drains inoperative.

The analysis covered overflow blocks 2 to 4 and 7, as well as non-overflow blocks 3 to 5, 8, 12, 18, and 21. For Spillway Blocks 5 and 6, a 15m wide key intercepting a shallow weathered seam below 3m depth was considered, and this seam material was removed during foundation preparation due to the shallow rock cover.

4.1.2. Shear Friction Factor (SFF) Values of dam blocks

Table 1. Shear Friction Factor (SFF) Values of dam blocks under different loading conditions

Loading Condition	Range of SFF Values		Minimum value of SFF Specified in IS
	Overflow blocks (Spillway)	Non-overflow blocks	
1. Condition B: FRL without EQ & Drains operative	2.372 to 3.922	4.585 to 15	4.0
2. Condition C: FRL with EQ & drains operative	1.902 to 3.16	3.548 to 23.135	3.0
3. Condition D: FRL with EQ & drains inoperative	1.444 to 2.873	3.379 to 49.896	1.5



I. Longitudinal geological section of dam

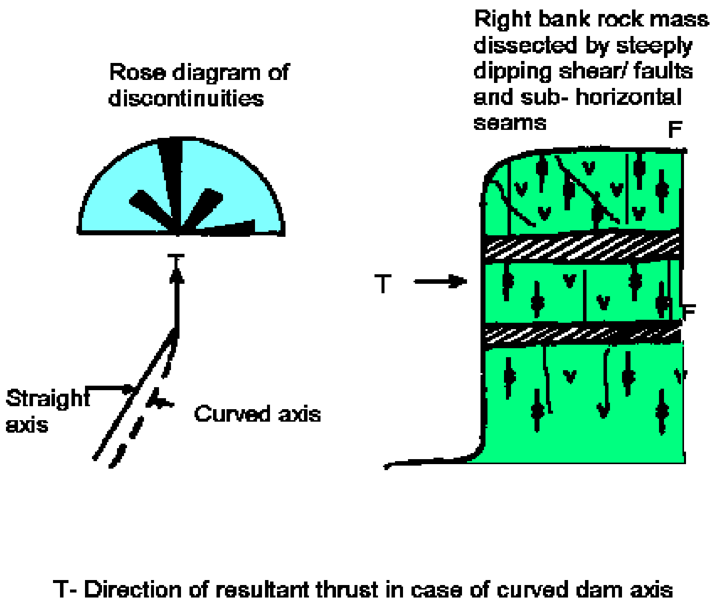


Fig. 7. Unfavourable geological conditions for proving curvature in the axis of spillway blocks: 1. Sub horizontal weathered rocks seams in the foundations 2. Sheared and weathered abutment rocks (Adopted from [6])

Based on the stability analysis following Shear Friction Factor (SFF) values obtained for Overflow and non-overflow blocks under different loading conditions are mentioned in Table 1. The Table 1 illustrates that the required SFF values were met only for the non-overflow blocks, where sufficient downstream rock cover was present. Notably, exceptionally high SFF values (greater than 22.969) were observed for the right non-overflow blocks 18 and 21, where approximately 20m of rock cover was available over the seam on the downstream side. On the other hand, there was not much available downstream rock cover in the spillway blocks due to unfavourable disposition of the seam. To enhance the SFF of dam blocks, the treatments designed and implemented include concrete shear keys extending below the weathered seams, widening the base width of dam blocks, and flattening the upstream slope of the spillway blocks. Curvature in the axis of the spillway blocks was not considered in view of the sheared and weathered nature of the abutment rocks [12] (Fig.7).

4.1.3. Treatment of weathered rock seams to prevent sliding

To ensure the dam blocks were safe against sliding, several treatments were considered and provided, especially for blocks resting over weathered rock seams. The remedial measures included flattening of the upstream batter, roughening of the foundation base, combining two or more blocks, and incorporating concrete shear keys.

The initial idea was to create a curvature in the alignment of the dam, laying the blocks in the riverbed in an arch-like manner with a mild upstream curvature. This design aimed to induce the blocks to act as a monolith, thereby mobilizing greater combined resistance against sliding. However, this idea was abandoned for two reasons: all the blocks had seams beneath them, and the abutment rocks were not geologically suitable for arch action.

Instead, alternative measures were adopted to increase the stability of the blocks over weathered rock seams. These measures included flattening the upstream batter, roughening the foundation base to increase friction, and combining two or more blocks to act as monoliths. Although these measures improved the factors of safety against sliding, they did not meet the required minimum values for sliding (F1) and shear friction factor (F2). Therefore, concrete shear keys were necessary to achieve required SFF [12].

Open concrete shear keys were provided where seams were located at shallow depths, and concrete drifts (plugs) were provided where there was sufficient rock cover over the seam or where dam blocks were already partially constructed. This approach ensured that the stability and safety requirements were met effectively [8].

4.2. Seepage Problem

There is always permanent movement or normal seepage of the water after the construction of the dam from the reservoir under and around the dam and at the rims of the reservoir. If this movement or escape of water from the reservoir through the fissures and openings in the rock, buried channels etc. becomes abnormally large it is known as leakage (flow >125 Ltr./ minute/ 10m length as per Bieniawiski classification [13]). Fissures characteristics of the rocks at Karjan dam sites were investigated through pressure testing in drill holes and also by direct observations of foundation treatment shafts and drifts during their excavation. Water pressure tests in the basalt were misleading as adjacent holes often gave entirely different permeability values. Natural lava tunnels and caverns were not found present in the area.

Conspicuous seepage was observed through weathered rock seams during the excavation of shafts and drifts in the foundations of spillway blocks [14]. Nearly all the drill holes during pre-construction stage investigations recorded high permeability (upto 75 Lugeons). To reduce the permeability of foundation rock mass, initial curtain grouting was done in four stages with 5,10,15 and 20kg/cm^2 pressures, gradually increasing with depth. Depth of curtain grouting in spillway section varied from 42 to 60m. It was observed that in five spillway blocks post-grouting seepage was more than 100 litres/minute. It clearly indicated ineffectiveness of initial curtain and consolidation grouting. Therefore, to reduce the seepage and to seal remaining gaps/permeable windows in the grout curtain additional curtain grouting was done with uniform high pressure of 20kg/cm^2 in all the stages, after filling of the reservoir upto El.78m. Seepage was reduced in general by about 70 to 90% after providing additional curtain grouting [15] (Fig. 10).

Grouting was extensively used to fill voids and fractures in the foundation and abutments, reducing permeability. An upstream cutoff wall was constructed to prevent seepage through the shallow seams in the foundation, and drainage systems were installed to collect and safely discharge seepage. High-pressure grouting was particularly effective in treating weathered rock seams from a seepage consideration.

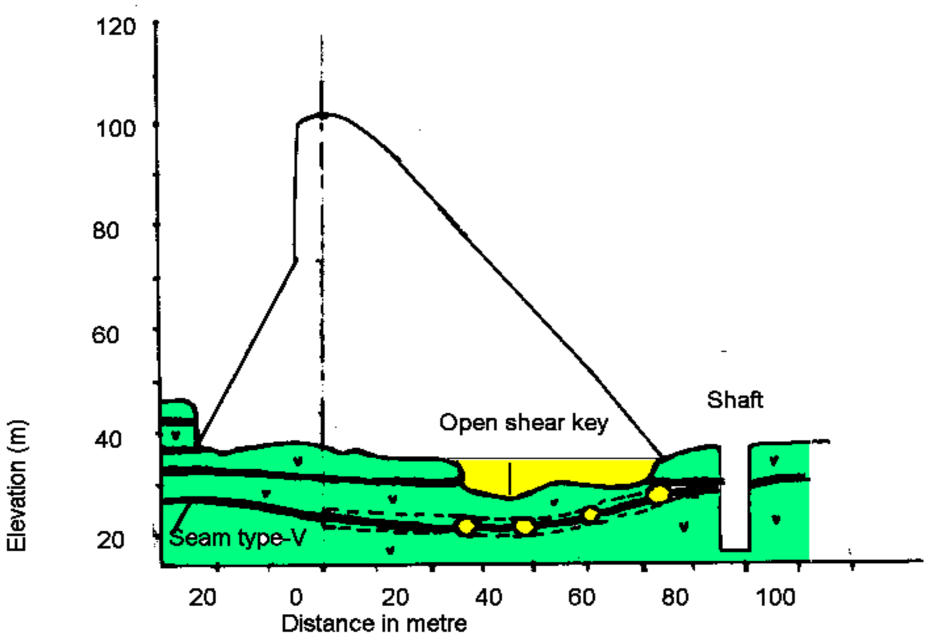
5. Foundation Treatments of Karjan Dam Blocks

5.1. Treatment of Spillway Blocks

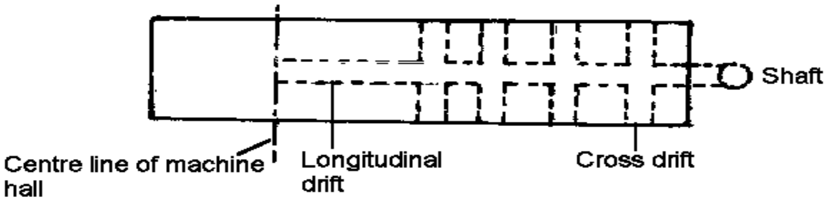
Spillway blocks 1 to 7 rest over various weathered seams located at varying depths in the foundations. Sliding analysis showed that three to four drifts/plugs of 6 to 8 meters widths were required for spillway blocks 1 to 5 to ensure the minimum required values of factors F1 and F2. Accordingly, concrete drifts were provided in the foundation of spillway blocks 1 to 5 and open concrete shear keys in the foundation of spillway blocks 6 and 7 (Fig. 6). Pump concrete was used in the top one-third portion of the drift. Shear keys were provided in the foundation of spillway blocks 6 and 7 without any joint in between to take advantage of the available cross shear, though it was not considered in the stability analysis.

5.2. Treatment of Right Non-Overflow (RNOF) Blocks

The factors and criteria involved in the stability analysis of the RNOF blocks over the weathered seam were similar to those adopted for the left NOF and spillway blocks. Shear failure was considered through the downstream rock cover along a plane at an angle of 22° 33’ (45° - ϕ/2) for design purposes only for RNOF blocks R-0, R-1A, R-1B, and R-2 (Fig.7).



Geological cross-section of spillway block



Foundation plan of treatment drifts

Fig. 8. Treatment of Weathered rock seams: Open concrete shear keys at shallow depth and underground concrete shear keys at depth (Adopted from [6]).

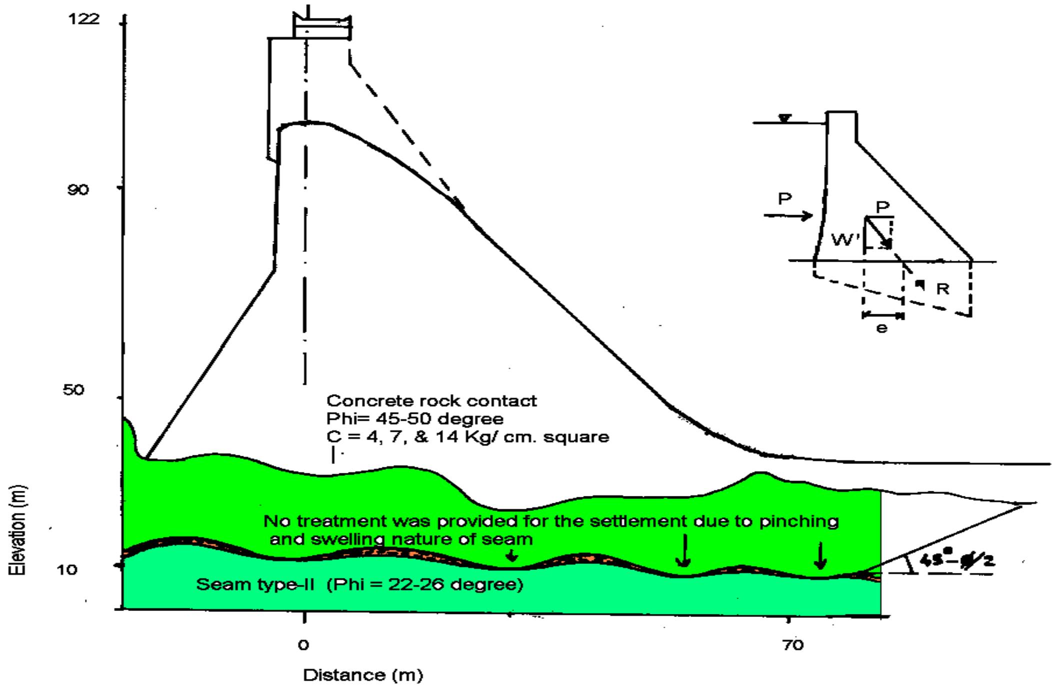


Fig. 9. Downstream Rock cover was considered in the Non-overflow blocks in the stability analysis (Adopted from [6]).

5.3. Additional Treatment

Analysis showed that to obtain extra resistance through shear keys/drifts alone, very large shear keys/drifts were required. This would have involved high costs and considerable construction difficulties, as concrete was already laid in a few blocks. To minimize this treatment and reduce the width of the keys/drifts, it was decided to provide a flatter upstream batter of 1:2 below El. 75m in the spillway blocks, instead of the original 1:1.5 below El. 85.70m. This would increase the vertical load due to water column, thus helping mobilize larger frictional resistance along the weak seams [16]. To obtain extra frictional strength, the foundation rocks' surface was roughened; seam material was scooped out laterally to the maximum possible depth inside the rock mass, and contact grouting was done between concrete and rock face in the spillway and NOF blocks.

5.4. Changes in Spillway Design

The design of a spillway with a stilling basin, horizontal apron, and flip bucket serves several key purposes to ensure the safety and functionality of a dam. The stilling basin helps dissipate the energy of flowing water, reducing its erosive force and protecting downstream structures and the riverbed from scouring [17]. The horizontal apron provides a smooth transition for the water flow, distributing the energy evenly and further mitigating the potential for erosion [18]. The flip bucket redirects the high-velocity water flow away from the base of the dam, throwing it into the air and allowing it to fall harmlessly downstream, thus preventing erosion, scouring and structural damage to the dam's foundation [19]. Together, these components enhance the dam's overall stability, prolong its lifespan, and ensure the safe management of overflow water.

5.5. Seepage Treatment

Conspicuous seepage was observed through weathered rock seams in the foundation of the Karjan Dam. Low-pressure consolidation and curtain grouting were initially ineffective in treating these seams. However, seepage was significantly reduced by adopting high-pressure (20 kg/cm²) curtain grouting (Fig. 10).

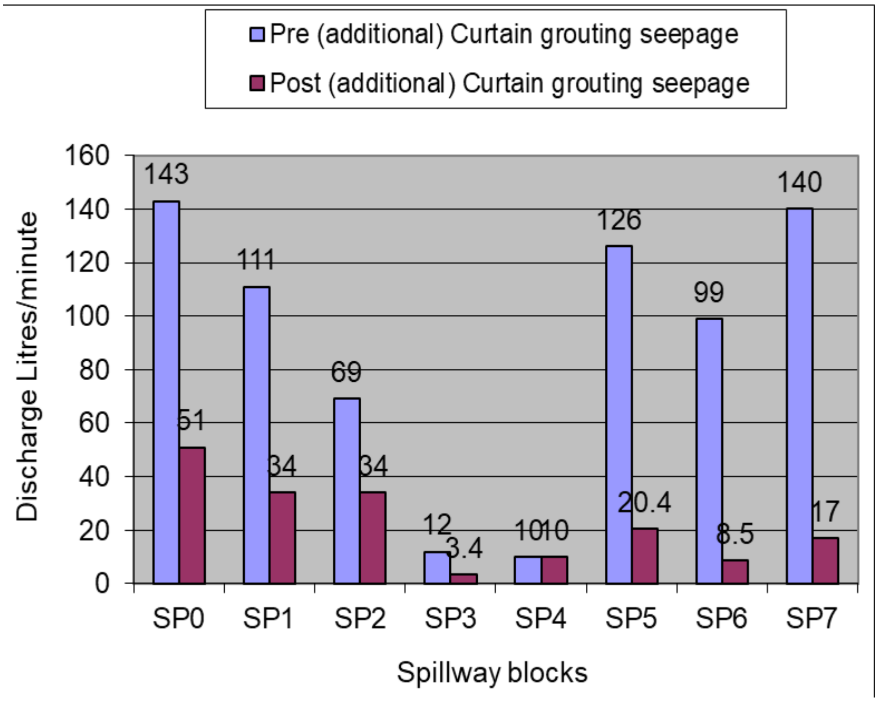


Fig. 10. A comparative study of pre and post curtain grouting seepage results: Reduction in seepage was observed after curtain grouting in the foundation of spillway blocks (Adopted from [6]).

This indicates that weathered rock seams can be effectively treated for seepage by using high-pressure grouting methods. Extensive grouting and consolidation techniques enhanced foundation stability and reduced seepage risks.

An array of monitoring instruments, including piezometers, settlement gauges, and inclinometers, were installed to track the dam's performance and detect early signs of distress. Continuous monitoring is necessary to enable the timely detection and intervention of any potential geotechnical issues. To date, no signs of distress have been observed that would necessitate any intervention.

6. Results and Discussion

Geotechnical forensic engineering plays a crucial role in identifying potential issues and preventing failures that could arise during the operation of large gravity dams if not addressed promptly. The Karjan Dam in Gujarat, India, a 100-meter-high masonry-cum-concrete gravity dam built 38 years ago on Deccan basalt, encountered significant geotechnical problems due to oversights in pre-construction and early construction stage investigations. These investigations failed to detect sub-horizontal weathered rock seams in the dam's foundations, leading to seepage and sliding issues. These weaknesses were discovered through visual assessment during partial construction, prompting a temporary halt to reassess the foundation conditions for all dam blocks. Comprehensive engineering geology and geotechnical investigations were then conducted, revealing the continuity of weathered rock seams throughout the foundation at various depths.

The Karjan Dam Project serves as a practical illustration of the geotechnical challenges associated with basalt rocks. Located on Deccan basalt flows of "Aa" and "Pahoehoe" types, the Karjan Dam faces seepage and sliding challenges due to weathered rock seams [6]. Physico-engineering properties and shear tests were conducted to evaluate foundation suitability. In-situ shear tests on weathered rock seams indicated low cohesion, prompting the provision of concrete shear keys to resist sliding forces.

In-situ tests of seams indicated values of cohesion were almost negligible (C ~ 0) and the angle of internal friction (ϕ) varied at different locations, with values of 22°, 24°, and 26°. Shear values obtained for concrete over rock contacts were C = 4 kg/cm² and $\phi = 50°$. The factor of safety against sliding (F1) was 1.5, and the shear friction factor (F2) was 3.0. The minimum value of SFF was scaled down from 4.0 for condition B (FRL with earthquake and drains operative) as stipulated in IS: 6512-1972 to 3.0 per United States Bureau of Reclamation (USBR) practice. This adjustment was made due to intensive investigations during the construction stage, which narrowed down the margin of uncertainty, and the shear values were based on actual site tests. An earthquake factor of 0.125g (identical to Narmada Dam) was considered in the design [6].

Concrete shear keys were also provided at other major dam projects, including Ichari Dam, Srisailam Dam, Kadana Dam, Eddahbi Hydroelectric Scheme in Morocco, Itaipu Hydroelectric Project in Brazil [20], and Sardar Sarovar (Narmada) Dam [6], to treat sub-horizontal weak layers occurring in the foundations of these dams. All these dams have not faced sliding problems after the provision of concrete shear keys, confirming adequate treatment design and implementation in the foundation of Karjan Dam to prevent sliding of dam blocks.

The Karjan Dam forensic study underscores and reiterates the critical need for thorough geotechnical investigations at various stages of construction. Engineering geological studies of the dam, founded on basalt rocks with associated weak features, provide compelling evidence of this necessity. The study demonstrates that meticulous geotechnical evaluation and appropriate remedial measures can facilitate successful construction on challenging foundations, ensuring the dam's safe operation since 1986. These findings open up opportunities for dam construction in geologically complex areas and contribute significantly to the field of geotechnical engineering. It is hoped that this comprehensive review will inspire further research and innovation in this crucial domain.

7. Conclusion

The geotechnical forensic investigations conducted during the construction of the Karjan Dam emphasize the critical need for comprehensive geotechnical studies to identify and mitigate potential issues in dam foundations. The early oversight of sub-horizontal weathered rock seams in the Deccan basalt foundation could have resulted in significant problems, such as seepage and sliding, which were fortunately detected during construction. The proactive implementation of measures, including concrete shear keys, extensive grouting, and design modifications, was essential to ensure the dam's safety and stability.

This case study highlights the indispensable role of geotechnical forensic engineering evaluation in preventing failures and ensuring the long-term stability of dam structures. While the measures taken have proven effective, the unique geological conditions at each dam site necessitate continuous monitoring and adaptive management to address future challenges. Ongoing monitoring and tailored investigations are vital in maintaining the stability and safety of large infrastructure projects.

The success of the Karjan Dam underscores the importance of thorough geological investigations, expert engineering judgment, and the integration of site-specific solutions in the design and construction of important infrastructure. This case study offers valuable insights that can be applied to the construction and maintenance of other dams worldwide, particularly those built on challenging geological formations.

The lessons learned from the geotechnical forensic investigations of the Karjan Dam will provide the engineering community with valuable insights to enhance design, construction, and maintenance practices for dams and other large infrastructure projects. These findings underscore the need for thorough engineering geology and geotechnical investigations at every stage of construction. Ultimately, this is expected to contribute to safer and more reliable construction of dams.

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