Article

Assessment and Remedial Measures for Persistent Seepage in the Right Abutment of Sarobi Small Dam, North Waziristan, Pakistan

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Abstract

The Sarobi small dam having crest length of 134.5 m and height of 31m, constructed on Ping algad/stream near Sarobi village, North Waziristan, Pakistan, has exhibited a persistent seepage problem since its completion in 2019, preventing the reservoir from attaining and sustaining its designed water level. Despite perennial inflow, observations during construction and subsequent floods indicated leakage concentrated in the right abutment near the spillway. Geotechnical investigations, including borehole data and geological mapping, revealed highly fractured and weathered strata consisting of alternating limestone and weak shale layers, contributing to seepage through the right abutment. Visual inspections confirmed piping and seepage at the downstream face corresponding to reservoir levels. This paper presents the investigation findings, evaluates the geological controls influencing seepage, and proposes two remedial solutions: construction of a 75 m long and 4.5 m wide clay core to create an impermeable barrier, and a targeted drilling-grouting program to seal fractured zones. Cost to benefit ratio, field implementation considerations, and the necessity for expert site monitoring and critical design reviews are also discussed in this paper.

Keywords: Dam seepage, Piping, Geotechnical Investigation, Clay Core, Drilling and Grouting.

1. Introduction

Seepage is widely known as most critical factors affecting safety, performance, and long-term stability of embankment and rockfill dams. When seepage becomes uncontrolled, it can lead to piping, internal erosion, progressive enlargement of subsurface flow paths, and ultimately compromise structural integrity of a dam [1–3]. Modern dam engineering therefore places emphasizes significantly on seepage mechanisms, early detection, and the selection of appropriate remedial measures tailored to site-specific geological conditions. The Sarobi Small Dam is located on Ping algad/stream is about 30.57 km southwest of Miranshah and 2.73 km upstream of the confluence with Jaler Algad. The site is half a mile upstream from Sarobi village. The catchment area of the stream I up to dam axis is 20.98 square km. Mean annual rainfall is about 330 mm. The stream carries perennial flow and was reported 0.5 cusec as per design report and mean annual inflow is estimated as 1035 Acre-ft. Despite perennial inflow between 0.25 and 0.50 cusec, the reservoir has consistently failed to achieve and maintain its design dead storage of 330 A-ft (acre-feet) and live storage of 921 A-ft. After the recent flood the water level in reservoir raised to 1158 masl which was still 4 m below the dead storage level. Some whirls were observed on the right abutment of dams in the approach area of spillway. It was reported that the seepage was oozing out from shale section downstream of the spillway right side. It was apprehended that both the surface and subsurface condition were favorable for seepage path and need some treatment. The reservoir dropped at an average rate of 30 cm per day. After minor dumping of clay near right side the depletion rate was recorded as 15 cm per day. Field observations during construction, along with post-flood inspections, revealed whirlpool formation upstream and visible leakage manifested by sink holes (Fig 5 and 6), clear indicators of interconnected subsurface flow paths.

Figure 1. Sarobi dam body

Figure 2. Seepage path along right abutment

Figure 3. Water was observed seeping through the encircled portion

Figure 4. Seepage water trickling through the right abutment of dam

Figure 5. Piping and sloughing in the reservoir body as a result of seepage

Figure 6. Sink holes due to seepage and piping

Geological mapping and borehole logs, showed that the right abutment comprises intensely fractured limestone interbedded with weak, weathered shale layers. Such lithological alternation is known to predispose abutments to seepage because limestone provides open joint networks while shale deteriorates under hydraulic loading, forming expanded seepage paths. These characteristics closely parallel those documented in international seepage studies, which report similar behavior in dams founded on fractured, heterogeneous, or weathered rock masses [4–7]. A 2025 global review on seepage control highlights that fractured bedrock foundations typically require deep and continuous seepage barriers, such as grout curtains or cutoff walls, rather than shallow clay interventions, which cannot intercept deep fracture networks [1]. Numerical and experimental research from (2020-2025) further confirms that seepage behavior in zoned and homogeneous dams is highly sensitive to rock mass discontinuities, permeability contrasts, and hydraulic gradients [3, 5, 8].

Recent advances in dam remediation technologies since 2015 have expanded the engineering toolkit available for seepage control. Field applications of grout curtains in fractured foundations, such as at Wala Dam (Jordan), demonstrated effective sealing of deep fractures using systematic drilling and cementitious grout injection [9]. Contemporary numerical modeling studies corroborate these findings, showing significant hydraulic gradient reduction and improved dam safety when grout curtains are properly designed and installed [10–12]. These studies emphasize the necessity of pairing grout curtains with robust geological investigation to ensure that major flow paths are targeted.

Furthermore, modern research has investigated the longevity and degradation mechanisms of seepage barriers. Concrete cutoff walls may experience dissolution, cracking, or seepage-induced degradation over time [5, 13], while clay cores may deteriorate under cyclic wetting and drying. These findings underscore the need for durable design and proper construction oversight.

Beyond traditional materials, chemical grouts, particularly colloidal silica, have emerged as viable solutions for sealing fine fissures and soluble rock formations where cement grout is ineffective [12]. Coupled seepage–deformation modeling has also improved understanding of how transient reservoir level changes induce stress redistribution that may affect barrier performance [7, 14].

Non-invasive geophysical methods such as electrical resistivity tomography and self-potential mapping have become increasingly popular in detecting and delineating seepage paths prior to remediation [8, 15]. Meanwhile, long-term monitoring has gained prominence, with several case studies demonstrating the importance of continuous piezometer readings, deformational surveys, seepage flow measurement, and data-driven predictive modeling to ensure dam safety [11, 16, 17]. Machine learning–based seepage forecasting, introduced in recent hydrology literature, further enhances early-warning systems for seepage-prone dams under changing climate conditions [6, 18–20].

Collectively, these studies illustrate that seepage problems such as those at Sarobi small dam require a comprehensive approach combining geological characterization, deep seepage barrier installation, and long-term monitoring. Shallow measures like clay cores may reduce surface leakage but are insufficient against deeper fracture-controlled seepage typical of limestone-shale sequences [4, 5]. By contrast, drilling and grouting programs directly address the deeper fractured pathways and have proven effective in similar geological conditions worldwide [9–11]. A hybrid system integrating both clay core and grout curtain, a strategy increasingly recommended in the literature [1, 3, 12], offers a robust and practical solution tailored to the Sarobi Dam's geological setting.

2. Materials and Methods

The assessment integrates geotechnical, geological, and hydrological data collected during and after construction. Boreholes drilled near the spillway, notably BH-04 and BH-05, revealed a highly variable sequence of fractured limestone and soft, weathered shale. Limestone units contained open joints and interconnected discontinuities, while shale layers (1–3 m thick) were weakened through weathering. Together, these units form a permeable network capable of transporting significant seepage flow beneath the abutment.

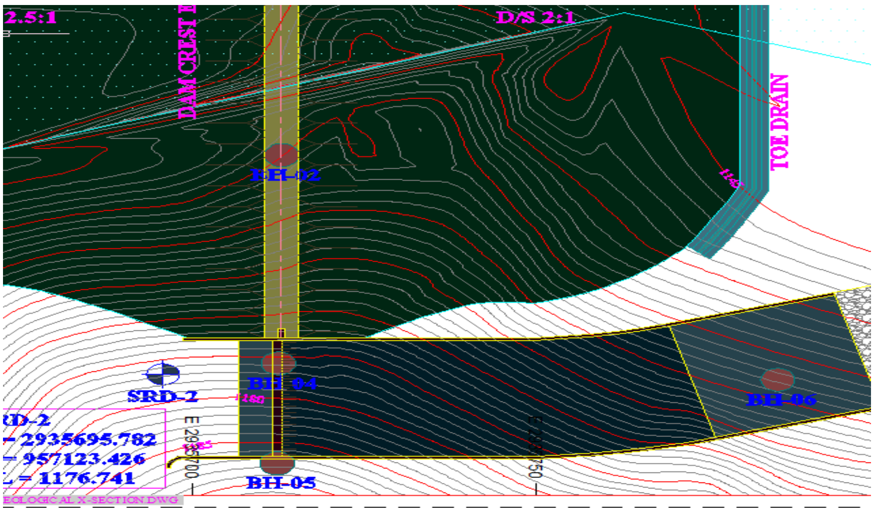

Figure 7. Borehole locations

Figure 8. Right side of spillway (Right Abutment of Dam), extremely fractured & weathered rocks

Seepage behavior was evaluated by correlating reservoir elevations with seepage discharge characteristics. Turbid seepage indicating internal erosion was repeatedly observed at the downstream face, particularly during high reservoir levels. Whirlpool formation upstream confirmed hydraulic connectivity between reservoir water and downstream emergence points. These indicators allowed identification of probable seepage pathways.

Two remedial approaches were assessed. The first was a shallow clay core cutoff, designed to intercept near-surface seepage along a 75 m stretch of the abutment. The second was a deep drilling–grouting program with 35 m deep boreholes spaced at 3 m intervals to seal fractured rock zones. Key parameters, including cost, technical feasibility, material availability, and expected performance, were examined using dam engineering guidelines and global case studies.

3. Remedial Measures for Treatment of Right Abutment's Seepage Issue

a) Option-I

Clay Core: As clay is the water tight material, having very low permeability coefficient (10-9 cm/sec), in earth core rock filled dams. It is proposed that a clay core having length of 75 m along and 4.5 m wide to be provided, near the approach of the spillway, and right abutment. The depth will be carried up to hard rock or firm strata, approximately (4-9) m depth.

b) Option-II

Drilling Grouting: Another way to cater the seepage problem is to provide drilling grouting. 35 m deep holes to be drilled with 3 m c/c spacing along the approach slab and then properly grouted. 11 holes are to be drilled and grouted straight while 6 holes are to be drilled inclined along the right abutment and grouted (as shown in figure 9). The suggested grout must contain 1 part cement mix with 3 parts of water (by weight) with 1 percent of finely grained high activity bentonite

Financial Impact of both proposed Seepage Control Measures

S. No	Options	Costing (PKR in Million)	Remarks
1	Option-I (Clay Core)	3.3	Average depth of clay core is considered 4.5 m wide and in 75 m in length
2	Option-II (Drilling grouting)	5.2	Total 17 no. of vertical and inclined drilled and grouted holes with 3 bags per meter depth

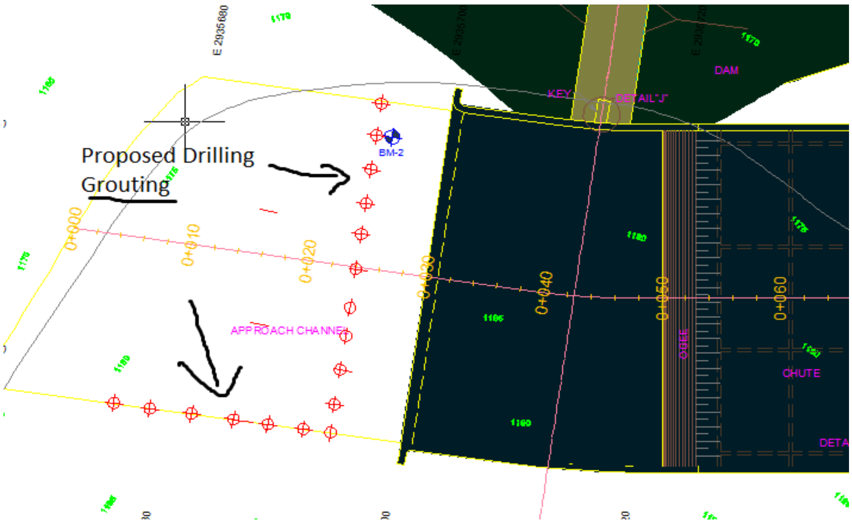

Figure 9. Proposed Drilling Grouting on Approach of Spillway

Figure 10. Picture with Proposed drilling grouting & clay blanket

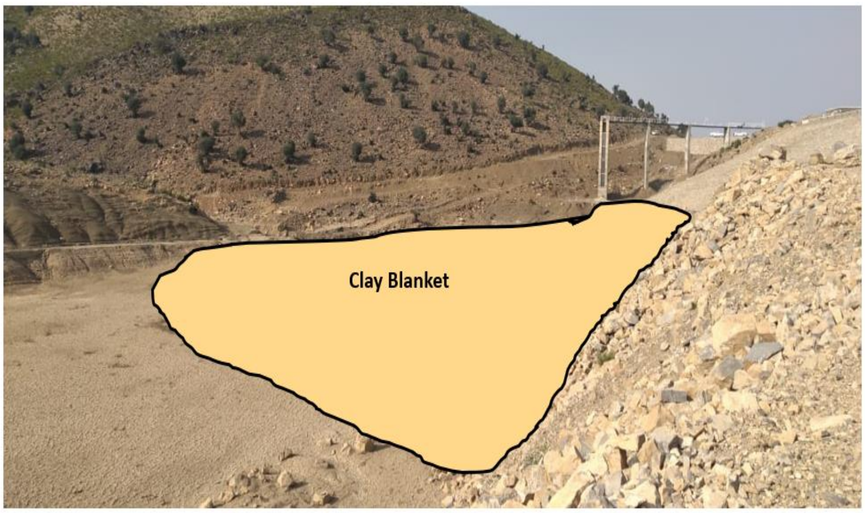

Figure 11. Proposed clay blanket

4. Results and Discussion

Field observations confirms that seepage originates primarily from deep fractured zones within the limestone, shale sequence in the right abutment of the dam. The correlation between seepage rate and reservoir elevation, together with surface indicators such as whirlpooling, suggests a continuous subsurface flow system. Weak shale layers appear to be actively eroding, facilitating enlargement of seepage channels.

The clay core cutoff, although economical, cannot address deep fractured pathways and may be vulnerable to cracking due to differential settlement between limestone and shale. It would primarily treat shallow seepage.

Drilling and grouting provide a more robust solution, directly targeting fractured rock at depth. Cementitious and low-viscosity grouts can effectively penetrate joint systems when applied using staged pressures. 35 m deep holes are suggested to be drilled with 3 m c/c spacing along the approach slab and then properly grouted. 11 holes are to be drilled and grouted straight while 6 holes are to be drilled inclined along the right abutment and grouted. However, this method requires strict supervision, geological validation, and potential adjustments due to variable grout take.

A hybrid solution, clay core + grout curtain, is considered optimal. This approach aligns with international best practice for dams founded on fractured rock, combining shallow seepage reduction with deep barrier sealing. It also enhances resilience against unknown subsurface conditions.

5. Conclusions and Recommendations

The persistent seepage at, Sarobi small dam, is controlled by the fractured limestone, shale geology of the right abutment. Shallow interventions alone cannot provide long-term seepage control. Deep drilling and grouting, supplemented by a shallow clay core cutoff, offers the most effective remediation strategy. Trial grouting, rigorous monitoring, and expert supervision are essential for ensuring success.

Continuous monitoring through piezometers, seepage weirs, and visual inspections is recommended during and after remediation. A full grout curtain should be implemented following trial validation, and the clay core should be constructed to mitigate shallow infiltration. Adoption of this integrated approach will enhance the dam's performance and ensure long-term safety and reliability.

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