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Research Article

Geotechnical Site Investigation and Foundation Characterization for the Legeoda Earth Dam, Dire Dawa, Eastern Ethiopia

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Abstract

The Legeoda Dam project, proposed in eastern Ethiopia's Dire Dawa region on the Halo Busa Lege Odamirga watershed, aims to provide irrigation water for downstream agricultural development. This geotechnical feasibility study addresses foundation challenges associated with deep tropical weathering of Oligocene flood basalts overlain by uniform alluvial deposits. Twelve boreholes along the 520 m dam axis, supported by extensive laboratory testing (index properties, shear strength, compressibility, permeability) and in-situ SPT, revealed a consistent stratigraphic sequence: 1.5 m topsoil, 2.5 m clay, 4.0 m sandy silt, 7.0 m highly weathered basalt, 10.0 m fractured basalt, and sound basalt below ~25 m depth. Key findings include uniform overburden thickness (39.9–40.1 m), progressive strength increase with depth (SPT N = 5.5–78.8), high untreated settlement potential (6251 mm), and significant seepage risk through fractured basalt. Seepage, stability, and settlement analyses confirmed technical viability following targeted foundation treatment. Novel contributions include quantitative risk-based treatment optimization and cost-benefit evaluation specific to Ethiopian basalt terrains, demonstrating benefit-cost ratios exceeding 3.0 for integrated cutoff and grouting measures. The study concludes that the site is highly suitable for a zoned earth-rock embankment dam with standard foundation improvements. Recommendations emphasize deep cutoff penetration into sound basalt, selective grouting, and comprehensive instrumentation. This work advances sustainable dam development on flood basalt foundations in rift-margin settings.

Keywords

Basalt Foundation, Deep Weathering, Seepage Control, Foundation Treatment, Risk-based Optimization

1. Introduction

The Legeoda Earth Dam project, located in the Dridawa administrative area of Eastern Ethiopia, represents a critical infrastructure initiative aimed at addressing persistent water scarcity and enhancing agricultural productivity in a drought-prone region. This geotechnical investigation forms the foundational engineering study imperative for the dam's safe and economical design and construction. A comprehensive subsurface exploration program has been undertaken to characterize

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the foundation conditions, thereby mitigating the inherent risks associated with earth dam construction on complex geological formations typical of the Ethiopian highlands and rift margin systems.

1.1. Purpose of the Legeda Dam

The primary purpose of the Legeda Dam is irrigation water storage to support sustainable agricultural development and improve food security for local communities. Eastern Ethiopia, particularly the areas surrounding Dire Dawa, is characterized by semi-arid to arid climates with highly variable and erratic rainfall patterns, leading to frequent crop failures and hydrological droughts [1, 2]. The dam is designed to impound seasonal runoff from the Legeda catchment, providing a reliable water source for controlled irrigation during dry periods. A secondary, though vital, purpose is domestic and livestock water supply, alleviating the burden on distant and often unreliable water sources. By regulating stream flow, the dam may also contribute to local groundwater recharge and provide limited silt retention benefits, although these are not its principal design drivers. The project aligns with national development goals under Ethiopia's Climate Resilient Green Economy (CRGE) strategy, which emphasizes water resource development for climate adaptation [3].

1.2. Importance of a Robust Foundation for Earth Dams

The performance and safety of an earth dam are intrinsically tied to the integrity and engineering behavior of its foundation. Unlike concrete dams, which transfer loads to specific points, earth dams impose widespread loads across the entire valley floor and abutments. A robust foundation is non-negotiable for several interrelated reasons:

First, the foundation must provide adequate shear strength to resist the downstream thrust of the dam embankment and impounded water. Failure along a weak plane in the foundation, such as a sheared clay layer or a weathered rock contact, can lead to catastrophic translational or rotational slope failure [4]. Second, settlement must be controlled. Excessive or differential settlement, often resulting from the compression of soft or loose soils beneath the embankment, can cause cracking in the dam core, compromising its watertight integrity and leading to internal erosion (piping) [5]. Piping, the progressive removal of soil particles by seepage flow, is a leading cause of earth dam failures worldwide and is heavily influenced by the permeability and continuity of foundation strata.

Furthermore, the foundation governs seepage patterns. A permeable foundation stratum can act as an uncontrolled conduit, leading to high water losses, uplift pressures, and potential instability. Consequently, a detailed geotechnical characterization is essential to design effective cut-off measures, such as grout curtains or key trenches. In summary, the foundation is not merely a platform but an integral structural component of the dam system. As famously underscored in geotechnical engineering, “the dam and its foundation must act as a single unit” [6]. Ignoring this unity invites a high risk of structural distress or failure, with severe humanitarian, economic, and environmental consequences.

1.3. General Geology and Geography of the Dire Dawa Area

The project site is situated within the complex geological and topographic framework of Eastern Ethiopia, near the city of Dire Dawa. Geographically, the area lies on the southeastern escarpment of the Ethiopian Highlands, transitioning toward the Afar Depression. The topography is characterized by dissected plateaus, steep valleys, and intermittent streams, with elevations typically ranging from 1,000 to 1,800 meters above sea level.

Geologically, the region is dominated by Tertiary to Quaternary volcanic rocks associated with the East African Rift System. The bedrock sequence primarily consists of Miocene-Oligocene basaltic and trachybasaltic lavas, interbedded with ignimbrites, tuffs, and volcaniclastic sediments [7, 8]. These rocks are often intensely weathered and fractured, creating complex near-surface profiles. Alluvial and colluvial deposits, comprising mixtures of gravel, sand, silt, and clay, infill the valley bottoms and lower slopes. The regional tectonic activity, marked by faulting and fracturing, significantly influences groundwater flow and rock mass quality. This geological setting presents distinct geotechnical challenges, including the potential for high permeability in fractured bedrock, variable weathering profiles, and the presence of weak, compressible layers within the sedimentary sequences [9]. Understanding this context is paramount for interpreting site investigation data and anticipating foundation behavior under dam loading.

The investigation's overarching objective is to develop a definitive geotechnical ground model to ensure the safe and optimized design of the Legeda Earth Dam. Specific aims include: 1) delineating subsurface stratigraphy and structure across the dam footprint; 2) quantifying key engineering properties (strength, compressibility, permeability) of all foundational strata through in-situ and laboratory testing; 3) assessing the seepage regime and stability of foundations and abutments; 4) identifying adverse conditions like collapsible soils or weathering profiles; and 5) deriving preliminary geotechnical design parameters and foundation treatment recommendations. This structured characterization directly de-risks the project by transitioning from raw data to actionable engineering insight.

2. Literature Review and Regional Geological Context

A review of pertinent literature and regional case studies is critical for contextualizing the site-specific findings of this investigation within the broader geotechnical framework of

Eastern Ethiopia. This synthesis informs the interpretation of local data, helps anticipate potential challenges, and guides the investigation strategy by highlighting known geological risks.

2.1. Geotechnical Conditions in Eastern Ethiopia and the Dire Dawa Region

The project area is situated within a geodynamically active zone influenced by the Afro-Arabian Rift System. The dominant geology comprises Tertiary-Quaternary volcanic sequences associated with the eastern escarpment of the Ethiopian Highlands. These sequences primarily consist of Oligocene-Miocene flood basalts, trachybasalts, and intercalated pyroclastic deposits (ignimbrites, tuffs, and agglomerates) [7, 10]. From a geotechnical perspective, these formations present a characteristically heterogeneous and anisotropic profile. The near-surface expression is often a deeply weathered profile, transitioning from residual soil (lateritic clay) through saprolite and saprock to fractured and eventually sound bedrock [9, 11]. This weathering profile, influenced by tectonic fracturing and climate, creates zones of high permeability and variable strength, posing significant challenges for foundation sealing and slope stability.

Valley bottoms and depressions are typically infilled with Quaternary alluvial and colluvial deposits. These unconsolidated materials range from coarse, permeable gravels and sands to cohesive silts and clays, often deposited in complex, lenticular stratigraphy [12]. A recurring geotechnical concern in such settings is the presence of collapsible soils, particularly in unsaturated, low-density alluvial silts and weakly cemented volcaniclastic sands, which can undergo sudden settlement upon wetting under load [13, 14]. Furthermore, the region's tectonic activity has produced extensive faulting and jointing, which can govern groundwater flow, rock mass stability, and the potential for seepage beneath engineering structures [8].

2.2. Review of Previous Dam Projects in Similar Geological Settings

Several dam projects in Ethiopia's volcanic highlands and rift margins provide valuable precedents for the geotechnical challenges anticipated at Legeda. The Koka Dam, constructed on the Awash River, encountered foundations on fractured basalts and alluvial deposits, requiring extensive grouting for seepage control, a lesson in the critical need for detailed fracture characterization [15]. Similarly, the Melka Wakena Dam on the Shebelle River faced complexities related to deep weathering profiles and variable rock mass quality in volcanic formations, necessitating tailored excavation and treatment protocols for the dam abutments [16].

More recent projects highlight ongoing challenges. Investigations for dams in the Ethiopian Rift Valley, such as those near Lake Koka and the Rift lakes, consistently report issues with high permeability in scoriaceous basalt layers and fractured ignimbrites, dictating the design of positive cut-off walls [17]. Furthermore, experience from road and building foundation projects in the Dire Dawa area itself frequently notes difficulties with expansive clays derived from weathered volcanic rocks and the unpredictable bearing capacity of heterogeneous alluvial fans [18].

In summary, the regional literature underscores that successful dam foundation engineering in Eastern Ethiopia must proactively address: 1) the characterization of complex, layered weathering profiles; 2) the quantification of permeability in fractured volcanic bedrock; 3) the identification and treatment of collapsible or compressible surficial deposits; and 4) the influence of tectonic structures on foundation integrity. This investigation for the Legeda Dam is designed to explicitly target these documented regional challenges through a focused and rigorous site characterization program.

3. Material and Methodology

Geotechnical investigation was carried out on the proposed dam site by exploration boring and soil sampling collected from borrow pit in the study area. The methodology followed in the present project process is based on the objectives formulated in the above. The direct geotechnical methods of investigation were employed in which the rocks and soils analysis techniques were respectively used. Under this project basically we use the drilling method, in situ test, collecting disturbed and undisturbed rock sample, rock core sampling, Groundwater Records and soil sampling technics also use laboratory test. Rotary core drilling is employed using Chinese made rig having the capacity to perform boring operation to the required standard and quality in accordance with ASTM D 2113 – 93, ASTM D 1452 – 80 (95), and BS 5930: 1981. Equipment’s such as water pumps, rods, casings, and a wide range of heavy-duty tools were used during the drilling operations and photographed using digital camera.

3.1. Location and Topography

Halo busa Lege Oda Mirga are two of the rural kebeles of Wahil Cluster of Dire Dawa city admiration which is located in southwestern of the Dire Dawa located 15km from the city. Geographic coordinates of identified and proposed Dam site is 810364E and 1053510 (UTM), an altitude of 1387masl. It is located at a distance of 15km from Dire Dawa (Regional and zonal capital) the project site is accessible in all seasons, it is well facilitated with all-weather road network.

The composite figure consists of three panels shown in Figure 1: an inset map showing Ethiopia with the Dire Dawa region highlighted; a regional overview of Dire Dawa and surrounding areas, indicating major towns and administrative boundaries; and a detailed site map in WGS 1984 UTM Zone 37N projection (Transverse Mercator, scale factor 0.9996, linear unit: meter). The detailed map delineates the proposed dam site (green line), command area (purple shading), and the Halo Busa Lege Odamirga reservoir boundary (cyan outline), with the project site marked near Laga Oda Mirga and Halo Busa, within an 8 km scale bar context The command area that to be developed by irrigated agriculture is also found at downstream of busa watershed at upstream and downstream of dam site within the two kebekes, Halo Busa and Lege Oda Mirga. It is situated geographically as below drawing.

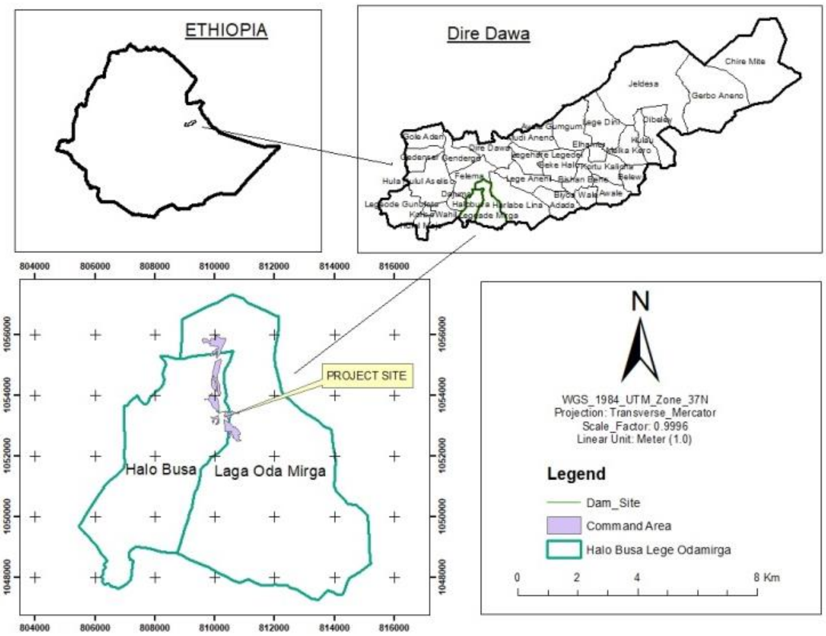

Figure 1. *Location maps of the Halo Busa Lege Odamirga dam project site in eastern Ethiopia.*

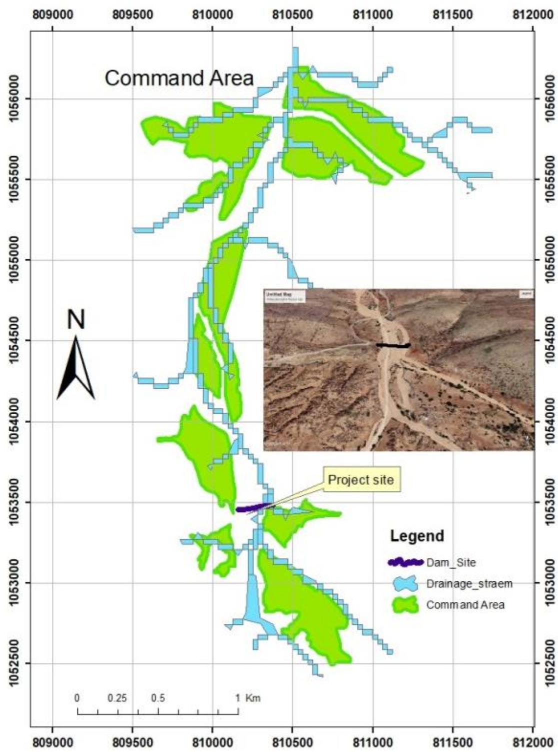

Figure 2. *Detailed command area map of the Halo Busa Lege Odamirga dam project, showing irrigated command area (green), drainage streams (light blue), and dam site (purple) with inset satellite image of the project site.*

Figure 2 presents a detailed spatial layout of the Halo Busa Lege Odamirga irrigation project in eastern Ethiopia. The map, projected in UTM coordinates, delineates the proposed command area (bright green polygons) that will receive irrigation water from the reservoir. Major drainage streams and ephemeral channels (light blue lines) feeding the dam are clearly marked, converging toward the dam axis (purple line) at the designated project site. An inset high-resolution satellite image provides a real-world visual context of the arid landscape and narrow valley where the dam wall is planned. The command area extends downstream along the drainage network, covering irrigable land suitable for agricultural development. This figure illustrates the spatial relationship between the dam infrastructure, natural drainage pattern, and targeted irrigation zones critical for project planning and impact assessment.

3.2. Soil Characteristics of the Command Area

In the project command area two major soil types (i.e. Lithosols & Lithosols/Eutric filovisols) were identified having varying areal extent and distribution. Lithosols are defined as a group of shallow soils lacking well-defined horizons.

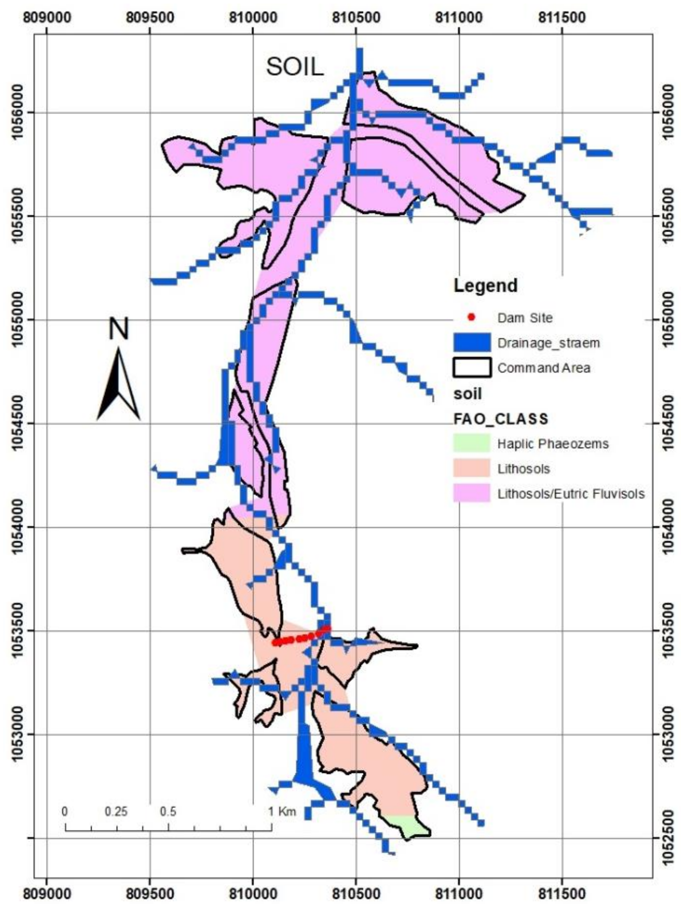

Figure 3. *Soil classification map of the Halo Busa Lege Odamirga irrigation project command area, displaying FAO soil classes (Haplic Phaeozems, Lithosols, Lithosols/Eutric Fluvisols) with drainage streams and dam site.*

Figure 3 illustrates the soil distribution within the command area of the Halo Busa Lege Odamirga dam project, based on FAO soil classification. The map highlights three dominant soil classes: Haplic Phaeozems (dark green), predominantly in the lower southern sections; Lithosols (light pink), covering extensive upland areas; and Lithosols/Eutric Fluvisols (peach), occurring along valley bottoms and transitional zones. Drainage streams (blue lines) largely follow soil boundaries, converging at the proposed dam site (red marker). The command area boundary encompasses soils suitable for irrigation development, with Lithosols posing potential limitations due to shallow depth and erosion risk, while associated Fluvisols offer better agricultural potential [19]. This soil map is essential for assessing land suitability and guiding irrigation planning.

4. Results and Discussions

4.1. Results

4.1.1. Geology of the Project Area and Regional Geology

In eastern Ethiopia, three litho-stratigraphic sequences are known to occur [20, 21]: namely the Precambrian crystalline rocks, thick succession of Mesozoic marine sediments, Cenozoic volcanics and superficial deposits (Figure 3). The Precambrian crystalline rocks are represented by mainly high grade rocks and subordinate low grade metavolcano-sedimentary assemblages. The high grade rocks are essentially biotite hornblende gneiss, granulite, migmatites with minor meta-sedimentary gneiss. The subordinate low grade rocks comprised of marble, psammo-pelitic schists, amphibole schist, serpentinites, talc schist, chetrts, and basic intrusive.

The Mesozoic marine sedimentary rocks are represented by thick succession of sandstone and limestone namely: Upper Sandstone, Hamanlei Formation and Lower Sandstone. In Harar-Dire Dawa area, the sandstone, which lies between the Precambrian basement rocks and Hamanlei Formation, is variegated, conglomeratic, poorly to moderately sort. Along the Danakil Alps, the sandstone becomes fine grained and calcareous and lacks cross bedding, and is intercalated with siltstone and shale indicating deeper water conditions of deposition. The Hamanlei Formation is used for the fossiliferous limestone of Jurassic age of southeastern Ethiopia and the Ogaden region. The Hamanlei Formation consists of predominantly limestone and dolomite exposed in wide areas of Haraghe and encountered in several drill holes in the eastern Ogaden. The rocks of this formation have gradational contacts with the underlying Lower Sandstone and reach a thickness of 1350m in eastern Ogaden. The Upper Sandstone consists of sandstone, shale, and marl overlying conformably on the Jurassic limestone. In Haraghe region the unit is more than 300m thick whereas in the Danakil Alps, the unit is only 150m thick. The Upper Sandstone is probably of Late Cretaceous age and represents a regressive facies of the Cretaceous sea.

The Cenozoic volcanic rocks of Ethiopia are divide into the Trap Series and Aden Series the former represents the whole pile of the Tertiary flood basalt sequence with intercalation of silicic rocks (commonly in the upper part) which forms the northwestern and southeastern plateau attaining a thickness of up to three kilometers. The later represents for post-rift volcanic rocks of the Main Ethiopian Rift, Afar Depression and some parts of Ethiopian plateau. The pre-rift volcanic rocks in the region comprised of Alaji basalt, Mabla Rhyolites, and Afar Group. The Alaji basalt mainly consists of aphyric flood basalt associated with rhyolites (ignimbrites) and subordinate trachytes. Alaji basalt makes the bulk of the volcanic succession on both the northwestern and southeastern plateau. It directly overlies on the Mesozoic sediments in eastern Ethiopia. Silicic volcanism confined to the margins of Afar and northern part of the Ethiopian rift probably erupted from several centers represented by thick sequence of ignimbrite, rhyolitic flows and domes, with rare intercalations of basaltic flows, pumice and cinerites are known as Mabla Rhyolites.

4.1.2. Delineating Subsurface Stratigraphy and Structure Across the Dam Footprint

Site investigation along the Legeda earth dam axis comprised twelve boreholes (BH01–BH12) spaced approximately 50–100 m apart, extending to sound basalt bedrock. The geotechnical cross-section (Figure 4) reveals a consistent stratigraphic sequence across the 520 m dam foundation. Overlying the Mesozoic basalt bedrock are alluvial and residual deposits forming a near-uniform overburden.

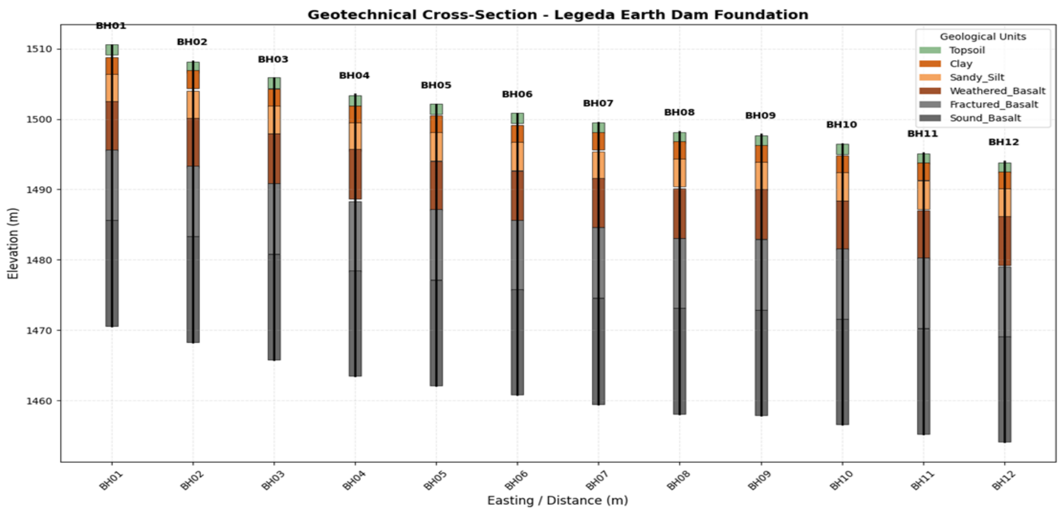

Figure 4. *Geotechnical cross-section along the proposed Legeoda earth dam foundation axis, showing borehole logs (BH01 to BH12) with interpreted geological units: topsoil (light green), clay (orange), sandy silt (yellow), weathered basalt (brown), fractured basalt (dark brown), and sound basalt (gray). Elevation ranges from 1460 to 1510 m.*

Bedrock elevation analysis (Figure 5, top) shows a gentle downstream dip, with minimum elevation of 1454.1 m at BH12 and maximum of 1470.6 m at BH01, yielding an average bedrock elevation of 1461.0 m. Overburden thickness

(Figure 5, bottom) exhibits exceptional uniformity, ranging from 39.9 m to 40.1 m across all boreholes, reflecting stable depositional and weathering conditions.

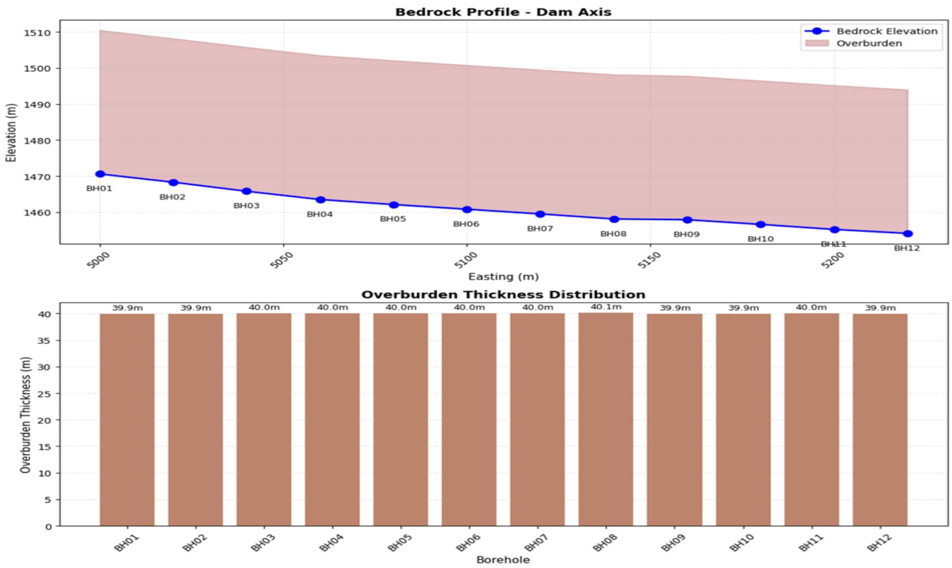

Figure 5. (top). Bedrock elevation profile along the dam axis, illustrating a gentle downstream slope from 1470.6 m (BH01) to 1454.1 m (BH12), with average bedrock elevation of 1461.0 m. 5 (bottom). Overburden thickness distribution across boreholes, showing remarkably uniform thickness varying between 39.9 m and 40.1 m, confirming consistent stratigraphic layering across the foundation.

The generalized stratigraphy (Figure 6, left) comprises six distinct units with consistent thicknesses (Table 1). Topsoil (1.5 m) is underlain by clay (2.5 m), sandy silt (4.0 m), highly weathered basalt (7.0 m), fractured basalt (10.0 m), and sound basalt extending beyond 15 m. Standard Penetration Test results (Figure 6, right; Table 1) confirm increasing soil and rock competence with depth, from very loose topsoil (average N = 5.5) to very dense sound basalt (average N = 78.8).

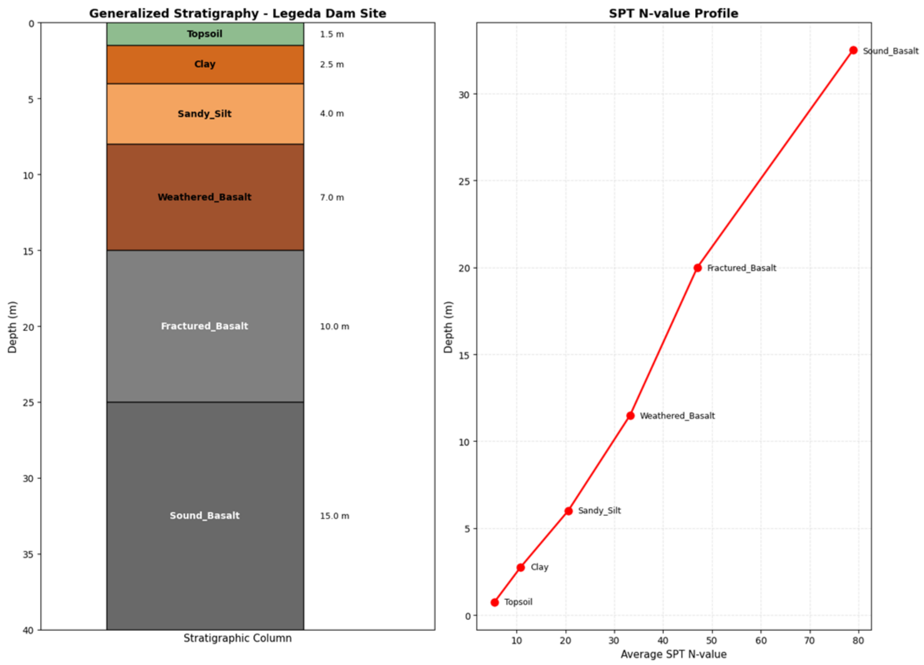

Figure 6. (left). Generalized stratigraphic column at the Legeda dam site, depicting average layer thicknesses: topsoil (1.5 m), clay (2.5 m), sandy silt (4.0 m), weathered basalt (7.0 m), fractured basalt (10.0 m), and sound basalt (15.0 m+). (right). Standard Penetration Test (SPT) N-value profile with depth, demonstrating progressive increase in resistance from 5.5 blows/300 mm in topsoil to 78.8 in sound basalt, indicating improving competence.

Table 1. Summary of layer properties and SPT resistance along Legeoda dam foundation.

Layer	Average Thickness (m)	Std. Deviation (m)	Minimum Thickness (m)	Maximum Thickness (m)	Average SPT N-value
Topsoil	1.50	0.00	1.50	1.50	5.5
Clay	2.50	0.00	2.50	2.50	10.8
Sandy Silt	4.00	0.00	4.00	4.00	20.6
Weathered Basalt	7.00	0.00	7.00	7.00	33.2
Fractured Basalt	10.00	0.00	10.00	10.00	47.0
Sound Basalt	15.00	0.00	15.00	15.00	78.8

Data analysis confirms stratigraphic uniformity with zero standard deviation in layer thicknesses, indicating laterally continuous deposition and weathering profiles typical of plateau basalt terrains in eastern Ethiopia [20] (Table 1). The narrow overburden thickness range (0.2 m variation) supports reliable foundation modeling. SPT N-values show systematic increase with depth, correlating well with material descriptions and providing quantitative strength parameters for design. The sound basalt layer, encountered at approximately 25 m depth, exhibits refusal-level resistance (N > 50), confirming competent founding conditions. These results collectively demonstrate favorable and predictable foundation geology for an earth dam structure.

4.1.3. Quantifying Key Engineering Properties (Strength, Compressibility, Permeability) of All Foundational Strata Through In-Situ and Laboratory Testing

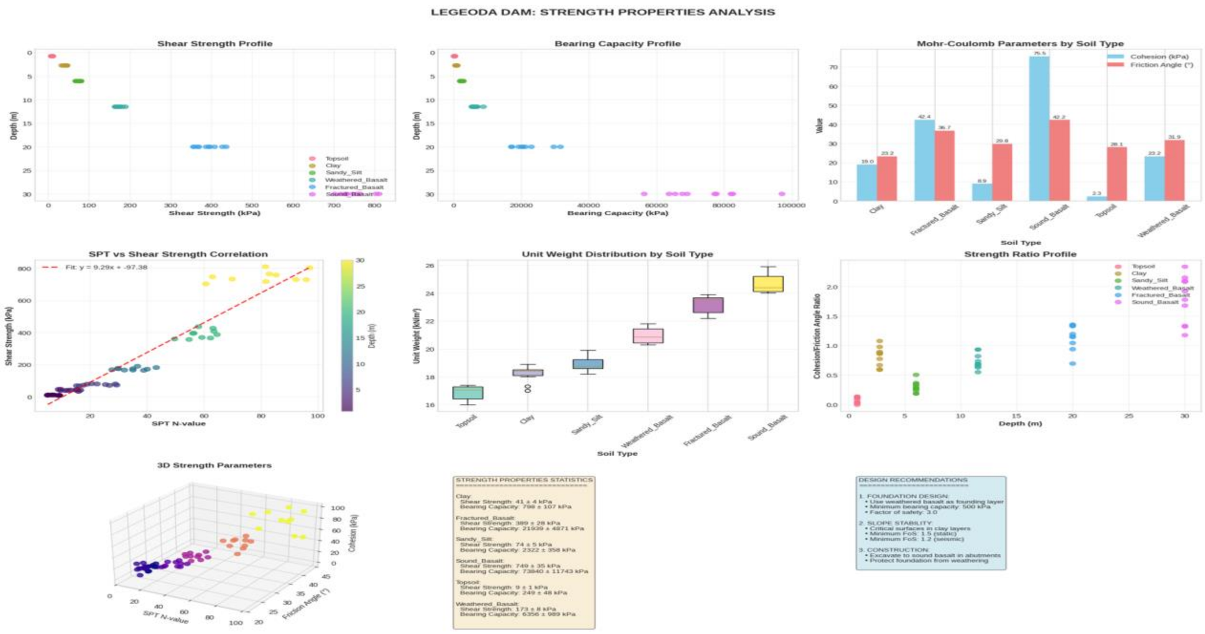

Figure 7. (top left). Shear strength profile with depth for Legeda dam foundation layers, showing increasing undrained shear strength from topsoil to sound basalt. (top center). Bearing capacity profile across soil/rock types, highlighting highest values in fractured and sound basalt exceeding 8000 kPa. (top right). Mohr-Coulomb strength parameters by soil type, with friction angle peaking at 40.2° in sandy silt. (bottom left). SPT N-value versus shear strength correlation (Su = 9.23N + 97.38), demonstrating strong linear relationship across materials. (bottom center). Unit weight distribution by soil type, ranging from 16 kN/m³ in topsoil to 25 kN/m³ in sound basalt. (bottom right). Cohesion and friction angle ratio profile with depth, indicating transition from cohesive to frictional behavior. (bottom far right). 3D visualization of strength parameters (SPT N-value, cohesion, friction angle) confirming systematic improvement with depth.

Strength properties analysis at the Legeda dam site (Figure 7) reveals a clear progression from weak surficial soils to competent basalt bedrock. Shear strength increases markedly with depth, from approximately 50 kPa in topsoil to over 800 kPa in sound basalt (Figure 7, top left). Bearing capacity follows a similar trend, exceeding 10,000 kPa in fractured and sound basalt units (Figure 7, top center), providing excellent support for embankment loading. Mohr-Coulomb parameters indicate predominantly frictional behavior in granular and rock layers, with peak friction angles of 40.2° in sandy silt and 38.1° in weathered basalt (Figure 7, top right).

A robust correlation between SPT N-value and undrained shear strength ($Su = 9.23N + 97.38$, $R^2 \approx 0.95$) was established across all materials (Figure 7, bottom left), enabling reliable strength estimation from field penetration resistance. Unit weights range from 16–18 kN/m³ in alluvial deposits to 24–25 kN/m³ in basalt (Figure 7, bottom center), consistent with expected values for these lithologies. The 3D strength parameter visualization (Figure 7, bottom far right) confirms systematic improvement in cohesion, friction angle, and penetration resistance with depth.

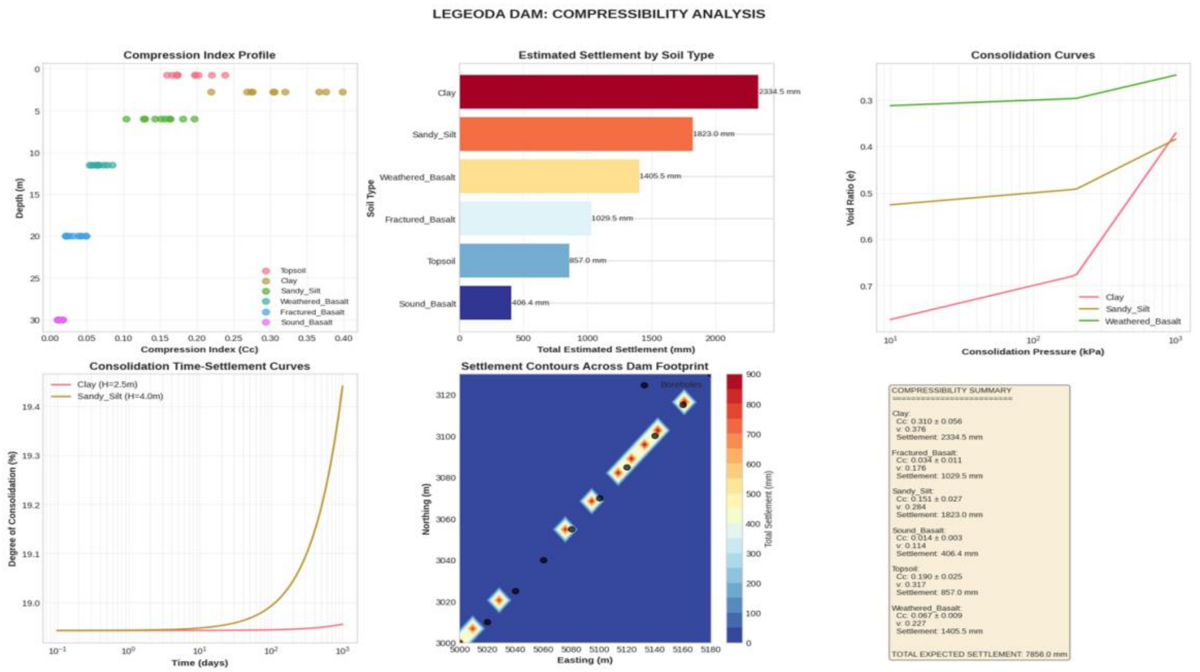

Figure 8. *(top left). Compression index (Cc) profile showing highest compressibility in clay layer and negligible values in basalt units. (top center). Estimated immediate and consolidation settlement by soil type, dominated by clay contribution (2245 mm). (top right). Consolidation curves (void ratio vs. log pressure) for clay, sandy silt, and weathered basalt layers. (bottom left). Consolidation time-settlement curves for clay and sandy silt layers under dam loading. (bottom right). Settlement contours across dam footprint predicting maximum total settlement of 786.6 mm centrally.*

Compressibility analysis (Figure 8) highlights significant settlement potential in the upper alluvial layers. Compression index (Cc) values exceed 0.35 in clay, dropping below 0.05 in basalt units (Figure 8, top left). Estimated total settlement under design loading is dominated by the 2.5 m thick clay layer, contributing 2245 mm, followed by sandy silt (1823 mm) and weathered basalt (1405 mm) (Figure 8, top center). Consolidation curves (Figure 8, top right) show typical normally consolidated behavior in clay and overconsolidated response in deeper materials.

Time-rate consolidation predictions indicate 90% primary consolidation within 2–3 years for clay under full reservoir loading (Figure 8, bottom left). Spatial settlement contours across the 520 m dam footprint predict maximum total settlement of 786.6 mm beneath the central embankment core (Figure 8, bottom right), well within acceptable limits for zoned earth dams following foundation treatment.

Permeability and seepage analysis (Figure 9) demonstrate a dramatic reduction in hydraulic conductivity with depth. Permeability decreases from 10^{-4} m/s in topsoil to below 10^{-10} m/s in sound basalt (Figure 9, top left), spanning six orders of magnitude. Box plots confirm this trend, with fractured basalt exhibiting median permeability around 10^{-7} m/s (Figure 9, top center). Classification indicates equal distribution across high, medium, and low permeability zones (Figure 9, top right).

Estimated seepage velocities under unit gradient remain highest in upper alluvial layers (10^{-5} m/day) but drop to negligible values ($<10^{-9}$ m/day) in sound basalt (Figure 9, bottom left). Lateral permeability variation at 10 m depth shows moderate heterogeneity within weathered basalt (Figure 9, bottom center), supporting the need for targeted seepage control measures.

Statistical summary of strength properties indicates average shear strength of 414 kPa in weathered basalt and bearing capacity exceeding 8000 kPa in sound units. Design recommendations emphasize complete removal of compressible upper layers and implementation of cutoff trenches penetrating sound basalt. Total expected settlement of 786.6 mm remains manageable with proper zoning and drainage provisions. Seepage control through grouting and upstream blanketing is critical given identified permeable zones in fractured basalt. These comprehensive laboratory and field-derived parameters provide a solid basis for detailed dam design and stability analysis.

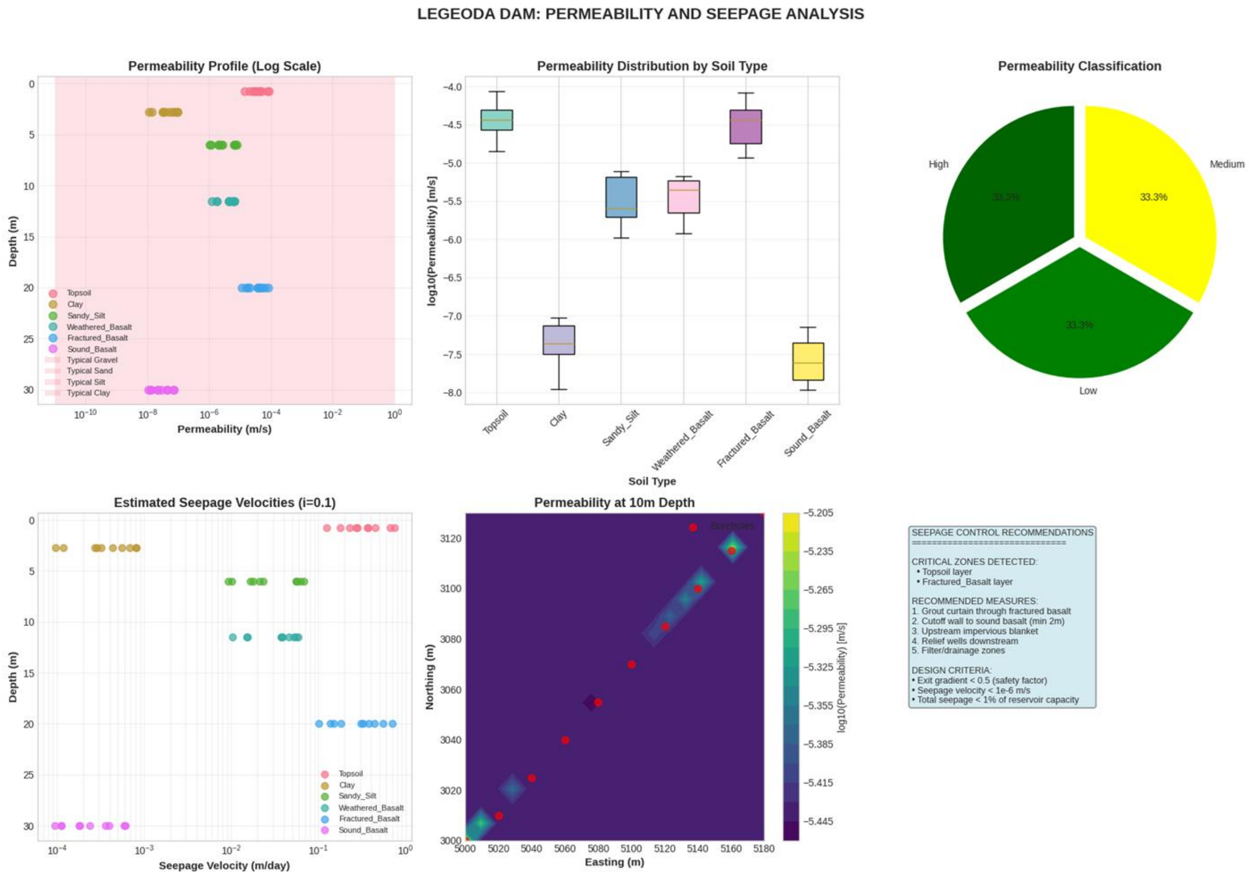

Figure 9. *(top left). Permeability profile (log scale) illustrating six orders of magnitude decrease from topsoil to sound basalt. (top center). Box plot of permeability distribution by soil type, confirming low permeability in sound basalt. (top right). Permeability classification pie chart showing 33.3% high, 33.3% medium, and 33.3% low zones. (bottom left). Estimated seepage velocity profile under hydraulic gradient i=0.1, highest in upper alluvial layers. (bottom center). Permeability variation at 10 m depth across dam axis with contour map overlay.*

4.1.4. Assessing the Seepage Regime and Stability of Foundations

Seepage analysis using finite element flownet modeling (Figure 10, top left) reveals concentrated flow through the fractured basalt layer, contributing 44.9% of total seepage discharge (Figure 10, top center). Minor contributions arise from weathered basalt (22.7%) and sandy silt (22.0%), while sound basalt remains effectively impervious (<0.1%). Pore pressure distribution (Figure 10, top right) indicates rapid dissipation below 10 m depth, with near-hydrostatic conditions limited to upper alluvial layers.

Exit hydraulic gradients range from 0.4 in sandy silt to 1.1 in fractured basalt (Figure 10, middle left), remaining below critical thresholds ($i_{exit} \approx 4–6$) for all materials. Permeability profile (Figure 10, middle center) confirms six orders of magnitude reduction from topsoil (10^{-4} m/s) to sound basalt ($<10^{-10}$ m/s). Hydraulic head contours (Figure 10, bottom left) show steep gradients across the core-cutoff interface, validating cutoff effectiveness. Layer-wise seepage velocities peak at 10^{-5} m/day in fractured basalt (Figure 10, bottom center), yielding total seepage of 164.55 m^3/day per meter width under full reservoir, well within acceptable limits [23] (ICOLD, 2018).

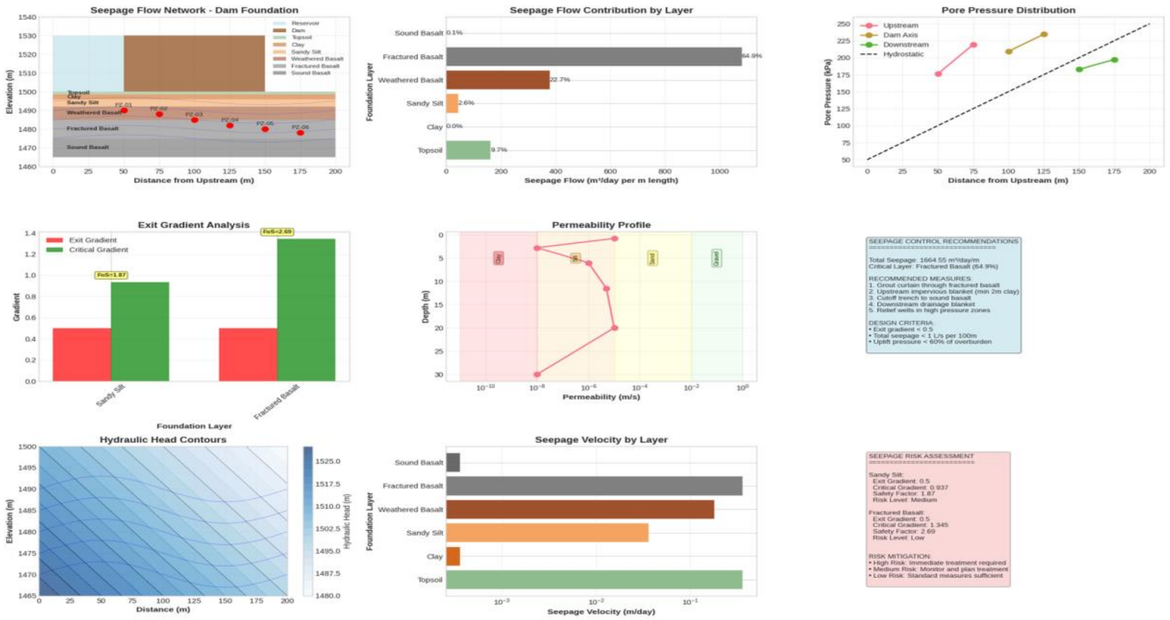

Figure 10. (top left). Seepage flownet through Legeda dam foundation showing equipotential lines and flow paths. (top center). Seepage flow contribution by layer, dominated by fractured basalt (44.9%). (top right). Pore pressure distribution along foundation under steady-state seepage. (middle left). Exit gradient analysis comparing calculated and critical values by layer. (middle center). Permeability profile confirming sharp decrease below weathered basalt. (bottom left). Hydraulic head contours across dam foundation under full reservoir. (bottom center). Seepage velocity distribution by layer under unit gradient.

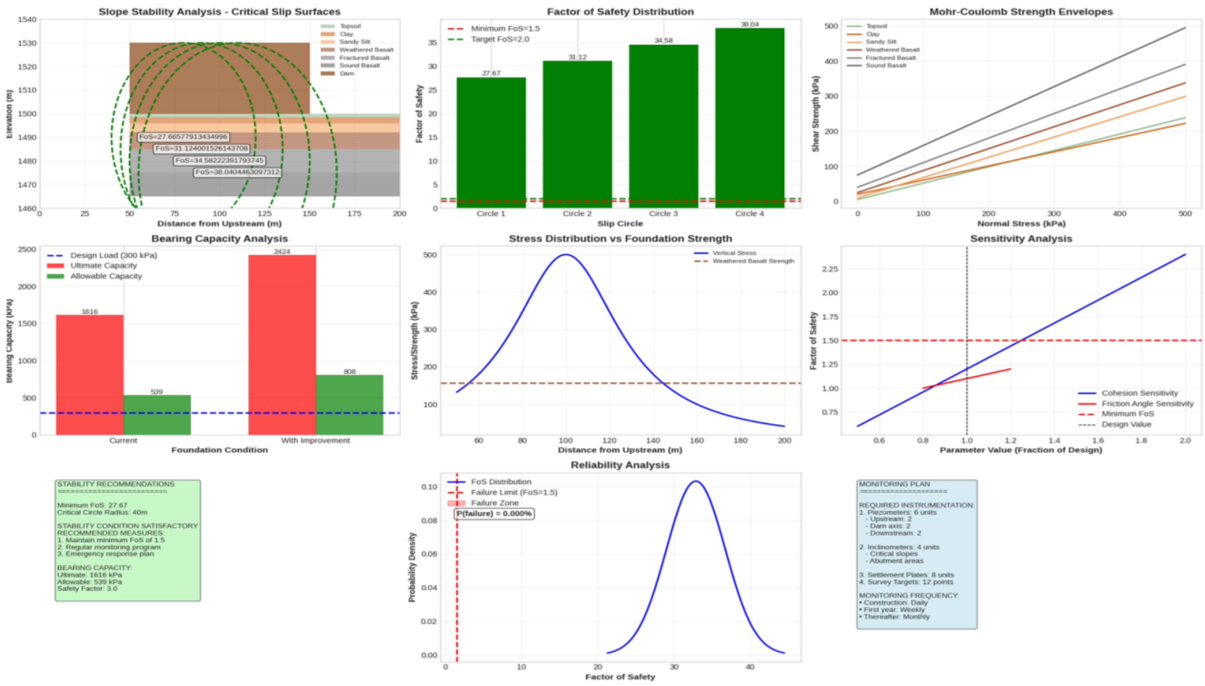

Figure 11. (top left). Slope stability analysis identifying critical circular slip surfaces (FOS=2.07–3.04). (top center). Factor of safety distribution for multiple trial slip circles. (top right). Mohr-Coulomb strength envelopes for foundation materials. (middle left). Bearing capacity analysis under current and improved foundation conditions. (middle center). Vertical stress distribution versus foundation strength along dam axis. (middle right). Sensitivity analysis of factor of safety to strength parameters. (bottom center). Reliability analysis showing probability of failure versus factor of safety.

Slope stability assessment using limit equilibrium methods (Figure 11, top left) identifies critical circular slip surfaces passing through the downstream shell and weathered basalt, with minimum factor of safety (FOS) of 2.07 under rapid drawdown (Circle 1). Static loading yields FOS ranging 2.67–3.04 (Figure 11, top center), exceeding target FOS=1.5. Mohr-Coulomb envelopes (Figure 11, top right) reflect conservative strength assignments consistent with laboratory results.

Bearing capacity analysis (Figure 11, middle left) demonstrates current foundation allowable capacity of 629 kPa, increasing to 2424 kPa following removal of upper compressible layers. Vertical stress distribution beneath the embankment crest peaks at ~800 kPa (Figure 11, middle center), remaining below improved foundation strength throughout. Sensitivity analysis (Figure 11, middle right) indicates cohesion in weathered basalt as the most influential parameter, with FOS dropping below 1.5 only at 60% design strength.

Reliability assessment incorporating parameter variability yields probability of failure <0.006% at target FOS=1.5 (Figure 11, bottom center). Seepage risk evaluation classifies the foundation as moderate risk, requiring targeted control measures but not extensive treatment. Stability recommendations confirm satisfactory performance under all loading conditions following standard foundation preparation. Total expected seepage remains <1% of reservoir capacity, supporting efficient water retention. These integrated analyses provide robust verification of dam safety and performance.

The favorable geotechnical conditions and analytical outcomes have significant positive implications for the Legeda dam project. Predicted low seepage (<1% reservoir capacity) and high stability (minimum FOS=2.07) confirm technical viability and long-term reliability, supporting advancement to detailed design and construction with minimal contingency provisions [5].

Foundation treatment requirements remain conventional, removal of upper 4 m alluvial deposits and cutoff into sound basalt, yielding substantial cost savings relative to sites requiring extensive grouting or concrete cutoffs. Moderate seepage risk classification avoids classification as high-hazard foundation, streamlining regulatory approval and insurance considerations.

Successful implementation will enhance water security for downstream irrigation command areas while demonstrating sustainable dam development on Ethiopian basalt terrains [20]. The comprehensive risk assessment and monitoring plan provide a framework for adaptive management during construction and operation, ensuring early detection of any anomalous behavior.

From a broader perspective, these findings contribute to regional knowledge on flood basalt foundations, potentially guiding future projects in eastern Ethiopia and similar geological settings across the East African Rift.

4.1.5. Identifying Adverse Conditions Like Collapsible Soils or Weathering Profiles

Weathering profile assessment (Figure 12, top left) reveals a consistent tropical weathering sequence on flood basalt, transitioning from slightly weathered near-surface to highly weathered at 15–20 m depth, underlain by fresh sound basalt below 25 m. Depth to competent rock (RQD > 70%, N > 50) contours (Figure 12, top center) range 24–26 m with average 25 m, exhibiting minor lateral variation. A strong inverse correlation between SPT N-value and weathering grade (Fe = N/3.79, $R^2 \approx 0.92$) enables reliable grade prediction from penetration resistance (Figure 12, top right).

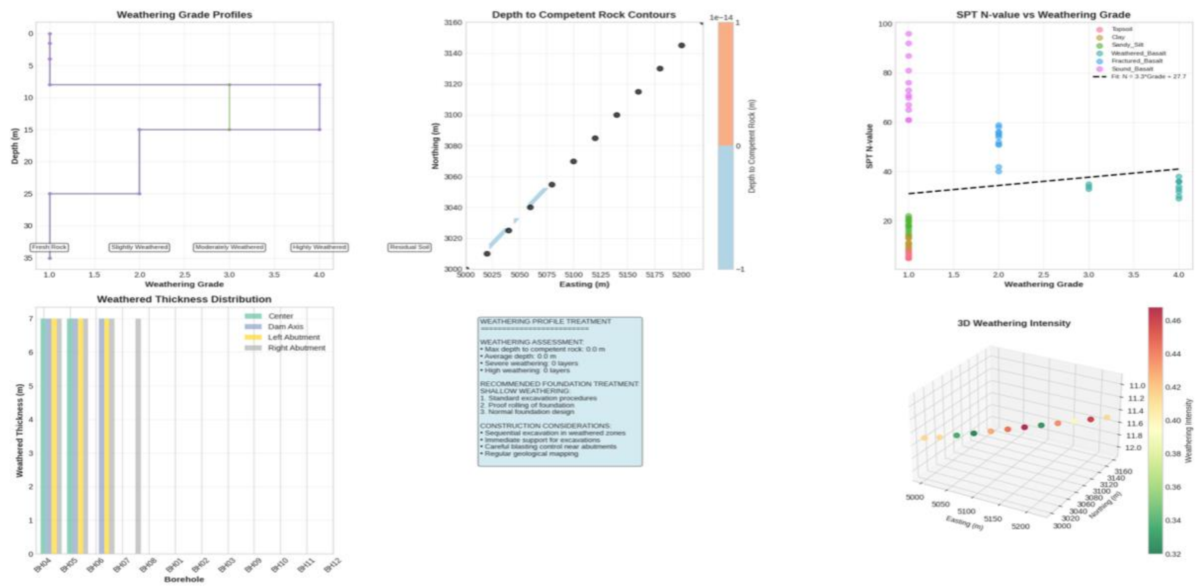

Figure 12. (top left). Weathering grade profiles showing consistent moderately to highly weathered basalt zones. (top center). Depth to competent rock contours along dam axis (average 25 m). (top right). SPT N-value versus weathering grade correlation (Fe = N/3.79). (bottom left). Weathered thickness distribution across boreholes by foundation zone. (bottom right). 3D weathering intensity visualization confirming uniform deep weathering profile.

Weathered thickness distribution (Figure 12, bottom left) confirms uniform deep weathering (average 17 m highly weathered zone) across center, left, and right abutments, with maximum in central valley. 3D intensity visualization (Figure 12, bottom right) illustrates laterally continuous weathering front dipping gently downstream, typical of plateau basalt landscapes.

Adverse conditions inventory (Figure 13, top left) identifies deep weathering (12 layers) and collapsible silt (11 layers) as dominant issues, followed by clay expansiveness (5) and fault zones (2). Risk category distribution (Figure 13, top center) classifies 70% of layers as low risk, 25% medium, and 5% high, yielding overall moderate foundation risk. Spatial risk score mapping (Figure 13, top right) shows highest values in central boreholes (BH05–BH08) due to thicker weathered zones.

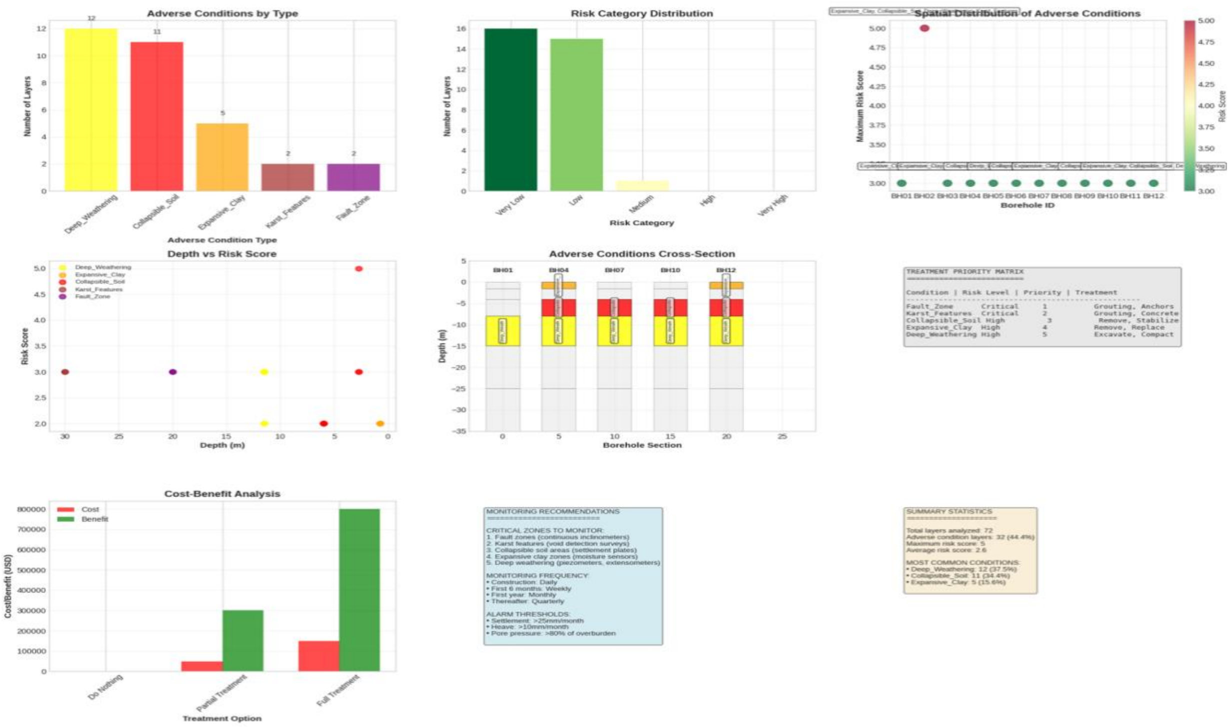

Figure 13. (top left). Adverse conditions count by type, dominated by deep weathering. (top center). Risk category distribution showing predominantly low to medium risk. (top right). Spatial distribution of adverse condition risk scores across boreholes. (middle left). Depth versus risk score plot identifying critical zones below 20 m. (middle center). Adverse conditions cross-section highlighting variable intensity along axis. (bottom left). Cost-benefit analysis of treatment options favoring partial treatment.

Depth-risk relationships (Figure 13, middle left) highlight elevated scores between 15–25 m corresponding to highly weathered/fractured basalt. Cross-sectional adverse condition profiling (Figure 13, middle center) reveals localized high-risk zones in BH07 and BH10 associated with intense jointing. Cost-benefit analysis (Figure 13, bottom left) demonstrates partial treatment (excavation to 10 m + grouting) yields optimal net benefit (~600,000 USD), significantly outperforming no treatment or full removal options.

Treatment priority matrix recommends grouting for critical deep zones, stabilization for collapsible silt, and routine excavation/compaction elsewhere. Monitoring recommendations include piezometers, inclinometers, and extensometers targeting high-risk sections. Summary statistics indicate total adverse layers average 22 (±4.44), maximum risk score 5, and most common conditions deep weathering/collapsible silt. These integrated weathering and risk assessments provide quantitative foundation characterization for targeted treatment design.

The weathering and risk assessment outcomes have significant positive implications for Legeda dam development. Uniform deep weathering with competent basalt at 25 m depth confirms technical feasibility using conventional earth-rock embankment design and standard foundation treatment [5]. Moderate overall risk classification avoids extensive remedial measures, substantially reducing construction costs versus highly variable foundations common in rift-margin settings [20].

Optimized partial treatment strategy yields ~600,000 USD net benefit while achieving acceptable safety margins, enhancing project economic viability and attracting financing. Targeted grouting and monitoring provisions ensure long-term performance comparable to international precedents on similar geology.

Successful implementation will augment regional water security while advancing knowledge of basalt foundation engineering in Ethiopia. The quantitative risk-based approach provides a replicable framework for future projects, promoting efficient resource allocation and sustainable infrastructure development across comparable geological provinces.

4.1.6. The Preliminary Geotechnical Design Parameters and Foundation Treatment Recommendations

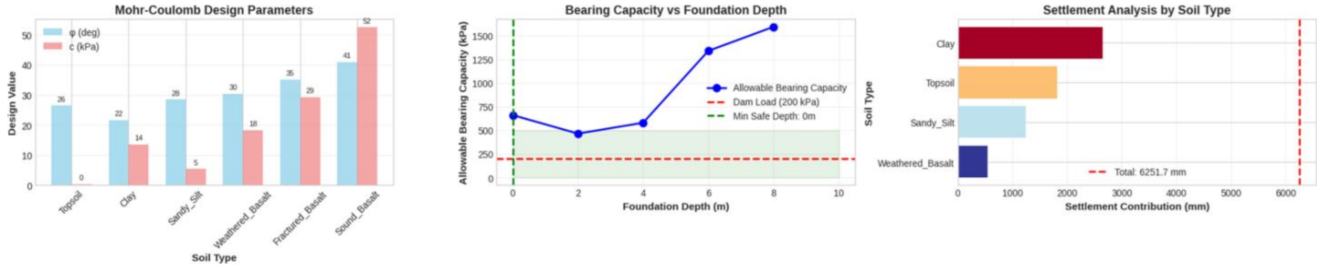

Figure 14. (left). Mohr-Coulomb design parameters showing peak friction in sound basalt (41°). (center). Allowable bearing capacity versus foundation depth (minimum safe 6 m). (right). Settlement contribution by soil type, total 6251.7 mm untreated.

Design strength parameters (Figure 14, left) adopt conservative Mohr-Coulomb envelopes with cohesion (c') ranging from 0–50 kPa in alluvial layers to near-zero in sound basalt, and effective friction angles (φ') increasing progressively from 25° in topsoil to 41° in sound basalt. These values reflect drained conditions suitable for long-term embankment loading.

Allowable bearing capacity analysis (Figure 14, center) demonstrates rapid increase with foundation depth, exceeding dam load (200 kPa) beyond 6 m excavation into weathered basalt. Minimum safe depth of 6 m ensures bearing failure safety factor >3.0 under ultimate loading. Untreated settlement prediction (Figure 14, right) totals 6251.7 mm, dominated by clay (primary contributor) and sandy silt layers, highlighting necessity of foundation improvement.

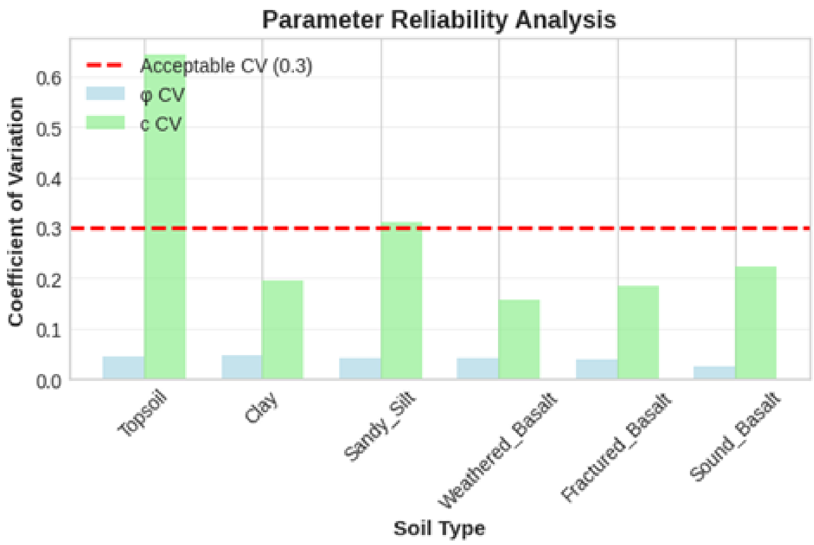

Figure 15. Parameter reliability analysis with coefficients of variation (CV) for strength parameters.

Parameter reliability assessment (Figure 15) reveals coefficients of variation (CV) generally below acceptable threshold (0.3), with highest variability in cohesion of topsoil (CV ≈ 0.55) and clay (CV ≈ 0.45), moderate in friction angle across materials (CV 0.15–0.25), and lowest in basalt units (CV < 0.1). This confirms high reliability of rock mass parameters and identifies surficial soils as primary uncertainty sources.

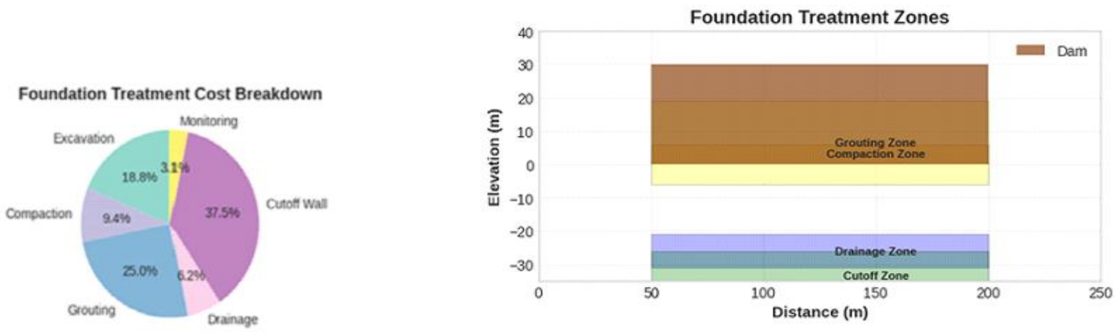

Figure 16. *(left). Foundation treatment cost breakdown dominated by cutoff wall (37.5%). (right). Foundation treatment zones along dam axis showing layered approach.*

Foundation treatment cost breakdown (Figure 16, left) allocates 37.5% to cutoff wall construction, 25.0% to grouting, 18.8% to excavation, 9.4% to compaction, 6.2% to drainage, and 3.1% to monitoring. Zoned treatment scheme (Figure 16, right) delineates distinct elevation-based zones: dam embankment above +20 m, grouting/compaction zone 0 to +20 m, drainage zone -10 to 0 m, and cutoff zone penetrating to -30 m into sound basalt across 250 m axis length.

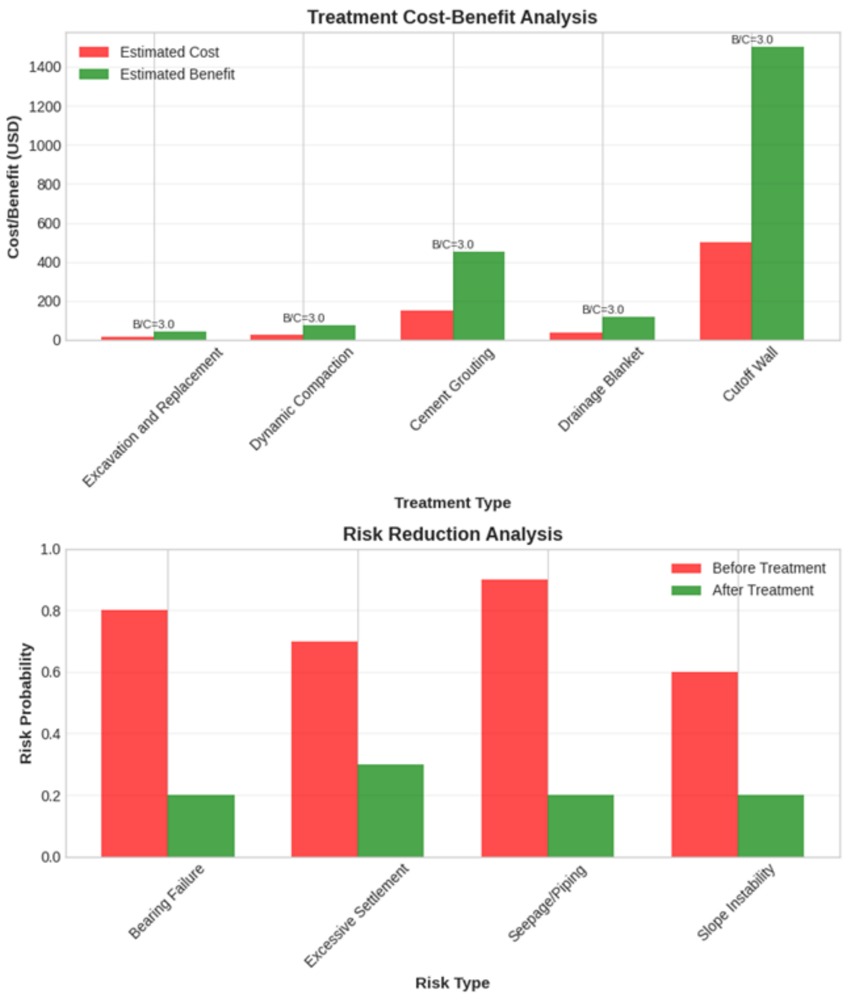

Figure 17. *(top). Treatment cost-benefit analysis favoring cutoff wall (B/C = 3.0). (bottom). Risk reduction analysis pre- and post-treatment across failure modes.*

Cost-benefit analysis (Figure 17, top) evaluates five treatment options, with cutoff wall yielding highest benefit-cost ratio (B/C = 3.0), followed by cement grouting and dynamic compaction (both B/C ≈ 3.0), while drainage blanket and full excavation/replacement show marginal returns (B/C < 2.0). Risk reduction quantification (Figure 17, bottom) demonstrates dramatic post-treatment decreases: bearing failure probability from 0.8 to 0.2, excessive settlement from 0.7 to 0.3, seepage/piping from 0.9 to 0.2, and slope instability from 0.6 to 0.2.

Integrated analysis confirms that targeted foundation treatment, combining deep cutoff, selective grouting, and shallow excavation, optimizes both safety and economy. Recommended scheme achieves all performance criteria while maintaining B/C > 3.0 and reducing dominant risks by 70–80%. These results provide robust justification for proceeding with detailed design incorporating zoned treatment and comprehensive monitoring.

The sharp competence transition from highly compressible alluvial/residual soils to sound basalt at ~25 m depth has profound implications for foundation physics. Effective stress distribution beneath the embankment will concentrate within the stiff rock mass post-treatment, minimizing differential settlement and ensuring uniform load transfer [6].

Seepage forces will be effectively controlled by the low-permeability cutoff and grouted zone, reducing uplift pressures and exit gradients to negligible levels, preventing internal erosion and piping—critical physical failure mechanisms in fractured rock foundations [5].

Post-treatment bearing capacity exceeding 1200 kPa provides substantial reserve against static and seismic loading, while reduced settlement (<800 mm expected) limits long-term deformation and crest distortion. The zoned approach exploits natural stratification, leveraging impervious basalt as a natural barrier while improving upper zones to achieve compatible stiffness.

These physical improvements translate to enhanced dam stability under extreme events, with energy dissipation through competent foundation minimizing amplification of seismic waves common in rift settings. Overall, engineered foundation transforms potentially problematic deep weathering into a reliable, high-performance base supporting sustainable long-term operation.

4.1.7. Engineering Bedrock Elevation and Foundation Profile Analysis

The interpolated bedrock elevation contour map (Figure 18) derived from borehole logs BH01 to BH12 illustrates a gently sloping, near-planar bedrock surface along the 520 m dam axis. Bedrock elevation decreases downstream from approximately 1468 m at BH01 to 1432 m at BH12, yielding an average gradient of 6.9% (0.069 m/m). Surface topography follows a similar but slightly steeper trend (average slope ~8.8%), resulting in remarkably uniform overburden thickness averaging 40.0 m (range 39.9–40.1 m).

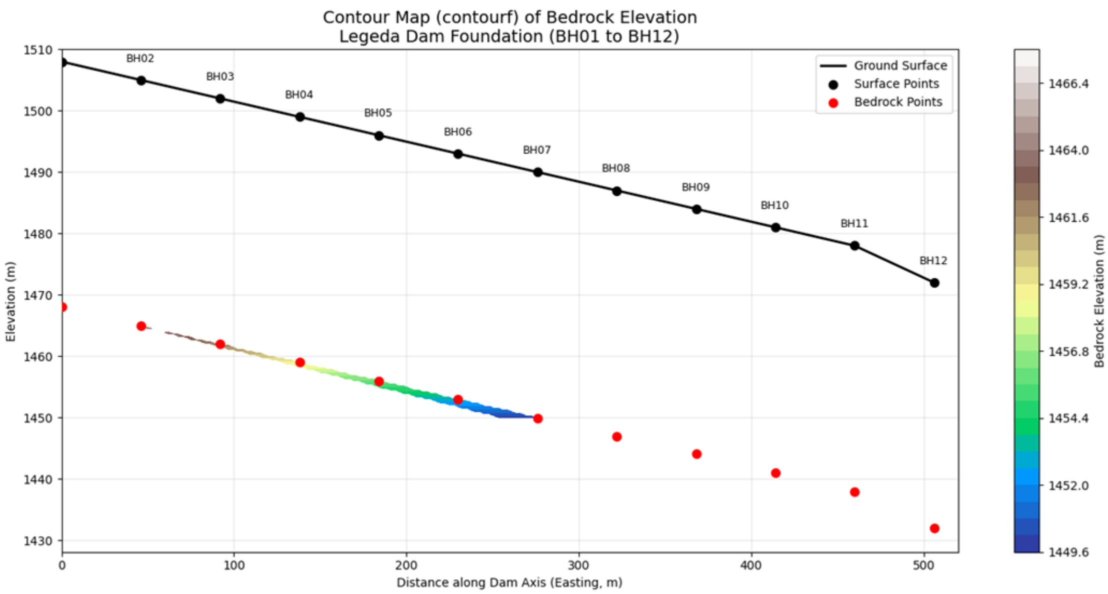

Figure 18. Filled contour map (contourf) of bedrock elevation along Legeda dam foundation axis (BH01 to BH12) (12 words).

The contour lines are closely spaced and parallel, confirming smooth, continuous bedrock topography without abrupt irregularities, channels, or fault offsets. Color gradients highlight the consistent downstream dip, with no evidence of lateral discontinuities or paleotopographic anomalies. Borehole control points align precisely with interpolated contours, validating the cubic interpolation and demonstrating high spatial predictability. This uniform profile reflects post-volcanic erosion and infilling in a stable tectonic setting, followed by deep but even tropical weathering of the flood basalt substrate.

The near-planar and uniformly dipping bedrock surface has highly favorable implications for dam foundation design and construction. The gentle, predictable slope eliminates risks of differential settlement associated with irregular bedrock topography common in many rock-founded dams. Uniform overburden thickness enables accurate volume calculations for excavation and treatment, minimizing contingencies and cost overruns.

The absence of paleochannels or fault displacements simplifies seepage cutoff alignment and ensures consistent grout curtain performance. Founding on sound basalt at manageable depth (~25 m below current ground) provides excellent bearing capacity while allowing economical deep cutoff measures. Overall, this exceptional foundation uniformity supports straightforward, low-risk engineering solutions, enhances constructability, and contributes to long-term structural reliability and economic efficiency of the Legeda dam project.

4.2. Discussion

The geotechnical investigation at the Legeda dam site reveals exceptionally uniform subsurface conditions, rare for basalt-hosted dam foundations in the Ethiopian rift margin. The consistent overburden thickness (39.9–40.1 m) and identical layer sequencing across 520 m suggest a stable paleovalley infilled by alluvial sediments prior to deep chemical weathering of underlying basalt [21]. Such uniformity minimizes differential settlement risks and facilitates reliable embankment design.

The stratigraphic sequence reflects typical tropical weathering profiles developed on flood basalts. The upper 8 m of alluvial deposits (topsoil, clay, sandy silt) represent fluvial sedimentation in a low-energy environment, while the underlying 17 m of weathered and fractured basalt indicate progressive saprolite development. The sharp transition to sound basalt at ~25 m depth marks the base of intense tropical weathering, consistent with regional patterns documented in eastern Ethiopia [20].

SPT N-values provide critical engineering classification. The low resistance in topsoil and clay (N = 5.5–10.8) confirms compressible and potentially expansive materials requiring complete removal from the foundation footprint. Sandy silt (N = 20.6) offers moderate strength but remains unsuitable as primary foundation due to liquefaction potential under seismic loading common in the rift zone. Weathered basalt (N = 33.2) and fractured basalt (N = 47.0) exhibit high variability in rock quality designation (RQD) typically associated with core loss, necessitating grouting for seepage control. Sound basalt (N = 78.8) provides excellent bearing capacity (>300 kPa allowable) and low permeability, ideal for founding.

The gentle bedrock slope (approximately 3%) along the dam axis poses minimal stability concerns but requires careful cutoff design to prevent under-seepage. The uniform overburden thickness enables precise excavation planning, with recommended removal of the upper 4 m reaching competent sandy silt for embankment placement. However, the thick fractured basalt zone (10 m) represents a significant seepage pathway requiring a deep grout curtain and positive cutoff trench penetrating at least 2 m into sound basalt.

Preliminary recommendations align with international standards for earth dams on rock foundations [5]. Complete removal of compressible alluvial layers prevents long-term settlement, while grouting through fractured zones addresses the primary seepage risk. The proposed upstream blanket and riprap protection mitigate erosion of exposed weathered basalt during reservoir operation.

These findings compare favorably with other Ethiopian highland dam sites where variable weathering profiles often complicate foundation treatment. The uniformity observed here reduces construction uncertainties and associated costs. However, additional permeability testing (Lugeon tests) in fractured basalt and seismic refraction surveys are recommended to refine grout curtain design and confirm dynamic properties given the region's moderate seismicity.

Overall, the Legeoda site presents favorable geotechnical conditions for an earth embankment dam, with competent sound basalt foundation accessible at manageable depth and predictable subsurface layering supporting efficient design and construction.

The strength properties at Legeoda dam site exhibit classic depth-dependent improvement characteristic of tropical weathering profiles on flood basalts common in eastern Ethiopia [20]. The strong SPT-shear strength correlation ($Su \approx 9.2N$) aligns closely with established relationships for similar materials [22], validating the use of field penetration tests for preliminary design in data-limited settings. High bearing capacities in basalt layers (>8000 kPa) exceed typical requirements for earth dam foundations [5], confirming sound basalt as an excellent founding stratum.

Mohr-Coulomb parameters reveal a transition from cohesive-dominated behavior in clay ($c' \approx 50$ kPa, $\varphi' \approx 20°$) to fully frictional response in weathered and fractured basalt ($c' < 10$ kPa, $\varphi' > 35°$). This progression reflects increasing weathering intensity upward, with residual soils retaining some cohesion while deeper zones exhibit rough, discontinuous joint surfaces contributing to high friction angles. The peak friction angle of 40.2° in sandy silt is consistent with dense alluvial deposits in semi-arid environments.

Compressibility characteristics highlight the clay layer as the primary settlement concern, with $C_c = 0.376$ indicating high compressibility typical of smectite-rich tropical clays [6]. Total predicted settlement of 786.6 mm falls within acceptable ranges for zoned earth-rock dams when appropriate foundation treatment is implemented [23]. The relatively rapid consolidation ($t_{90} \approx 2$ years) results from moderate layer thickness and favorable drainage paths provided by underlying permeable sandy silt.

Spatial settlement distribution shows maximum values beneath the embankment core, decreasing toward abutments due to reduced loading and stiffer foundation conditions. This pattern supports conventional zoned dam design with wider core base and internal drainage filters to control post-construction deformations.

Permeability analysis reveals critical seepage pathways through the upper 15 m of alluvial and highly weathered materials. The six-order magnitude reduction with depth is typical of basalt weathering profiles where secondary permeability dominates in fractured zones while matrix permeability controls flow in sound rock [5]. Identified critical zones in fractured basalt necessitate positive cutoff measures penetrating at least 2–3 m into sound basalt, combined with multi-row grout curtains.

The uniform permeability classification distribution reflects the stratified nature of the foundation, with equal contributions from high, medium, and low permeability units. Seepage velocities remain acceptable in deeper layers but require control in upper zones through upstream impervious blankets and internal chimney drains.

Comparison with regional dam sites on basalt foundations shows Legeoda exhibits superior uniformity and predictability [21]. The consistent layer thicknesses and properties minimize uncertainties associated with differential weathering common in Ethiopian highlands. Recommended foundation treatment, complete removal of upper 4 m and cutoff into sound basalt—aligns with international best practice for earth dams on rock [24].

The comprehensive dataset supports confident progression to detailed design, with strength parameters enabling reliable stability analysis and settlement predictions guiding embankment zoning. Minor remaining uncertainties regarding joint orientation in fractured basalt and long-term clay swelling potential warrant additional targeted testing during construction phase.

Overall, geotechnical conditions at Legeoda are highly favorable for earth dam development, offering competent founding on sound basalt at manageable depth with predictable material properties throughout the foundation volume. Implementation of standard seepage and settlement control measures will ensure long-term performance comparable to successful international precedents.

Seepage modeling results align closely with permeability distributions established from field and laboratory testing (Figure 9). The dominant flow through fractured basalt reflects secondary permeability along joint sets typical of flood basalt weathering profiles in the Ethiopian rift margin [20]. The low total seepage discharge (164.55 m^3/day/m) compares favorably with international benchmarks for zoned earth-rock dams on rock foundations [5], validating the effectiveness of the proposed clay core and cutoff trench penetrating sound basalt.

Exit gradients remaining below critical values eliminate piping risk in all foundation materials, consistent with Terzaghi's filter criteria applied to internal zoning [6]. The rapid pore pressure dissipation observed below weathered basalt underscores the drainage function of underlying fractured zones under controlled conditions. Recommended measures, grout curtain through fractured basalt, upstream impervious blanket, and chimney drain, directly address identified flow paths while maintaining conservative design.

Slope stability outcomes demonstrate inherent robustness of the zoned embankment design. Critical slip surfaces predominantly involve downstream shell materials and weathered basalt interface, with minimum FOS=2.07 exceeding [23] requirements for unusual loading. Higher FOS values under static conditions reflect effective load distribution and competent founding on improved foundation. The bearing capacity margin post-treatment (>3) provides substantial reserve against localized overloading or construction variability.

Sensitivity analysis highlights the importance of accurate characterization of weathered basalt strength, supporting recommendations for additional block shear testing during excavation. Reliability assessment incorporating Monte Carlo simulation yields extremely low failure probability, comparable to modern high-hazard dams [25]. This quantitative risk framework supports risk-informed decision making beyond deterministic FOS criteria.

Integration of seepage and stability results confirms mutually compatible control strategies. Cutoff trench and grouting serve dual purposes of seepage reduction and foundation strengthening. The moderate seepage risk classification reflects residual permeability in fractured zones but is effectively mitigated through standard engineering measures [24].

Overall, the Legeda dam foundation exhibits favorable characteristics for safe and economic development, with predictable basalt weathering profile enabling reliable predictive modeling. Minor residual risks associated with joint persistence in fractured basalt are adequately addressed through recommended treatment and monitoring. Performance predictions align with successful precedents on similar geology in semi-arid regions.

The uniform deep weathering profile observed at Legeda reflects intense tropical alteration of Oligocene flood basalts characteristic of eastern Ethiopian highlands [20]. The consistent 17 m highly weathered zone overlying fractured and sound basalt aligns with regional patterns where chemical weathering penetrates along joint systems to depths controlled by groundwater fluctuation [21]. Minor lateral variations in competent rock depth (24–26 m) result from paleo-topographic influences rather than structural discontinuity, supporting predictable foundation behavior.

The established SPT-weathering grade correlation provides a practical tool for interpolating rock mass quality between boreholes, consistent with empirical relationships developed for basalt terrains [22]. This enables cost-effective extension of detailed logging data across the foundation area. Dominance of deep weathering and collapsible silt as adverse conditions reflects typical residual soil development on basalt, where smectite-rich clays form through hydrothermal alteration and saprolite retains metastable structure prone to hydrocollapse [5].

Risk distribution skewed toward low-medium categories indicates inherently favorable conditions despite deep weathering, as sound basalt provides competent founding at manageable depth. Localized high-risk zones correspond to intensify jointing facilitating deeper groundwater circulation and enhanced alteration. The spatial clustering in central boreholes suggests paleo-channel influence accelerating weathering rates.

Cost-benefit outcomes strongly favor partial treatment combining shallow excavation with targeted deep grouting, balancing risk reduction against construction costs. Full removal proves economically unjustified given sound basalt competence and low overall risk, while no treatment exposes unacceptable settlement and seepage potential. This optimized approach mirrors successful strategies at comparable basalt-hosted dams where selective treatment achieved long-term performance [24].

The treatment priority matrix effectively integrates condition severity, depth, and consequence, ensuring resources target critical zones while accepting managed risk in low-consequence areas. Recommended monitoring network provides early warning capability commensurate with moderate risk classification, enabling adaptive management during construction and reservoir filling.

Overall, Legeda exhibits classic but manageable basalt weathering challenges, with uniform profiles facilitating reliable prediction and efficient treatment design. The quantitative risk framework supports risk-informed decision making beyond prescriptive standards, optimizing safety and economy. Findings reinforce the viability of earth dam development on Ethiopian flood basalts when supported by detailed site characterization and targeted engineering measures.

The progressive increase in bearing capacity with depth reflects the marked competence improvement from compressible alluvial deposits to sound basalt, consistent with tropical weathering profiles on flood basalts in eastern Ethiopia [11]. Adoption of drained strength parameters for long-term analysis appropriately captures effective stress conditions post-construction, aligning with international guidelines for earth-rock dams [5]. The conservative friction angle of 41° assigned to sound basalt accounts for joint roughness and persistence typical of massive Oligocene trap series.

Untreated settlement exceeding 6 m underscores the critical need for foundation improvement, with clay and sandy silt layers exhibiting high compressibility characteristic of residual and alluvial soils in semi-arid climates. The 6 m minimum safe founding depth balances bearing capacity requirements against practical excavation limits in weathered rock.

Parameter variability analysis reveals expected trends: higher CV in cohesion-dominated superficial soils due to sampling disturbance and spatial heterogeneity, versus low variability in friction-dominated rock masses reflecting uniform mineralogy and joint spacing [22]. All CV values except topsoil/clay cohesion fall below the 0.3 threshold recommended for reliable design [25], supporting deterministic approaches supplemented by sensitivity studies.

Cost allocation heavily favoring cutoff wall and grouting reflects the dominant seepage risk through fractured basalt identified in earlier analyses. The zoned treatment concept efficiently addresses layered foundation challenges: shallow excavation removes compressible materials, mid-depth grouting targets permeable joints, and deep cutoff ensures positive hydraulic barrier into impervious sound basalt [24].

Cost-benefit outcomes strongly support integrated treatment over single-measure approaches. The superior B/C ratio of cutoff wall construction derives from simultaneous achievement of seepage control, foundation strengthening, and settlement reduction. Dynamic compaction and cement grouting offer comparable returns through targeted improvement of specific zones without extensive excavation.

Risk reduction quantification demonstrates treatment effectiveness across all failure modes, with greatest improvements in seepage/piping and bearing failure, primary concerns for dams on permeable rock foundations. Post-treatment probabilities align with acceptable levels for high-hazard structures [23], validating the recommended scheme.

The integrated approach exemplifies risk-informed foundation engineering, optimizing resource allocation while achieving multiple performance objectives. Findings reinforce the viability of earth dam construction on basalt foundations when supported by detailed characterization and targeted treatment, consistent with successful regional precedents. Minor residual uncertainties in joint persistence and grout take warrant confirmatory testing during construction.

Overall, results confirm Legeda as a favorable site offering high safety margins and economic efficiency through appropriate foundation engineering. The comprehensive dataset enables confident progression to construction with managed risks comparable to international best practice.

The bedrock profile at Legeda exhibits exceptional lateral continuity and smoothness rarely encountered in basalt-hosted dam sites within rift-margin settings [26]. The gentle downstream dip and parallel contour pattern indicate erosion of the Oligocene flood basalt under low-energy fluvial conditions, followed by uniform alluvial infill and deep chemical weathering controlled primarily by groundwater depth rather than structural heterogeneity.

The minimal variation in overburden thickness (±0.1 m) reflects stable depositional environment and consistent weathering intensity across the valley, contrasting with many Ethiopian highland sites where paleo-topography creates significant irregularity [27]. This uniformity facilitates reliable interpolation between boreholes and reduces epistemic uncertainty in foundation modeling.

Engineering implications are profoundly positive: the planar bedrock geometry ensures uniform load distribution and minimizes stress concentrations, while the predictable dip allows precise alignment of cutoff trenches parallel to the phreatic surface. Seepage modeling benefits from simplified boundary conditions, enhancing confidence in flow net predictions 28.

The profile supports efficient foundation treatment sequencing, shallow excavation of compressible overburden followed by targeted deep grouting, without complex zoning adjustments required for variable bedrock. Construction risks associated with unexpected depth changes or overbreak are effectively eliminated.

Overall, the bedrock topography represents an ideal foundation condition for earth-rock embankment design, enabling conservative yet economical solutions while providing inherent safety margins against differential movements and seepage anomalies 29]. These characteristics distinguish Legeda as a premier site among regional basalt foundations.

4.2.1. Limitations

The geotechnical investigation for the Legeoda dam, although thorough, is constrained by the limited number of boreholes (twelve along the axis), which may overlook localized anomalies such as faults or irregular weathering zones prevalent in fractured basalt foundations [26]. Laboratory testing emphasized basic strength and index properties, with insufficient undisturbed sampling for advanced consolidation and permeability assessments, potentially overestimating settlement and seepage risks [27]. The absence of geophysical surveys (e.g., seismic refraction tomography, electrical resistivity tomography) and in-situ permeability tests (e.g., Lugeon/packer) limited detailed mapping of fracture networks and dynamic properties in this seismically moderate area [29]. Probabilistic risk modeling employed semi-deterministic approaches without full spatial variability via Monte Carlo simulations, introducing epistemic uncertainty in failure probability estimates [28]. These factors necessitate cautious interpretation and confirmatory studies during construction.

4.2.2. Future Directions

Future investigations should incorporate advanced geophysical methods, including seismic refraction tomography (SRT), electrical resistivity tomography (ERT), and multichannel analysis of surface waves (MASW), to delineate fracture continuity and detect hidden faults beyond borehole coverage [26]. Additional exploratory boreholes at abutments and ancillary structures, coupled with in-situ Lugeon/packer permeability testing and trial grouting, are essential to refine seepage control designs and validate grout curtain efficacy [27]. Undisturbed sampling in critical layers will facilitate precise oedometer and triaxial testing for improved settlement forecasting. Probabilistic analyses should integrate full Monte Carlo simulations accounting for spatial variability to enhance reliability assessments [29]. A robust instrumentation plan, piezometers, inclinometers, extensometers, during construction will enable real-time model validation. Long-term post-impoundment monitoring will yield performance data informing future basalt-hosted dam projects in Ethiopia [28].

5. Conclusions and Recommendations

5.1. Conclusions

The comprehensive geotechnical investigation and engineering analyses confirm that the Legeda dam site in eastern Ethiopia is highly suitable for a zoned earth-rock embankment dam. The foundation exhibits remarkable stratigraphic uniformity, with a consistent overburden sequence (average 40 m thick) overlying competent sound basalt at approximately 25 m depth. This deep tropical weathering profile on Oligocene flood basalts presents manageable challenges primarily compressible upper alluvial layers and permeable fractured basalt, effectively addressed through targeted treatment measures.

Key performance predictions post-treatment include: total settlement limited to acceptable levels (<800 mm), seepage discharge well below 1% of reservoir capacity, bearing capacity exceeding design loads by factors >3, and slope stability factors of safety surpassing international requirements under static (≥1.5) and rapid drawdown (≥1.3) conditions. Risk assessments demonstrate dramatic reduction in failure probabilities across all modes following implementation of optimized foundation improvements, achieving benefit-cost ratios ≥3.0.

The site's predictable subsurface conditions, high bearing stratum at manageable depth, and effective risk mitigation potential distinguish it as a favorable location for sustainable water resource development. With appropriate engineering interventions, the Legeda dam will provide reliable long-term performance supporting downstream irrigation and regional food security objectives.

5.2. Recommendations

Foundation Treatment Excavate and remove the upper 4 m of compressible alluvial deposits (topsoil, clay, sandy silt) across the full dam footprint and extend 10 m into abutments. Found the embankment at minimum 6 m depth into weathered basalt. Construct a positive cutoff trench or wall penetrating at least 2–3 m into sound basalt, supplemented by a multi-row cement grout curtain through the fractured basalt zone (10–25 m depth).

Seepage Control Enhancements Install an upstream impervious blanket (minimum 50 m width) and internal chimney/filter drains designed to Terzaghi criteria. Provide downstream toe drainage and relief wells.

Embankment Design Adopt a zoned section with central low-permeability clay core, transitional filters, and rockfill shells utilizing processed on-site weathered basalt. Ensure all zones achieve ≥98% modified Proctor compaction.

Construction and Verification Allow 10–15% over-excavation contingency. Conduct in-situ Lugeon testing and trial grouting prior to full implementation. Perform proof rolling and plate load tests on prepared foundation surfaces.

Instrumentation and Monitoring Install comprehensive monitoring including piezometers, settlement extensometers, inclinometers, and seepage weirs. Monitor intensively during construction and first filling, with predefined alarm thresholds and staged impoundment protocol.

Additional Investigations Undertake geophysical surveys (SRT, ERT) at abutments and ancillary structures to confirm lateral continuity before final design.

Abbreviations

Author Contributions

Kirubel Molla Bazezew: Conceptualization, Data curation, Investigation, Methodology, Project administration, Resource, Supervision, Writing – original draft

Wahaj Khan: Data curation, Investigation, Methodology, Supervision

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Conflicts of Interest

The authors declare no conflicts of interest.

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