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GEOTECHNICAL SITE INVESTIGATION AND SEDIMENTATION ANALYSIS FOR THE OPTIMIZATION OF SAND TRAP DESIGN AT THE KOTO HYDRO POWER PROJECT, DIR LOWER, KHYBER PAKHTUNKHWA, PAKISTAN

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Abstract
The Koto Hydropower Project in Koto Town, District Lower Dir, Pakistan, focuses on harnessing Panjkora River energy, with this study detailing the geotechnical investigation informing its sand trap design. The site lies within the geologically complex Kohistan Complex, featuring major thrust faults, diverse crystalline rocks (granites, gneisses, schists), and varied weathering/metamorphism. Rock properties, including variable permeability due to foliated schists and weathering, plus fault-induced fractured zones, critically impact strength, permeability, and localized instability. A geotechnical investigation primarily utilizes data from four boreholes directly relevant to the sand trap investigation and in-situ SPT/CPT, revealed permeability from 10−3 to 10−7 cm/s and shear strength from 20° to 40° (average 30°), with lower strengths in weathered/fractured areas. These findings were crucial for optimizing the sand trap's design, influencing its sizing, hydraulic design for flow variations, foundation stability near faults, reinforcement in low-strength areas, and material selection for durability against erosion/clogging. The optimized sand trap ensures efficient sediment removal, crucial for the hydropower plant's longevity, operational efficiency, and reduced maintenance costs.

INTRODUCTION

Pakistan possesses significant hydropower potential, with an estimated 60,000 MW of exploitable capacity (Sibtain et al., 2021). Harnessing this potential is crucial for reducing the country's reliance on fossil fuels, mitigating climate change impacts, and meeting its growing energy demands (Khan et al., 2019; Ahmed et al., 2020). The Koto Hydro Power Project, located in District Lower Dir, is a vital undertaking that aims to tap into this potential, harnessing the energy potential of the Panjkora River, a major tributary of the Swat River (Kazmi & Jan, 1997; Alam et al., 2018). In hydropower projects, a sand trap plays a critical role in capturing and removing sediment particles from flowing water, protecting the turbine and other equipment from damage, ensuring efficient power generation, and preventing sedimentation in the reservoir (Butler, 1991;

Liu et al., 2017). The presence of pollutants and sediments in the Panjkora River can significantly impact sedimentation patterns, affecting the design and efficiency of sand traps at the Koto Hydro Power Project (Ullah et al., 2014). The sedimentation rates in the Hazara Intermontane Basin, ranging from 0.07 to 0.27mm/yr, provide valuable insights for understanding sedimentation patterns and optimizing sedimentation management strategies in hydro power projects, such as the Koto Hydro Power Project (Pivnic 1988). The sand trap's effectiveness relies heavily on its geotechnical properties and the surrounding sedimentation dynamics. Therefore, geotechnical analysis is necessary to ensure the sand trap's stability and safety, while sedimentation analysis helps predict and manage sediment loads, preventing potential issues downstream. "The values of specific gravity and water absorption of both the epidote amphibolite and gabbro-norite are within the range permissible for their use as dimension stones and construction material (Sajid et al., 2009)

The primary aim of this research, as extracted from the abstract, is to detail the geotechnical investigation informing the sand trap design for the Koto Hydropower Project. As the Kohistan complex is mentioned, detail about the specific rock types encountered, their weathering state, orientation and characteristics of the major thrust faults, how do these geological features specifically impact the sand trap design and stability of Koto Hydro Power Project, Dir Lower, Khyber Pakhtunkhwa, Pakistan are provided. By achieving these objectives, this study will contribute to the development of best practices in geotechnical investigations for hydropower projects in similar geological settings. The findings of this study will also provide valuable insights for the design and construction of future hydropower projects in Pakistan.

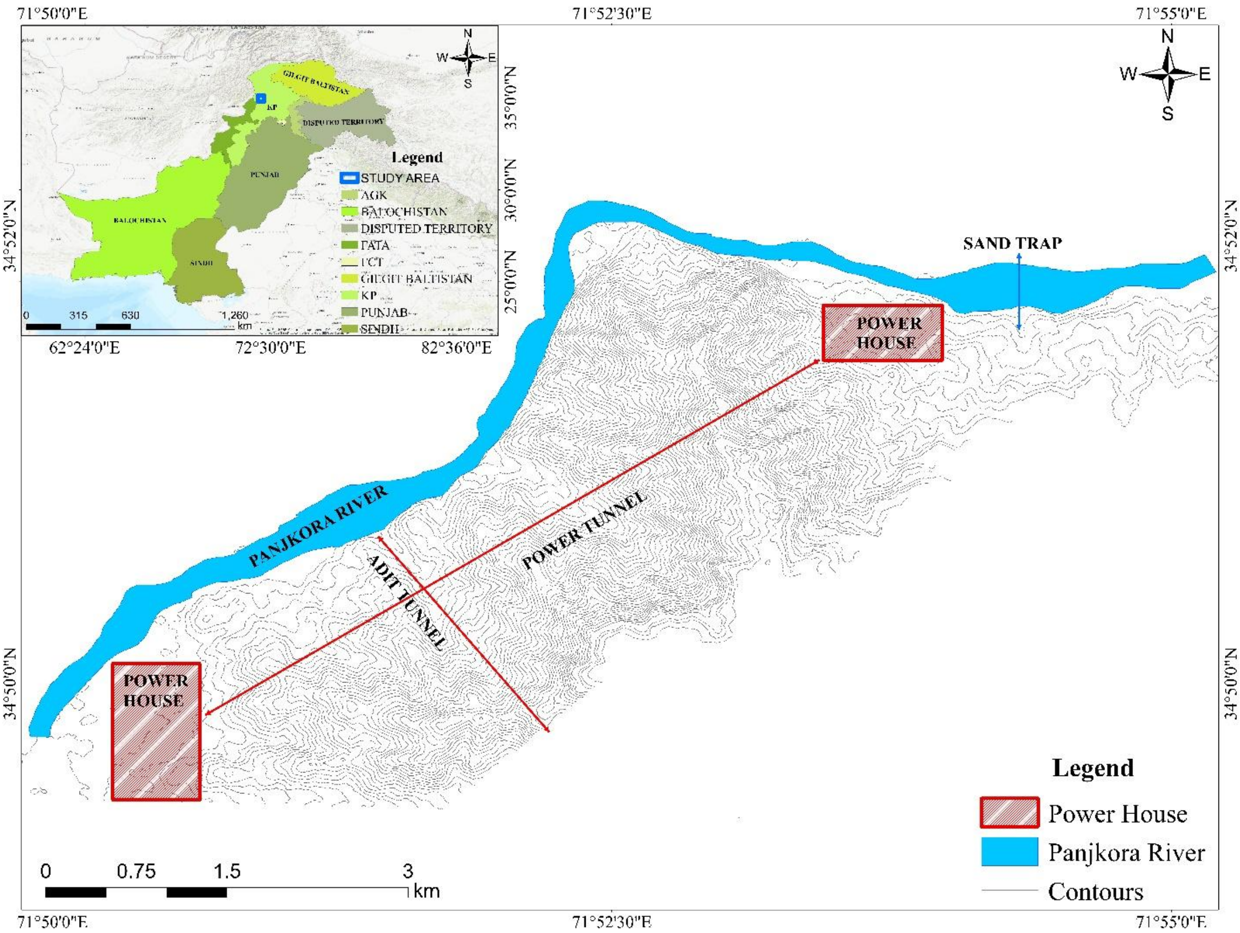

Figure 1: Study area, Koto Hydropower Project's layout along the Panjkora River, with an inset map locating the project in Pakistan (red rectangle).

Figure 2: Sand trap, Koto Hydro Power Project, Dir Lower, Pakistan

METHODOLOGY

This study employed a physical modeling to investigate the geotechnical setup of the Koto Hydro Power Project's sand trap.

Field Investigations

A comprehensive geotechnical investigation was conducted to evaluate the subsoil strata's properties for engineering design. Fifty-one boreholes were drilled to depths of 15-50 meters, totaling 1123 meters, using straight rotary drilling methods. Standard Penetration Tests (SPT) and Cone Penetration Tests (CPT) were performed to assess permeability and shear strength. Core samples, disturbed samples, and undisturbed samples were collected and preserved according to ASTM standards (ASTM D3550, D4220, D2487, D3080, D2166, D1586, and D3441). The boreholes are strategically placed to capture the variability of subsurface conditions relevant to the sand trap. The depths of the boreholes are chosen to properly collect essential subsurface data, such as soil, rock, and groundwater conditions. Standard Penetration Tests (SPT) and Cone Penetration Tests (CPT) were performed to assess permeability and shear strength. The Standard Penetration Test (SPT) involves drilling a borehole and driving a split-spoon sampler into the soil using a hammer that weighs 63.5 kg (140 lbs), dropped from a height of 76 cm (30 inches). The number of blows required to drive the sampler 30 cm (1 foot) is recorded as the N-value, which indicates soil resistance—higher N-values signify denser, harder soils. The test is conducted at various depths, and the soil sample retrieved is analyzed for classification and other properties. Data is corrected for factors like overburden pressure and hammer efficiency, and the results help determine soil strength, bearing capacity, compaction, and the potential for liquefaction, supporting geotechnical design decisions for foundations and other structures.

The Cone Penetration Test (CPT) involves pushing a cone-shaped penetrometer into the ground using a rig, while continuously measuring tip resistance (Qc), sleeve friction (Fs), and, in some cases, pore pressure (u). As the penetrometer advances at a constant rate, data is collected at Depth of the boreholes ranged from 10 – 25 m intervals to assess soil strength, stiffness, and stratigraphy. Tip resistance indicates the hardness or density of the soil, while sleeve friction provides insights into shear strength and cohesion. Pore pressure measurements, if taken, help assess liquefaction potential. The continuous data is analyzed to classify the soil and estimate its properties, such as shear strength and bearing capacity, creating a detailed subsurface profile essential for foundation design and geotechnical studies.

Data Analysis

The data collected from field investigations and laboratory testing were analyzed to evaluate the geotechnical properties of the sand trap and surrounding areas. The results of the SPT, CPT, and permeability tests were analyzed to evaluate the geotechnical properties of the sand trap. Statistical methods were used to identify trends and correlations between different parameters. The data were interpreted using established criteria to determine soil classification, strength, and deformation properties, which informed the design optimization of the sand trap.

Data interpretation

Standard Penetration Test (SPT) Data Interpretation

Blow Count (N-value): The primary data from an SPT is the blow count (N-value), which measures the number of hammer blows needed to drive a sampler a certain depth into the ground (usually 30 cm).

Soil Strength & Consistency: Higher N-values indicate stronger, more compact soil, while lower values suggest weaker or looser soils. The N-values are correlated with soil type (e.g., clay, sand, gravel) and used to estimate the bearing capacity, settlement, and shear strength of the soil.

Soil Classification: The N-values are used to classify the soil, and further correlations are used to estimate properties such as friction angle, cohesion, and compaction.

Stratigraphy: By performing SPT at different depths, a profile of the soil layers is created, helping engineers understand the stratigraphy and design foundations accordingly.

Cone Penetration Test (CPT) Data Interpretation

Tip Resistance (Qc): The cone tip resistance is measured during CPT and provides data about the soil's resistance to penetration. Higher values usually indicate denser soils or harder materials, while lower values suggest softer soils. Sleeve Friction (Fs): The friction on the sleeve of the probe is measured and used to assess soil shear strength and the frictional characteristics of the soil. Soil Stratigraphy and Layers: CPT provides continuous data from the surface to the depth of penetration (often deeper than SPT), allowing for detailed stratigraphy identification. Changes in resistance indicate different soil layers.

Pore Pressure (u): Some CPT tests measure pore pressure (in piezocone testing), which can provide additional insight into the water-bearing capacity of the soil and the potential for liquefaction in seismic areas. Soil Classification and Strength Parameters: CPT data is used to classify soils (e.g., sands, clays, silts) and estimate shear strength parameters such as friction angle and cohesion.

General Interpretation Process

Soil Profiling: The combined data from both SPT and CPT are used to create a detailed soil profile of the site, indicating the depth and type of materials present at various levels. Geotechnical Parameter Estimation: The data is analyzed to derive key geotechnical parameters such as bearing capacity, settlement potential, and strength properties, which inform the design of foundations, tunnels, dams, and other structures. Comparison with Standards: The SPT and CPT data are compared with established correlation charts and standards to ensure consistency and accuracy in the interpretation. This may include using empirical formulas to estimate soil stiffness, shear strength, and liquefaction susceptibility. Overall, these interpreted data help engineers design safe, stable structures for the hydropower project by understanding the behavior and strength of the subsurface materials at different depths.

RESULTS

The geotechnical investigation and sedimentation analysis were conducted following the methodology outlined in the preceding section. Data from field and laboratory tests were analyzed to characterize the geotechnical conditions of the Koto Hydropower Project's sand trap area. Detailed geotechnical profiles from four selected boreholes (ZK-31, ZK-32, ZK-33, ZK-34) are presented. The profile for ZK-31 indicates brown, loose silty clay from 0-5m. This transitions to dense to very dense gravel and boulders between 5-22.5m. Bedrock, comprising diorite and granodiorite, was encountered from 22.5-25m. The detailed lithological information presented in Table 1 for borehole ZK-32 include Diorite at 10-15m, Granodiorite at 15-20m, and Andesite at 20-25m. ZK-33 (Figure 8) exhibits a more uniform soil composition compared to ZK-32, lacking distinct layers of silty clay and gravelly sand. The geotechnical properties show relatively consistent density and stiffness throughout the borehole depth. The material is consistent from 0-25m, consisting of loose to medium dense silty sandy gravel with pebbles of igneous and metamorphic origin. No bedrock was encountered within this depth.

Borehole ZK-34 (Figure 10) shows a varied composition with depth. The top 0-4m comprises brownish clayey silt, as identified by SPT. From 4-17m, medium to coarse-grained sand containing greyish cobbles and pebbles of igneous origin is present, as indicated by CPT. Bedrock, identified as diorite, was encountered from 17-22m. A significant increase in density and stiffness is observed below 17m, correlating with the bedrock presence.

Figure 3: Drilling process in ZK-31

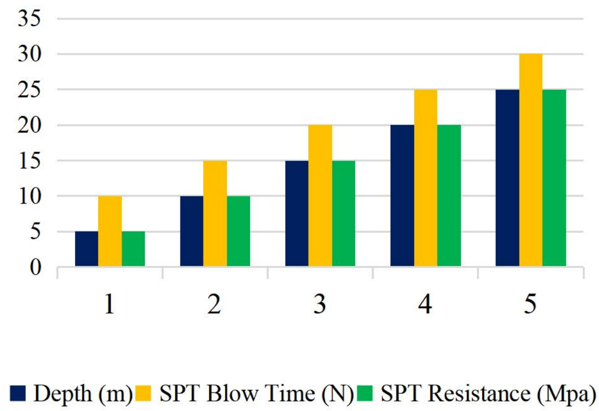

Figure 4: Geotechnical Properties of ZK-31

Figure 5: Drilling process in ZK-32

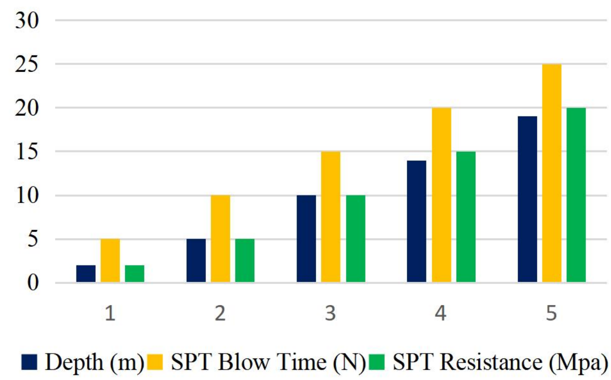

Figure 6: Geotechnical Properties of ZK-32

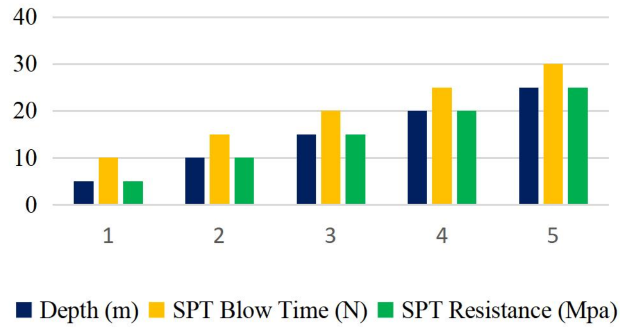

Figure 7: Drilling process in ZK-33

Figure 8: Geotechnical Properties of ZK-33

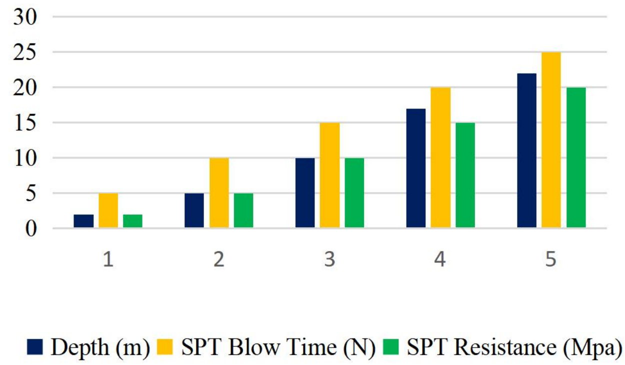

Figure 9: Drilling process in ZK-34

Figure 10: Geotechnical Properties of ZK-34

The geotechnical investigation results provide valuable insights into the subsurface soil and rock conditions at the Koto Hydropower Project's sand trap.

Permeability: Results of CPT analysis and other investigations (e.g., grain size distribution) revealed a permeability range from 10−3 to 10−7 cm/s, indicating significant variation in groundwater flow conditions across the site.

Shear Strength: Shear strength values ranged from 20◦ to 40◦ , with an average of 30◦ , reflecting a generally moderate to high strength rock mass. However, certain areas with weathered or fractured rock exhibited lower strength characteristics.

Based on the RQD values in Table 1, rock quality is classified as: Excellent (RQD ≥ 90%), Good (75% ≤ RQD < 90%), Fair (50% ≤ RQD < 75%), and Poor (RQD < 50%). This classification provides a basis for geological feasibility assessment and design decisions. Table 2 provide detailed information on subsurface geological structure, including lithology, rock type, fracture frequency, and water strike.

Lithology and Rock Type: The logs indicate a consistent pattern of soil, weathered rock, and fresh rock layers. Rock types encountered generally include granite, basalt, schist, and gneiss.

Fracture Frequency: Fracture frequencies vary between 1-2 fractures/m and 3-4 fractures/m, indicating moderate to high fracturing.

Water Strike: Water strike depths range from 10.0 m to 15.0 m, suggesting varying groundwater levels.

A comparison of the logs reveals similar lithological sequences (soil → weathered rock → fresh rock) across all four boreholes, though specific rock types vary in depth and frequency.

Table 3 provide P-wave and S-wave velocities, and density, which are essential for understanding rock mechanical properties.

P-Wave Velocity: Ranges from 5000 to 6200 m/s, with higher velocities in boreholes ZK-31 and ZK-33, suggesting more competent rock.

S-Wave Velocity: Ranges from 2800 to 3600 m/s, showing a similar trend to P-wave velocities, indicating a consistent relationship.

Density: Values range from 2.5 to 2.9 g/cm³, with higher densities in ZK-31 and ZK-33, suggesting denser, more competent formations.

Correlation analysis of seismic logs reveals positive correlations between P-wave and S-wave velocities, and between density and P-wave velocity, indicating that denser, more competent rock formations generally exhibit higher seismic velocities.

DISCUSSION

This section interprets the geotechnical investigation results and discusses their implications for the Koto Hydropower Project's sand trap design and overall project safety, particularly under extreme hydrological conditions.

Interpretation of Geotechnical Properties

The SPT and CPT results offer crucial insights into soil stability and load-bearing capacity. The shallow loose silty clay (e.g., 0-5m in ZK-31) suggests potential settlement or instability, contrasting sharply with the underlying dense gravels and boulders (below 5m in ZK-31) that indicate a more stable, load-bearing stratum. While CPT results generally show increasing cone resistance with depth, indicating improving soil density and stiffness, the presence of coarse-grained soils and gravels in ZK-32 and ZK-34 warrants consideration for potential liquefaction or instability under seismic loading.

Permeability, as inferred from CPT results and material descriptions (e.g., coarse-grained soils, gravels), varies significantly across the site. High permeability in certain areas directly impacts the project's hydrological design, necessitating careful consideration for potential high water infiltration rates and groundwater flow in the sand trap and associated structures.

The presence of bedrock at varying depths (e.g., ZK-31, ZK-34) provides a solid foundation for structures. However, the observed variability in bedrock depth and composition, including different rock types (e.g., granite, basalt, diorite, gneiss) and varying degrees of fracturing (Table 2, Table 3), necessitates thorough foundation design considerations to ensure adequate bearing capacity and stability.

Implications for Sand Trap Design and Project Safety

The integration of these geotechnical findings was crucial for optimizing the sand trap design. The varying permeability data influenced sedimentation dynamics, requiring specific sizing and hydraulic design to effectively manage both high-flow and low-flow zones. The presence of fractured and weathered rock masses, particularly near thrust faults, demanded careful attention to the stability of the trap's foundation and structural integrity. This led to reinforcement in areas with lower shear strength and specific material selection to ensure durability against erosion and sediment build-up. Furthermore, the variations in rock type and groundwater flow were factored into the sediment removal system's design to ensure efficient functioning and minimize clogging risks.

Evaluation of Design Parameters under Extreme Hydrological Conditions

To assess the robustness of the design under extreme events, an evaluation was conducted for flood hydrology scenarios. The projected peak flood discharge is 500 m^3/s (100-year return period) with a 72-hour duration and a water level elevation of 10.5 m above datum. Table 4: Summary of Design Parameter Evaluation under Flood Conditions (Table 4 with Parameter, Designed Value, Flood Condition Value, Evaluation Result). The evaluation (Table 4) indicates that the designed parameters (e.g., working depth, width, slope, flushing velocity) are generally adequate to handle these extreme hydrological conditions. For instance, a 2.5m freeboard for working depth provides sufficient margin. However, potential risks remain that require explicit mitigation strategies:

Flooding: Risk due to extreme rainfall or upstream dam failures. Mitigation involves implementing a flood warning system and developing an emergency response plan.

Sediment Buildup: Risk of accumulation reducing sand trap effectiveness. Mitigation includes regular inspection and maintenance, alongside a comprehensive sediment removal plan.

Erosion: Risk to the sand trap and surrounding structures due to high flow rates. Mitigation involves implementing erosion protection measures (e.g., riprap, concrete lining) and continuous monitoring of flow rates.

The working depth of 13.0 m was evaluated against the 10.5 m flood level, providing a sufficient 2.5 m freeboard that meets required safety margins based on standard engineering practices for similar structures. For width and slope, the sand trap's designed hydraulic capacity of 550 m^3/s was assessed against the 500 m^3/s peak flood discharge, confirmed as adequate through hydraulic calculations to safely convey extreme flood flow. Finally, the flushing velocity of 3 m/s was evaluated under flood conditions and confirmed through hydraulic analyses to be maintained at or above the minimum required for efficient sediment transport, preventing excessive buildup.

Table 1: The RQD data for the boreholes

Borehole ID	Depth (m)	RQD (%)	Rock Type	Description
ZK-32	10-15	85	Diorite	Fairly intact rock with few fractures
ZK-32	15-20	70	Granodiorite	Fractured rock with moderate weathering
ZK-32	20-25	90	Andesite	Competent rock with minimal fractures
ZK-33	5-10	60	Diorite	Highly fractured rock with significant weathering
ZK-33	10-15	80	Granodiorite	Fairly intact rock with few fractures
ZK-33	15-20	75	Andesite	Fractured rock with moderate weathering
ZK-34	10-15	95	Diorite	Competent rock with minimal fractures
ZK-34	15-20	85	Granodiorite	Fairly intact rock with few fractures
ZK-34	20-25	80	Andesite	Fractured rock with moderate weathering

Table 2: Borehole Logs detail

	Depth (m)	Lithology	Rock Type	Fracture Frequency	Water Strike
ZK – 31	0-5	Soil	Clayey silt	-	-
	5-10	Weathered rock	Granite	2-3 fractures/m	-
	10-15	Fresh rock	Granite	1-2 fractures/m	12.5 m
	15-20	Fresh rock	Basalt	3-4 fractures/m	-
	20-25	Fresh rock	Basalt	2-3 fractures/m	-
ZK – 32	0-5	Soil	Clayey silt	-	-
	5-10	Weathered rock	Schist	3-4 fractures/m	-
	10-15	Fresh rock	Schist	1-2 fractures/m	15.0 m

	15-20	Fresh rock	Gneiss	2-3 fractures/m	-
	20-25	Fresh rock	Gneiss	3-4 fractures/m	-
	0-5	Soil	Silty clay	-	-
	5-10	Weathered rock	Gneiss	2-3 fractures/m	-
ZK – 33	10-15	Fresh rock	Gneiss	1-2 fractures/m	10.0 m
	15-20	Fresh rock	Granite	3-4 fractures/m	-
	20-25	Fresh rock	Granite	2-3 fractures/m	-
	0-5	Soil	Clayey silt	-	-
	5-10	Weathered rock	Schist	3-4 fractures/m	-
ZK – 34	10-15	Fresh rock	Schist	1-2 fractures/m	12.0 m
	15-20	Fresh rock	Basalt	2-3 fractures/m	-
	20-25	Fresh rock	Basalt	3-4 fractures/m	-

Table 3: Seismic Logs detail

	Depth (m)	P-Wave Velocity (m/s)	S-Wave Velocity (m/s)	Density (g/cm³)
ZK – 31	10-15	5500-5800	3000-3200	2.6-2.7
	15-20	5800-6000	3200-3400	2.7-2.8
	20-25	6000-6200	3400-3600	2.8-2.9
	10-15	5000-5300	2800-3000	2.5-2.6
ZK – 32	15-20	5300-5600	3000-3200	2.6-2.7
	20-25	5600-5900	3200-3400	2.7-2.8
	10-15	5200-5500	2900-3100	2.5-2.6
ZK – 33	15-20	5500-5800	3100-3300	2.6-2.7
	20-25	5800-6100	3300-3500	2.7-2.8
	10-15	5000-5300	2800-3000	2.5-2.6
ZK – 34	15-20	5300-5600	3000-3200	2.6-2.7
	20-25	5600-5900	3200-3400	2.7-2.8

Table 4: Summary of design parameter evaluation

Parameter	Designed Value	Flood Condition Value	Evaluation Result
Working Depth	13.0 m	10.5 m	Sufficient (2.5 m freeboard)
Width and Slope	550 m3/s	500 m3/s	Adequate
Flushing Velocity	3 m/s	3 m/s	Maintained

Table 5: Summary of the key results

Parameter	Value	Unit
Permeability	0.0037 - 0.0034	cm/sec
Sedimentation Rate	0.499	-
Flushing Velocity	3	m/s
Head Loss	0.36	m

CONCLUSION

The comprehensive geotechnical investigation, encompassing borehole drilling, in-situ testing, RQD analysis, borehole logging, and seismic profiling, provides essential insights into the complex subsurface conditions at the Koto Hydropower Project site. The findings on soil/rock stability, permeability, bedrock characteristics, and seismic properties are directly applicable to the robust design and construction of the sand trap. By integrating these geological and geotechnical findings, the project aims to enhance the sand trap's performance, reduce maintenance costs, and ensure the long-term longevity and operational efficiency of the Koto Hydropower Project, even under extreme hydrological conditions. This detailed understanding will inform foundation design, hydrogeological analysis, stability assessments, and risk mitigation strategies for the entire project.

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