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GEOTECHNICAL GROUND INVESTIGATION AND PILE-FOUNDATION INTERACTION FOR HUB RIVER BRIDGE

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Abstract

This research paper presents a comprehensive geotechnical site investigation and analysis of pile-foundation interaction for the Hub River Bridge. The site under consideration is characterized by alluvial deposits overlying a continuous bedrock, with distinct variations in soil composition and scouring phenomena. The top 15.0 meters of soil on either abutment side comprises predominantly alluvial deposits, transitioning into weak sandstone from depths ranging between 15.0 and 45.0 meters. In the middle portion of the bridge, the alluvial deposit extends up to 5.0 meters, succeeded by weak sandstone reaching depths of 45.0 meters. The presence of scouring has been observed, indicating potential challenges in foundation stability. The proposed foundation depth is determined based on pile diameter considerations, ranging from 0.75 meters to 2.0 meters. The design parameters aim to accommodate a service load of 950 tons. The study incorporates a thorough analysis of the subsurface conditions, considering the variations in soil types and potential scouring effects. Additionally, the paper addresses the implications of different pile diameters on the foundation design, ensuring structural integrity and load-bearing capacity. The bridge piles undergo analysis and length determination using the All Pile software. This software facilitates a comprehensive examination of pile behaviour and foundation interaction, ensuring that the designed piles meet the specified load requirements. The utilization of All Pile software allows for a precise and efficient design process, considering the complex geological conditions and variations in soil types. The findings from this research contribute valuable insights into the geotechnical considerations and pile-foundation interaction for the Hub River Bridge, aiding in the development of optimal foundation designs for safe and resilient infrastructure in similar geological settings.

Keywords: Bridge Pile Analysis, Load Bearing Capacity On Rock Beds, Hub River Bridge, Pile Response to Loading, Composite Soil Conditions.

1. INTRODUCTION

The successful construction and performance of bridges rely fundamentally on the judicious design and implementation of foundation systems that are tailored to the specific geotechnical conditions of the site. This research paper delves into the geotechnical intricacies of the Hub River Bridge, focusing on the site's composition consisting of alluvial deposits underlain by continuous bedrock. As a critical component of bridge foundation design, understanding the interaction between piles and the underlying geological strata is imperative for ensuring the structure's stability and resilience [2].

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The topography of the Hub River Bridge site exhibits distinct characteristics, particularly in the soil composition across various sections. On both abutment sides, the uppermost 15.0 meters comprises alluvial deposits, transitioning to a layer of weak sandstone extending from 15.0 to 45.0 meters.

In the central span of the bridge, a 5.0-meter layer of alluvial deposits is succeeded by weak sandstone reaching a depth of 45.0 meters. The presence of scouring, a phenomenon observed at the site, further accentuates the complexity of the geotechnical conditions and necessitates meticulous consideration in the foundation design process.

To address the challenges posed by the geological conditions, the proposed depth of foundation is determined based on the diameter of the piles, ranging from 0.75 meters to 2.0 meters. These bridge piles are designed to support a substantial service load of 950 tons, emphasizing the importance of a robust foundation system that can withstand the imposed stresses [4].

To facilitate an in-depth analysis and design process, the All Pile software is employed. This specialized software enables the comprehensive assessment of pile length and the dynamic interaction between the piles and the foundation materials, ensuring that the designed foundation system meets the stringent requirements of the project.

In essence, this research endeavours to provide a holistic understanding of the geotechnical site conditions, the challenges posed by scouring, and the intricate interplay between pile foundations and the underlying strata for the Hub River Bridge.

The utilization of advanced software, such as All Pile, contributes to the development of reliable and optimized foundation designs, promoting the long-term structural integrity and safety of the bridge in question [3].

2. PROJECT DETAILS

The geotechnical investigation is carried out to evaluate the subsurface conditions at the proposed Hub River Bridge at KM: 22 (N-25).The details of site and the google map of the bridge are shown in Table 1 and Figure 1 respectively.

Table 1: Site Description

Owner	National Highway Authority (NHA)
Length of bridge	20 spans×24.4m = 488 m
Project Location	Hub River Bridge at KM: 22 (N-25)
Operated by	National Highway Authority

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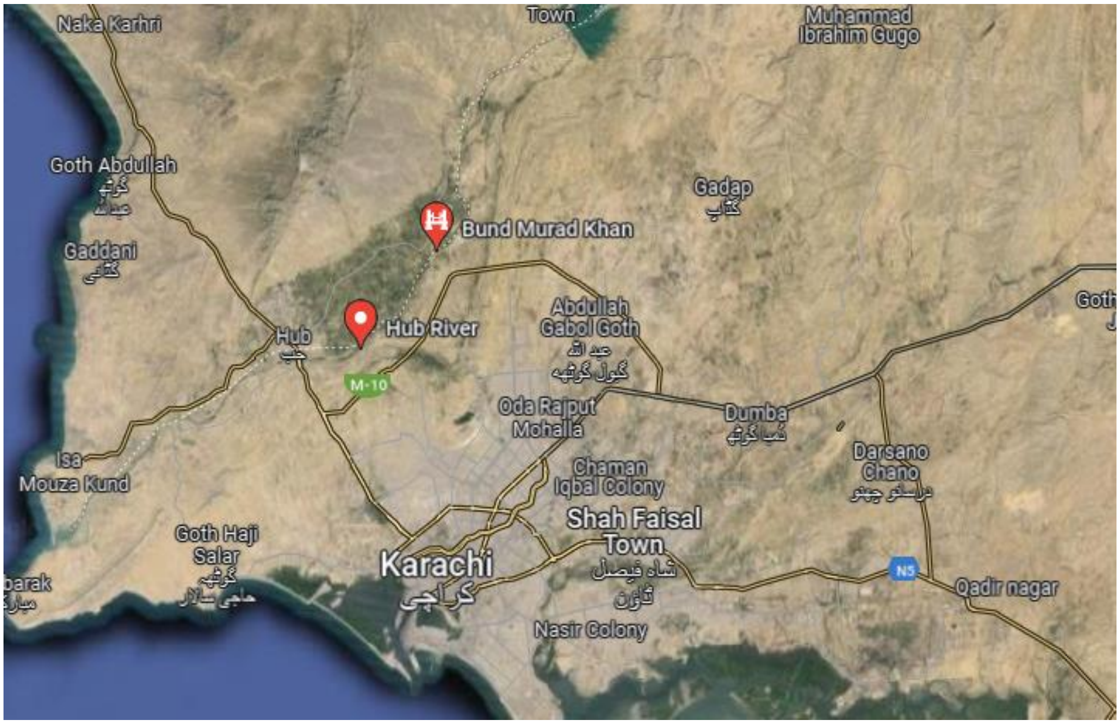

Figure 1: Google Map of Hub River Bridge

3. METHODOLOGY

A total of three boreholes were drilled to a depth of 45.0 meters for the Hub River Bridge project. Sampling involved the use of a double-core barrel for both drilling and sampling. Disturbed and undisturbed samples were collected at regular intervals using thin-walled sampling for soils and core drilling for rocks as shown in Figure 3. Disturbed samples were also obtained from Standard Penetration Tests (SPTs) and bulk sampling where SPTs were not conducted. As the Straight Rotary Drilling Machine on site is shown in Figure 4.All samples, whether soil or rock, were preserved in sealed plastic bags labelled with the date, borehole number, sample number, and depth of retrieval. Split-spoon samples were measured for length and stored in airtight bags. Rock core samples were placed in core boxes with spacers marking depths, and photographs were taken with a colour film camera to document their natural appearance. Testing focused on two depth intervals: 0-15 meters and 15-45 meters. Laboratory analyses included soil classification, density, and shear strength parameters for alluvial soil and sandstone cores. Rock samples were tested for rock type identification, uniaxial compressive strength, density, and other required parameters. Standard Penetration Tests (SPTs) were conducted and recorded in the Borelog, with additional tests performed between coring depths with poor recovery. Samples from SPTs were preserved for further classification and laboratory testing. This methodology ensured thorough data collection and analysis necessary for the structural assessment of the Hub River Bridge.

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Figure 2 (a): Double tube core barrel & thin wall sampler	**Figure 3 (b): Collected soil sample in sealed plastic bags**

Figure 4: Straight Rotary Drilling Machine on site at (BH-1)

4. RESULTS

4.1 Field and Laboratory Test Results

The results of the field and laboratory testing which are quite necessary for a comprehensive analysis of a site were summarized for all three boreholes. These data are indeed crucial for understanding different ground aspects and are essential for designing and constructing civil engineering infrastructure. Using design and analysis software can further enhance the interpretation and utilization of these data.

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4.2 Soil Profile

The soil profile is mainly based on field observations and field testing. The soil profile for the site consists of yellowish brown, dense, Gravels/Boulders, with some traces of sand up to a depth of 0.0 m to 15.0 m. From 15.0 m to 45 m the boring exhumed weak sandstone and occasional siltstone. The rock strength may be categorized as a weak rock with the rock category of R2 as shown in Table 2. The soil profile for the site consists of weak sandstone and occasional siltstone from 5.0 m to 45 m. The rock strength may be categorized as a weak rock with the rock category of R2 as shown in Table 3 . The soil profile for the site consists of yellowish brown, dense, Gravels/Boulders, with some traces of sand up to a depth of 0.0 m to 5.0 m. From 5.0 m to 45 m the boring exhumed weak sandstone and occasional siltstone. The rock strength may be categorized as a weak rock with the rock category of R2 as shown in Table 4.

Table 2: Soil Profile for BH No.1 Hub River Bridge

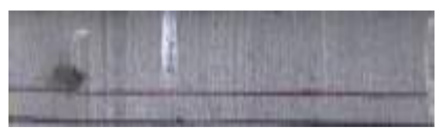
BH No.	Depth (m)	Sample of type	Soil description	Lithology	UBC soil profile
BH-01	0.0-15	DS-1	Gravel and alluvial deposits		S_c
	15-45	UDS-2	Sandstone and siltstone		S_B

Table 3: Soil Profile for BH No.2 Hub River Bridge

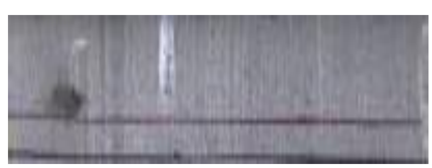
BH No.	Depth (m)	Sample of type	Soil description	Lithology	UBC soil profile
BH-02	0.0-5.0	DS	Gravel and alluvial deposits		S_c
	5.0-45	UDS	Sandstone and siltstone		S_B

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Table 4: Soil Profile for BH No.3 Hub River Bridge

BH No.	Depth (m)	Sample of type	Soil description	Lithology	UBC soil profile
BH-03	0.0-5.0	DS	Gravel and alluvial deposits		S_C
	5.0-45	UDS	Sandstone and siltstone		S_B

Based on uniformed Building code (UBC) classification the soil profile type is decided, based upon the uniaxial compressive strength the rock is classified as grade R2 weak rock, therefore, it is not considered SA. There is no third option for defining the profile type of the rock.

4.3 Index Properties

The index properties of soil consist of particle size analysis (PSD) and consistency limits (i.e., liquid limit, plastic limit and plasticity index). The index properties of soil for various boreholes and the Particle size distribution parameters of alluvial deposits for BH No.1, BH No.2 and BH No.3 are given in Table 5, Table 6 and Table 7 respectively.

Table 5: PSD parameters for Hub River Bridge alluvial deposits (BH No.1)

Depth (m)	Gradation parameters		
	D50 (mm)	D90 (mm)	D95 (mm)
1	0.19	38	40.2
6	42	58	60
11	28	43	48

Table 6: PSD parameters for Hub River Bridge alluvial deposits (BH No.2)

Depth (m)	Gradation parameters		
	D50	D90	D95
1	10	30	32
6	--	--	--
11	--	--	--

Table 7: PSD parameters for Hub River Bridge alluvial deposits (BH No.3)

Depth (m)	Gradation parameters		
	D50	D90	D95
1	15	20	35
6	--	--	--
11	--	--	--

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Only the top layer of borehole No.1 on the abutment site contains some fine contents. The rest of the samples were granular or consisted of weak to medium hard rock.

4.4 Physical Properties

Colour, texture, structure, porosity, density, consistency, aggregate stability, and temperature are among the physical characteristics of soil. These characteristics have an impact on biological activity, nutrient cycling, infiltration, and erosion. The swell potential tests were conducted particularly in the soil samples containing relatively high clay contents. The results were also compared with the dry density initial moisture contents and consistency characteristics. The results are summarized in Table 8. The swell potential results and classification of swell potential are given in Table 9 and Table 10 respectively.

Table 8: Physical Properties results

BH No.	Bulk density (kN/m^3)	Colour	Soil temperature (°C)	Specific gravity G_s
BH-No.1 to BH-No.3	14 to 18	Brown to grey-brown	22 to 25	2.65

Table 9: Swell potential results

BH No.	Swelling Index	Swell potential (%)	Swell pressure (kPa)	Swell potential class	Remarks
BH No.1 to BH No. 3	10 to 20	0.2-0.5	50-80	Low	Suppressible due to pile load

Table 10: Classification of swell potential

Swelling Index	Swell Potential
0 to 20	Very low
21to 50	Low
51 to 90	Medium
91 to 130	High
>130	Very high

The shrinkage of clay layers for various boreholes was investigated. The shrinkage results are given in Table 11.

Table 11: Shrinkage results

BH No.	Shrinkage limit, SL (%)	Shrinkage ratio SR
BH-No.1 to BH-No.3	8.5 to 10.5	1.1 to 1.3

4.5 Mechanical properties

The way soil behaves under pressure and tension is referred to as its mechanical characteristics. Among these characteristics are cohesion, or the capacity of soil particles to cling to one another; compressibility, or the degree to which soil may be compressed underweight; and internal friction, or the soil's resistance to deformation. In many engineering applications, such as the construction of foundations and the design of slopes

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and embankments, an understanding of these qualities is essential. The Mechanical properties of all bores are shown in Table 12.

Table 12: Mechanical Properties results

BH No.	Soil type	Friction angle (°)	Cohesion (kPa)	Unconfined Compressive Strength	One Dimensional Consolidation	Undrained Shear Strength
BH No.1 to BH No. 3	Alluvial soil	28 to 32	0-5.0	no undisturbed clayey soils were extracted	no undisturbed clayey soils were extracted for consolidation tests	No undisturbed clayey soils were extracted for UU-Triaxial and CU-Triaxial tests.

4.6 Chemical properties of soil

The chemical properties of soil as shown in Table 13 were determined through pH, chloride, and Sulphate content values. A significant number of tests were conducted on the soil samples exhumed from various boreholes, and organic matter content. The organic matter content was found to be varying from 1.5 to 10% for a depth of around 5.0 m. The organic matter contents for the deep soil samples were found in traces only.

Table 13: Chemical Properties of Soil

BH No.	pH	Sulphate content (%)	Chloride content (%)	Organic matter content (%) of alluvial deposits
BH-No.1 to BH-No.3	8.0 to 8.5	0.1 to 0.2	0.2 to 0.3	1.5 to 10.0

1 ppm= 1mg/liter = 0.0001%

5. ALL-PILE SOFTWARE OVERVIEW

All Pile is a software program designed for civil engineering projects, specifically for analyzing and designing pile foundations. It supports various pile types including driven piles, drilled shafts, and auger-cast piles, allowing engineers to analyze different foundation configurations. The software enables detailed load analysis for axial, lateral, and moment loads on piles, helping engineers determine suitable designs based on project requirements. All Pile incorporates soil-structure interaction analysis to assess pile behaviour under different soil conditions, evaluating parameters like pile capacity, settlement, and lateral response. Engineers can optimize pile designs by adjusting parameters such as diameter, length, and spacing while ensuring compliance with industry standards like AISC, ACI, and Euro codes. The software features a user-friendly graphical interface for inputting project data, visualizing analysis results, and generating detailed reports and drawings for documentation and communication purposes. Overall, All Pile facilitates comprehensive pile foundation analysis and design, ensuring structural integrity and meeting project specifications effectively. The complete step by step overview of the software are shown from Figure 5 to Figure 10.

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6. SOIL ANALYSIS THROUGH ALL-PILE SOFTWARE

The All-Pile Software provides a wide range of functions for geotechnical engineers. It calculates the total ultimate pile capacity in both downward and upward directions, crucial for understanding load-carrying capabilities. The software also evaluates pile settlement under applied loads, giving insights into potential post-construction settlement.

It assesses pile deflection under various loading scenarios, essential for ensuring foundation stability. Engineers can analyse the behaviour of pile groups and understand how neighbouring piles interact. The software predicts pile behaviour during driving, helping to optimize driving parameters. It also includes tools for non-destructive testing of existing piles to assess their integrity.

Additionally, All-Pile can simulate load tests to validate pile capacities and performance. Using the software starts with gathering all relevant data, such as site geotechnical properties, pile dimensions, applied loads, and specific project parameters. The intuitive user interface ensures accurate data entry.

Once the data is entered, engineers select appropriate analysis parameters based on the project's needs and the type of foundation system. This includes choosing analysis methods like axial capacity, settlement, deflection, and pile group analysis, considering soil behaviour models, and defining loading scenarios such as axial, lateral, and seismic.

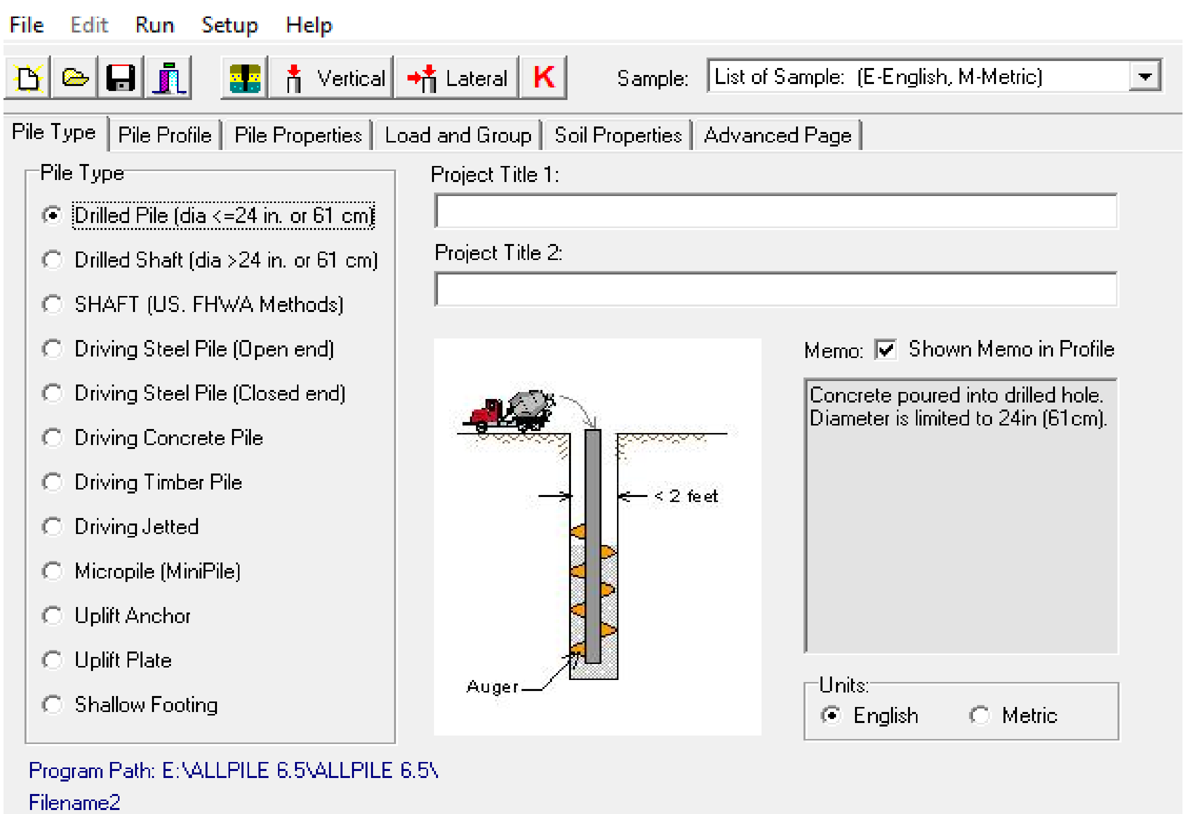

Figure 5: Pile Geometry Diameter or cross-sectional dimensions of the pile

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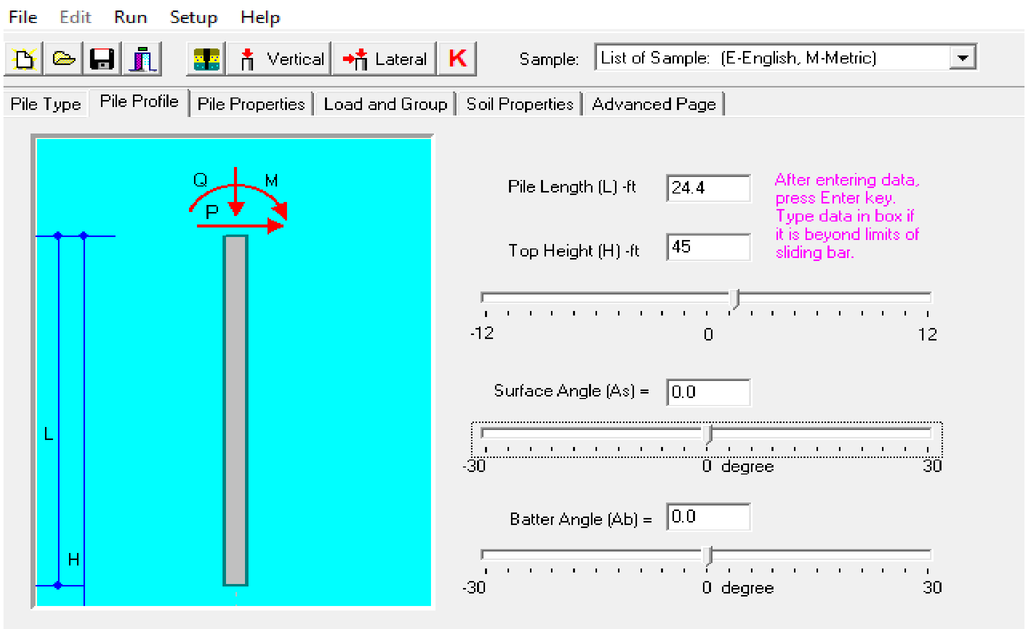

Figure 6: Cross-Sectional parameters of the Pile

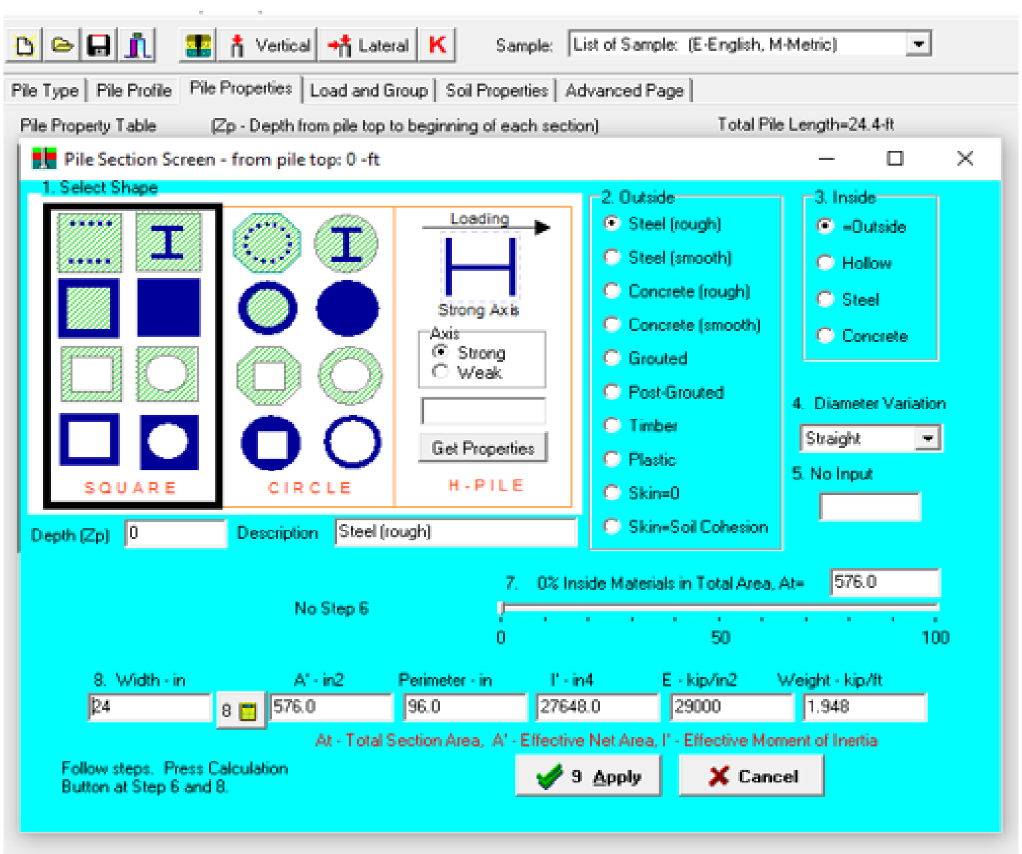

Figure 7: Material Properties of the Pile

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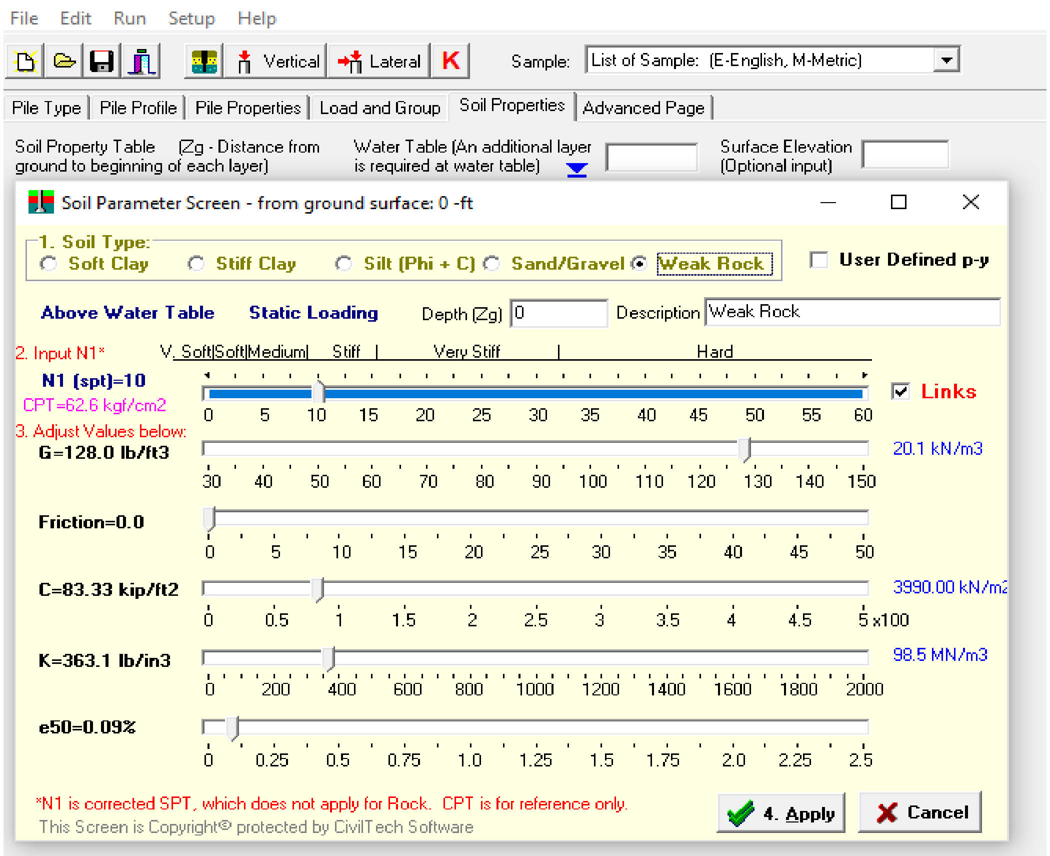

Figure 8: Soil Properties for Pile Analysis

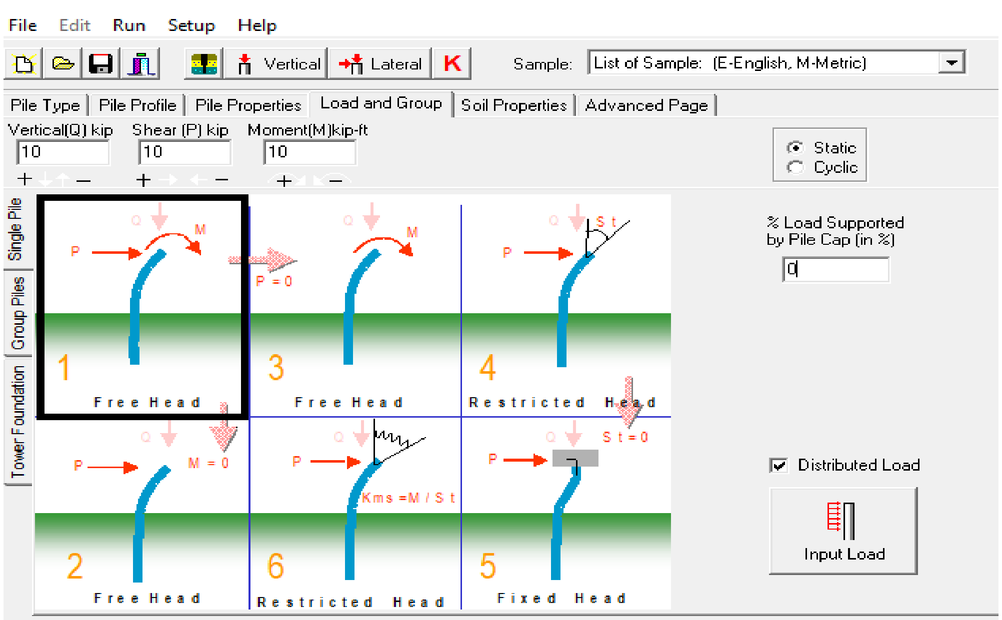

Figure 9: Different Loading Conditions for Pile Capacity Analysis

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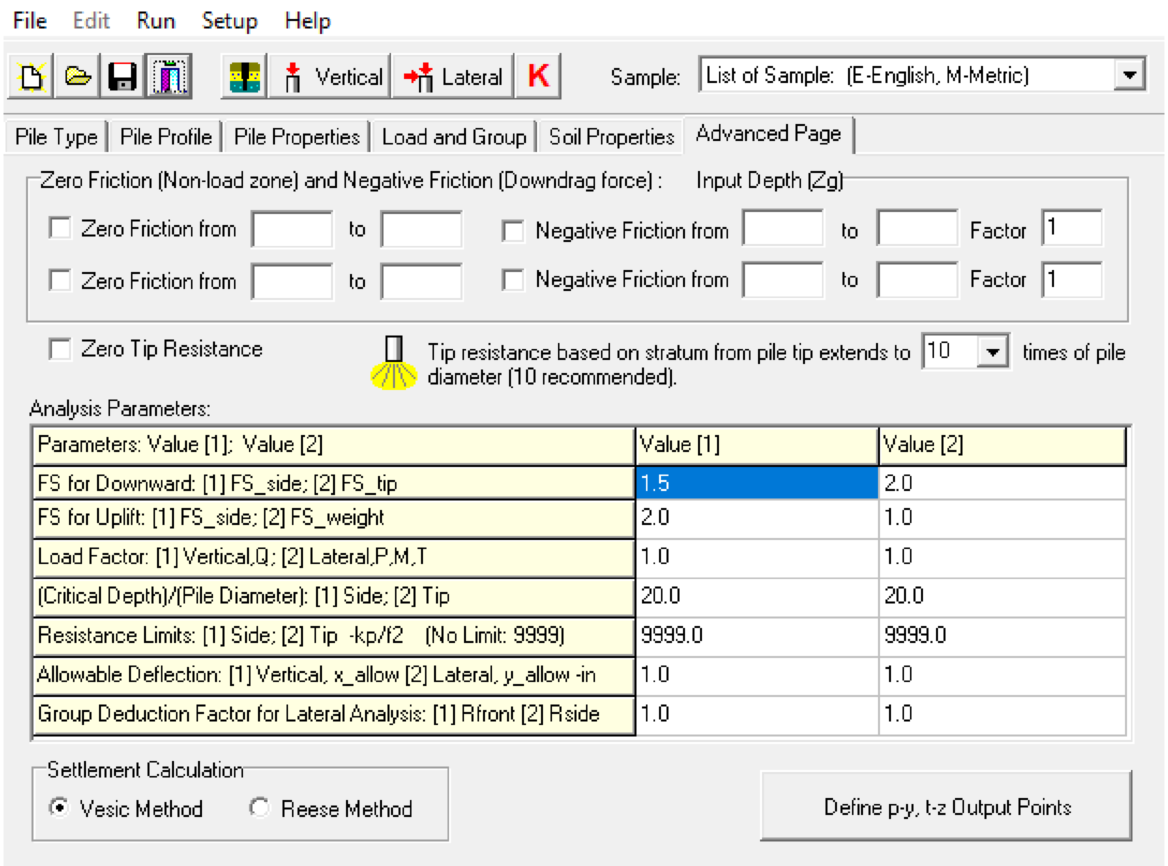

Figure 10: Different Analysis method for Pile analysis

7. ALL-PILE OUTPUT PARAMETERS/RESULTS

All Pile software generates comprehensive output parameters essential for understanding the behaviour and performance of piled foundations. The Output Parameters Generated from Software is shown in Figure 11.

These include ultimate and allowable bearing capacities, predicted settlement under applied loads, distribution of bending moments and shear forces along the pile length, predictions of pile deflection under varying loading conditions, assessment of pile integrity highlighting potential issues like buckling or overstressing, and analysis of soil-pile interaction effects such as mobilized soil resistance. These outputs provide engineers with valuable insights to optimize design, ensuring structural integrity and stability throughout the foundation's lifecycle. Soil properties. Load with Settlement and Axial Force, Shear Force & Bending Moment Analysis of the Pile are shown in figure 12 and figure 13 respectively.

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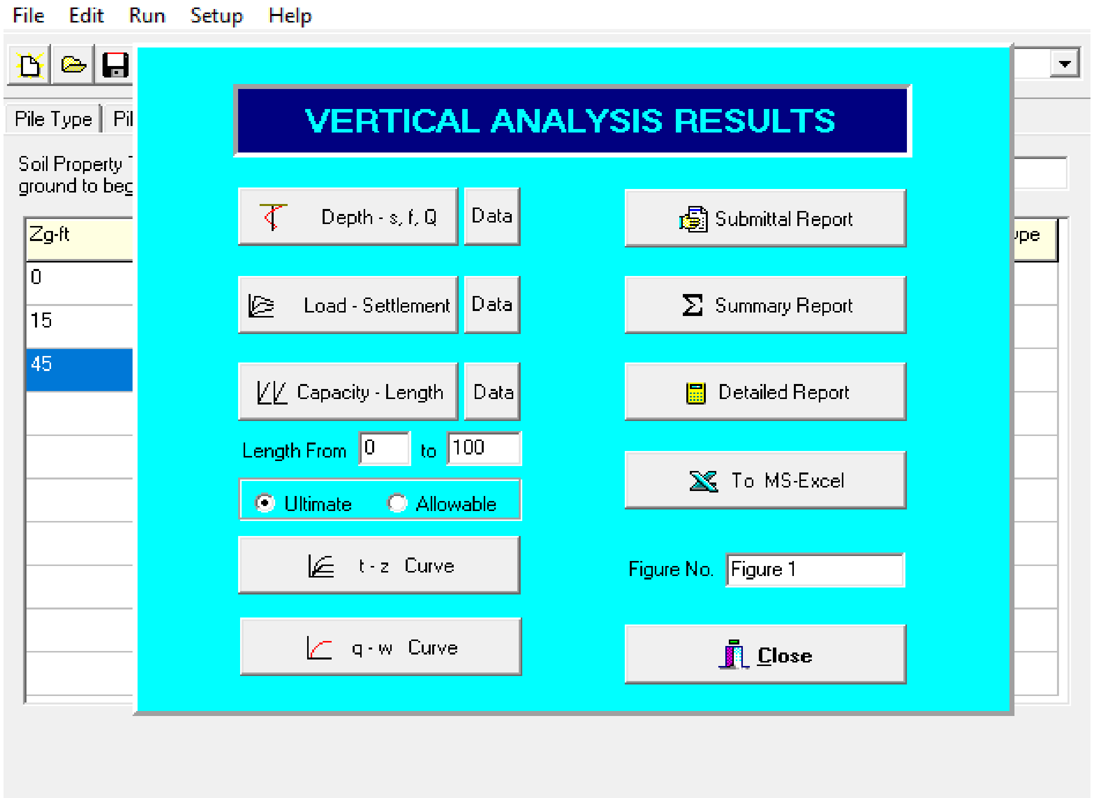

Figure 11: Detailed Output Parameters Generated from Software

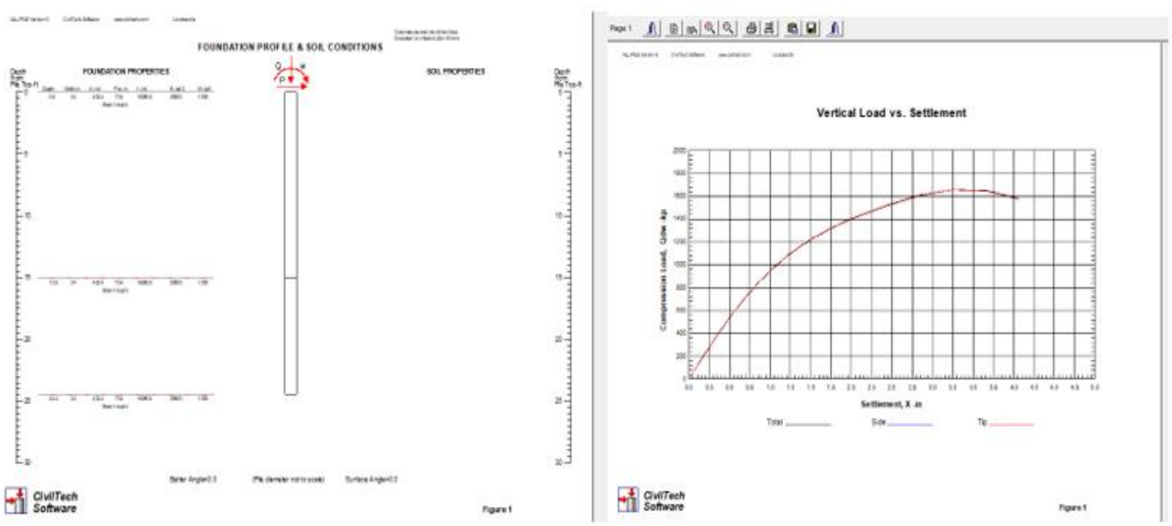

Figure 12: Soil properties & their respective Load and Settlement

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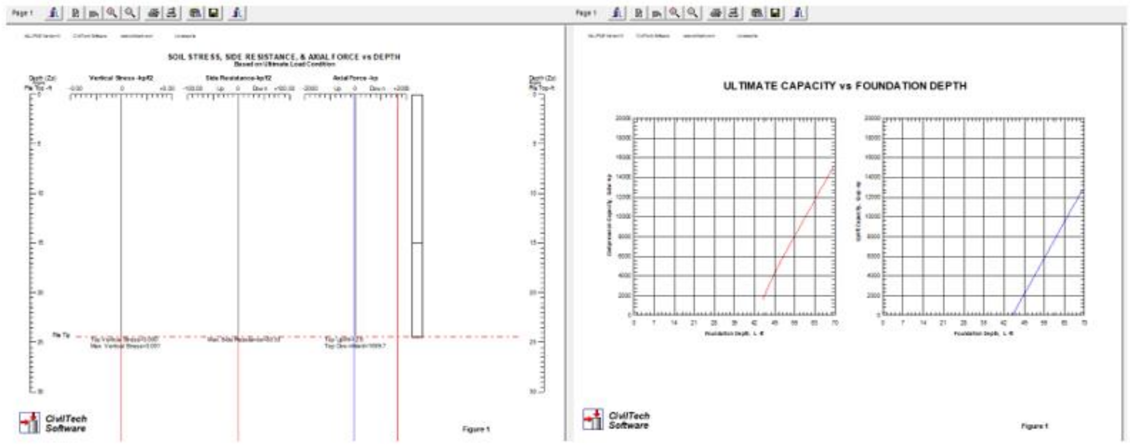

Figure 13: Axial Force, Shear Force & Bending Moment Analysis of the Pile

8. INTERPRETATION OF RESULTS

Once the analysis is complete, the engineer can interpret the results generated by the All-Pile Software as shown in Table 14. The software provides detailed output, including load-displacement curves, stress distributions, and safety factors. The engineer must carefully analyse and validate the results, ensuring they align with the project's design objectives and safety requirements.

Table 14: Relationships between Variables in All Pile Software from Pile Geometry to Analysis of Results

Variables	Relationship	Example
Pile Geometry		
Pile Length	Independent of other geometry parameters	Pile length can be changed without affecting Pile diameter or material properties.
Pile Diameter	Independent of other geometry parameters	Changing pile diameter doesn't affect the length
		Or material properties.
Pile Material Properties	Dependent on the Material chosen	Different materials have different strength
		Properties affecting pile behaviour.
Soil Properties		
Soil Type	Independent of pile geometry	Soil type can be clay, sand, etc.,
Soil Parameters	Dependent on soil type and testing	Parameters like cohesion, friction angle
		Depends on soil type and lab testing.
Applied Loads		
Load Magnitude	Independent of pile and soil parameters	Load magnitude can be changed without
		Altering pile geometry or soil properties.
Load Distribution	Independent of pile and soil parameters	Changing load distribution doesn't affect
		Pile or soil properties.

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Analysis Results		
Pile Capacity	Dependent on pile geometry and soil properties	Capacity influenced by pile geometry (length, diameter) and soil properties (cohesion, Friction angle).
Settlement	Dependent on pile geometry and soil properties	Settlement affected by pile geometry (length,
		Diameter) and soil properties (compressibility).
Lateral Resistance	Dependent on pile geometry and soil properties	Resistance influenced by pile geometry (length,
		Diameter) and soil properties (friction angle).

9. REPORTING AND DOCUMENTATION

The final step involves preparing a comprehensive report documenting the entire geotechnical analysis process using the All-Pile Software. The report should include a clear presentation of input data, analysis settings, results, and their interpretation. Proper documentation is crucial for project records, peer reviews, and future reference. The soil profile is shown in Table 15.

Table 15: Soil profile type

BH No.	Depth (m)	Sample of type	Soil description	UBC soil profile
BH-01	0.0-15	DS	Gravel and alluvial deposits	S_c
	15-45	UDS	Sandstone and siltstone	S_B
BH-02	0-5.0	DS	Gravel and alluvial deposits	S_c
	5.0-45	UDS	Sandstone and siltstone	S_B
BH-03	0-5.0	DS	Gravel and alluvial deposits	S_c
	5.0-45	UDS	Sandstone and siltstone	S_B

9.1 The density of rock mass

The density of rock samples collected from BH No. 1, BH No.2 and BH No.3 were determined. The statistical analysis of the density of the samples for both boreholes is given in Table 16.

Table 16: Statistical analysis of the density of rock samples

BH No.	Rock property	Maximum	Minimum	Mean	Median	Standard Deviation
1	Density (g/cc)	2.5	2.0	2.1	2.1	0.14
2	Density (g/cc)	2.5	1.9	2.1	2.1	0.15
3	Density (g/cc)	2.3	2.0	2.1	2.0	0.10

9.2 Uniaxial compressive strength of rock

The uniaxial compressive strength tests of rock samples collected from BH No. 1, BH No.2 and BH No.3 were conducted. The statistical analysis of the UCS of the samples for both boreholes is given in Table 17.

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Table 17: Statistical analysis of uniaxial compressive strength of rock samples

BH No.	Rock property	Maximum	Minimum	Mean	Median	Standard Deviation
1	UCS (MPa)	35.0	12.2	23.0	22.1	6.99
2	UCS(MPa)	34.3	16.8	23.8	22.2	5.73
3	UCS(MPa)	29.5	9.2	16.9	16.0	5.85

9.3 Rock classification and grading

The rock classification and grading are given in Table 18. The rock classification is based on unconfined compressive strength. Based on uniaxial compressive strength the rock may be classified as weak rock. In comparison with the rock grading, as described by Brown (1981), the rock may be graded as weak to medium strong as shown in Table 18. Considering the lower bound the rock is categorized as R2 (Weak rock) for a safer design.

Table 18: Rock classification and grading

Rock type	Classification	Grade
Sandstone	Weak rock	R_2

9.4 Settlement Criteria

In the research paper, the allowable settlement limits are set at 25 mm for isolated footings and 50 mm for raft foundations. Bearing capacity estimation was conducted according to these limits. For the pile foundation, the estimated settlement ranges between 3.0 mm and 4.0 mm. specifically, under a vertical load (Q = 9316 kN), our calculated settlement is 0.269 cm, whereas a permissible settlement of 2.53 cm has been allowed in our analysis. The loads and settlements are shown in Figure 14.

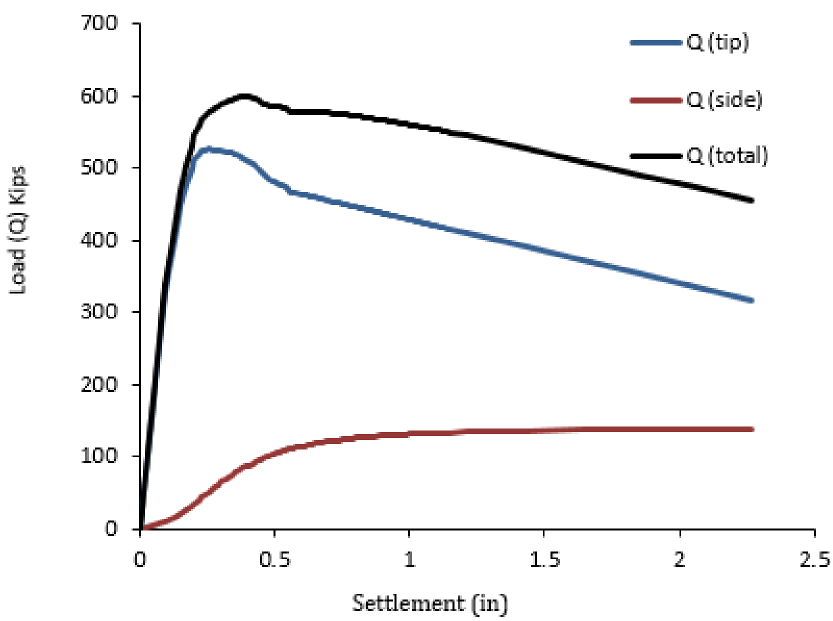

Figure 14: Loads vs Settlement graph

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9.5 Bearing capacity for shallow foundations

The bearing capacity for the top alluvial deposits for the Hub River Bridge is given in Table 19.

Table 19: Hub River Bridge top soil profile/bearing capacity.

BH	Top layer Depth (m)	Description	Bearing capacity (tsf) (top layer)
1	0.0-5.0	Alluvial deposit	2.2
2	0.0-5.0	Alluvial deposit	2.5
3	0.0-5.0	Alluvial deposit	2.4

9.6 Bearing capacity analysis for pile foundation

The bearing capacity analysis was based on the site investigations and laboratory test results of SPT and laboratory investigation results based on shear parameters. The allowable load of pile for bore hole No.1 is mentioned in Table 20.

Table 20: Allowable load as a function of diameter and depth of pile for BH No. 1

Depth (m)	Allowable Load (0.75m)	Allowable Load (1.0m)	Allowable Load (1.5m)	Allowable Load (2.0m)
7	3	4	6	8
8	7	9	13	18
9	11	15	22	30
10	16	22	33	44
11	22	30	45	60
12	29	39	58	77
13	36	49	73	97
14	45	60	89	119
15	54	72	107	143
16	116	158	249	347
17	192	260	402	552
18	269	363	556	757
19	346	465	710	961
20	423	568	863	1166
21	500	670	1017	1371
22	577	773	1170	1576
23	653	875	1324	1781
24	730	977	1478	1986
25	807	1080	1631	2191
26	884	1182	1785	2395
27	961	1285	1939	2600
28	1037	1387	2092	2805
29	1114	1490	2246	3010
30	1191	1592	2400	3215

9.7 Software-based analysis and design

The investigation seeks to learn more about the pile's vertical capacity, settlement patterns, and deflection traits under the 950 tons (9316 kN) applied load. The software is used to simulate and compute crucial parameters, including total ultimate capacity, real

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settlement, and top deflection, using the data in the table. With the help of this careful inspection, determine the pile's structural integrity, ensure that it can support the imposed load with plenty of safety margins, and confirm that it is appropriate for the intended application. The next analysis aims to offer insightful information about the performance and dependability of the pile under the specified loading scenario, supporting a strong foundation design for the project.

10. CONCLUSIONS

In conclusion, the comprehensive geotechnical investigation at the Hub River Bridge site has provided invaluable insights into the challenges posed by alluvial deposits, weak sandstone, and scouring phenomena. Addressing the observed scouring effects is crucial for ensuring the stability of the foundation, necessitating a tailored approach to foundation design. The proposed foundation depth and optimal pile diameter range, validated through All Pile software, offer a balanced solution that meets both structural requirements and cost-effectiveness considerations. This research contributes to advancing geotechnical engineering knowledge and lays a foundation for resilient infrastructure development in similar geological contexts, emphasizing the importance of continuous monitoring and future exploration for further optimization. Based on the comprehensive analysis performed on the pile using All-Pile Software, the following conclusions can be drawn;

Table 21: Pile length for given service load of 950 tons for BH No. 1

Location	BH No.	Pile Diameter (m)	Service load (tons)	Pile length (m)				
				Offset Above river bed	Scour depth	Alluvial	Bed Rock socketing	Total Pile length (m)
		0.75	950	x	6.0	9.0	12.0	27+x
Abutment sides	1	1.0	950	x	6.0	9.0	9.0	24+x
		1.5	950	x	6.0	9.0	6.0	21+x
		2.0	950	x	6.0	9.0	4.0	19+x

950-tons=9316-kN

The Table 21 provides a detailed analysis of pile lengths necessary for varying pile diameters and service loads, accounting for factors like scour depth, alluvial layer thickness, and bedrock socketing. For instance, with a pile diameter of 0.75 meters and a service load of 950 tons, the required pile length is approximately 27+ meters, where "+x" denotes the offset above the riverbed. Similarly, for pile diameters of 1.0 meters, 1.5 meters, and 2.0 meters, the corresponding pile lengths for the same load are approximately 24+x meters, 21+x meters, and 19+x meters, respectively. The pile exhibits outstanding performance across various metrics. Its vertical load-carrying capacity surpasses the applied load, ensuring structural integrity. Settlement is minimal, well below the allowable limit, indicating stable support. Additionally, deflection is negligible, far below the acceptable threshold, affirming structural stability under load.

11. PRACTICAL RELEVANCE AND IMPLICATIONS

This Research Paper offers a significant contribution to learners and practitioners in the field of geotechnical engineering by providing a comprehensive understanding of the challenges associated with bridge foundation design in complex geological settings. It emphasizes the critical importance of addressing scouring effects to ensure the stability of foundations, a factor often overlooked in conventional designs. By proposing a tailored approach to foundation design, incorporating optimal pile diameter ranges validated through sophisticated software, this research offers a unique perspective that balances structural integrity with cost-effectiveness. Moreover, it underscores the broader implications of the findings, highlighting their potential impact on infrastructure development in similar geological contexts worldwide. Learners can benefit from the insights gained here, applying them to real-world scenarios to enhance the resilience and longevity of various construction projects. Additionally, the emphasis on continuous monitoring and future exploration for further optimization opens avenues for ongoing research and innovation in geotechnical engineering, ensuring that learners remain at the forefront of advancements in the field. Overall, this conclusion not only offers valuable insights but also inspires learners to approach geotechnical challenges with creativity, adaptability, and a commitment to continuous improvement.

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