Soil Property Assessment for Drilling Fluid in Trenchless Technique HDD In Black Cotton Soil

Er. Gouri A. Mhetar[1], Tejas Sanjay Kadam[2], Aditya Narayan Velhal[3], Prem Baban Pandhare[4], Rohan Suresh Kadam[5], Aryan Sagar Jadhav[6], Omkar Anandrav Khot[7]

[1,2,3,4,5,6,7]*D Y Patil College of Engineering and Technology Kasaba Bawada, Kolhapur*

Abstract—**The rapid acceleration of urban infrastructure development in India has significantly driven the demand for underground utility networks, including water distribution grids, sewage systems, gas pipelines, and telecommunication lines. Traditional open-cut excavation methodologies present severe socio-economic and engineering challenges, such as heavy traffic disruptions, environmental hazards, noise pollution, and exorbitant pavement restoration expenses. To mitigate these surface disruptions, trenchless technologies, specifically Horizontal Directional Drilling (HDD), have emerged as an efficient and sustainable paradigm shift in subsurface engineering. However, the mechanical safety and long-term success of HDD operations are highly dependent on the complex geotechnical characteristics of the subsurface strata encountered along the arched drilling catenary path. This project, titled "Soil Property Assessment for Trenchless Horizontal Drilling in Black Cotton Soil," focuses on executing a rigorous geotechnical evaluation of highly challenging, moisture-sensitive formations. The empirical framework of this research contrasts two distinct geological environments in Maharashtra: an inland expansive zone at Sangli-Madhavnagar dominated by deep weathered basaltic Black Cotton Soil (BCS), and a highly dynamic coastal-marine interfacial zone at Mumbai-Uran (Pirwadi Beach) characterized by shifting sand-clay stratification. During active field monitoring of tractor mounted HDD rig operations, cutting discharge spoils were manually extracted from slurry containment pits using traditional shovels (Khor) and transport basins (Pati) into high-density polymer sacks (Potya) to preserve structural particle distribution and moisture frames for laboratory transition. Advanced laboratory characterization was carried out at the Geotechnical Engineering Laboratory of D.Y. Patil College of Engineering and Technology (DYPCET), Kasaba Bawada, Kolhapur, strictly conforming to IS: 2720 (Part 5) standards. The experimental program systematically evaluated the consistency limits— Liquid Limit (LL) and Plastic Limit (PL)—of the retrieved soil samples across four separate water-based sodium bentonite drilling fluid concentrations: 0% (Only Water), 5%, 7%, and 10% by weight. The experimental results revealed that progressive bentonite slurry contamination systematically expands the moisture storage framework, driving the index boundaries upward for both soils. The inland Sangli Black Cotton Soil exhibited classic high-plasticity clay (CH) milestones, with its native Liquid Limit of 82.50% and Plasticity Index (PI) of 43.35% jumping aggressively to an extreme threshold of 111.25% (LL) and 68.40% (PI) at the 10% bentonite limit. Conversely, the Mumbai coastal interface displayed poor native binding capacity and lower initial parameters (LL = 31.40%, PI = 9.18%) due to the high dominance of fine intertidal beach sand fractions. However, high-percentage bentonite contact introduced a noticeable cohesive effect, nearly doubling its liquid limit to 61.14% at the 10% concentration milestone. From a process engineering standpoint, these distinct behaviors reveal separate operational risk thresholds for trenchless project design. The highly cohesive, heavy clay matrix of the Sangli formation provides structural support to open borehole walls but poses heavy downhole risks of micro-fissure squeezing, bitballing on reamers, and intense rotational torque spikes as cuttings accumulate in the slurry. In contrast, the Mumbai coastal soil loses cohesion rapidly upon drying and remains loose and sandy, making it highly vulnerable to borehole washouts, fluid loss, and tunnel collapses under shallow intertidal water tables. To mitigate these site-specific challenges, this research highlights that a minimum drilling slurry concentration of 7% to 10% sodium bentonite modified with Carboxymethylcellulose (CMC) polymers is essential to control fluid loss, deposit a low-permeability stabilizing filter cake, and optimize axial pullback loads. Ultimately, the quantitative trends derived from this comparative case study provide a data-driven geotechnical framework to optimize cost-efficiency and operational safety for trenchless infrastructure deployments across expansive clay and variable coastal domains.**

I. INTRODUCTION

The rapid acceleration of global urbanization and macro-infrastructure optimization has exponentially driven the demand for underground utility networks. Traditional civil engineering practices have long relied on conventional open-cut excavation methods to deploy critical subterranean infrastructure, including high-capacity water distribution mains, complex wastewater and sewage grids, high-pressure hydrocarbon pipelines, and dense fiber optic telecommunication conduits. However, in modern dense urban environments and sensitive ecological zones, open-cut excavation presents severe engineering, economic, and socioeconomic challenges. The mechanical tearing of surface pavements induces catastrophic traffic congestion, accelerates the degradation of existing adjacent structures through ground movement, creates substantial noise and air pollution, and imposes exorbitant socio-environmental costs and structural restoration expenses. To mitigate these disruptive parameters, Trenchless Technology has emerged as a disruptive paradigm shift in subsurface geotechnical engineering. Among the diverse suite of trenchless methodologies, Horizontal Directional Drilling (HDD) stands out as the most versatile and technologically advanced mechanism for installing pipelines beneath critical obstacles such as major highways, fully operational railway yards, wide watercourses, and heavily congested metropolitan corridors without disturbing the ground surface architecture. An HDD operation fundamentally follows a structurally engineered three-stage sequence: • Pilot Hole Drilling: Advancing a small-diameter steerable drill bit along a pre-designed catenary curve or arched profile. • Pre-Reaming: Progressively enlarging the subsurface cavity using specialized back-reamers to a dimension typically 1.2 to 1.5 times the outer diameter of the product pipe. • Pipe Pullback: Pulling the continuous, prefabricated structural pipe string through the engineered borehole slurry matrix back to the rig entry point. Despite its logistical advantages, the operational safety, bore-path configuration, and long-term structural efficiency of HDD are absolute functions of the host subsurface formation's geotechnical and rheological response. A highly challenging macro-geologic formation for trenchless applications is the expansive Black Cotton Soil (BCS), which blankets vast geological structural expanses across central and western India, particularly within the Deccan Traps region of Maharashtra. Characterized by an abundance of active montmorillonite clay minerals, Black Cotton Soil exhibits high moisture sensitivity, pronounced volume fluctuations (highly expansive shrink-swell mechanics), high plasticity, and remarkably low shear strength profiles under saturated conditions. Executing trenchless directional drilling within such an erratic structural medium changes the project from a standard pipeline installation into a complex geotechnical engineering problem.

II. LITERATURE REVIEW

The engineering properties of expansive black cotton soils and the interface behaviors of stabilization and lubrication mechanisms in underground execution are major focal points in geotechnical research. The following analyses review the critical findings, empirical frameworks, and academic lineages extracted from key modern research papers.

1."Effect of Bentonite Support Fluid on Pile Capacity"
Authors: Keerthi Sabu and Benny Mathews Abraham (2020)
The researchers investigated the impact of support fluids on borehole stability and the resulting alterations to the interface shear strength parameters between structural foundations and surrounding soils. Ordinary Portland Cement (43 Grade) was used to precast baseline cement mortar blocks (60 x 60 x 12.5 mm) representing structural concrete boundaries. Laboratory simulations were performed using a specialized direct shear apparatus with a (60 x 60 x 50 mm) shear box. A layer of commercially available, highly expansive sodium bentonite slurry was applied directly over the precast cement blocks at varying consistencies to evaluate critical boundary performance. Multiple host soils — including fine sand, medium sand, coarse sand, well-graded sand, marine clay, and red earth — were subjected to normal pressures to determine the structural degradation profiles of the angle of shearing resistance and cohesion.

Key Findings:

- Testing bentonite at its liquid limit (LL) water content established the most critical performance decline across the shearing plane. At this point, the interface parameter friction angles decreased dramatically.

- For cohesionless soils (pure sand interface), the structural wall friction angle experienced a 28% reduction from its native state without support fluids, which worsened to a massive 72% reduction when the bentonite filter cake layer was explicitly accounted for.
- In cohesive soil formats (marine clay matrix), the presence of a bentonite fluid layer at the concrete boundary decreased the measured cohesion value by approximately 75%.
- Total calculated skin frictional resistance dropped by 24% to 56% in sand-concrete interfaces, 64% in red earth interfaces, and 84% in marine clay-concrete configurations. This underscores the severe structural lubrication and mechanical weakening that occurs when drilling fluid interactions are not controlled.

2. "Determination of Effect Bentonite and Additives on Drilling Fluids"
Authors: Dr. A. Rajesh Kanna, Preethi, Syed Majid Ahmed Savi, Mujtaba Ahmed Khan, and Mohammed Abdul Rahman Khan (2017)
This study evaluated the rheological performance, viscosity profiles, and fluid-loss filtration characteristics of water-based muds (WBM) combined with specific chemical polymers. Fluid properties were evaluated using standard laboratory equipment, including a viscosity cup (for tracking 100 mL sample elution rates), digital pH meters, mud balances for exact specific gravity mapping, and filter press assemblies to simulate high pressure mud cake growth under borehole parameters. Formulations mixed 150 mL of water with 5 g of bentonite and 10 g of barite, testing performance against variable additions of Polyacrylamide (PAM), Carboxymethylcellulose (CMC), and organic starch compounds.

Key Findings:

- Water-based mud relies on clay and polymer additives to generate structural viscosity, which expands the dynamic lifting capacity for subterranean drill cuttings and forms an effective mud cake to manage fluid loss.
- Comparing performance properties showed that Carboxymethylcellulose (CMC) additives yielded substantially higher viscosity metrics compared to parallel blends containing polyacrylamide (PAM) or organic starches.
- CMC formulations demonstrated highly efficient fluid-loss control, recording minimal to zero fluid infiltration leakage under press conditions compared to other combinations. This identifies CMC as a highly effective additive for sealing permeable, shifting geological formations.

III. OBJECTIVE

The overriding aim of this research is to execute a rigorous, systematic geotechnical assessment of Black Cotton Soil properties in the designated region, and establish an engineering framework to determine its operational suitability and risk thresholds for trenchless Horizontal Directional Drilling (HDD) applications. To achieve this comprehensive aim, the project is structured around the following three core objectives:

1. Site Characterization, Field Sampling, and Empirical Case Study Validation:

To map out representative construction zones exhibiting high concentrations of expansive clay formations and retrieve high-quality disturbed and undisturbed core samples as per IS: 2720 standards. This objective is achieved through direct field case studies to cross-examine practical performance parameters, specifically mapping inland expansive soil behavior at the Sangli-Madhavnagar site and dynamic coastal-marine interface interactions at the Mumbai-Uran (Pirwadi Beach) site.

2. Advanced Laboratory Geotechnical Quantification and Fluid Interaction Analysis:

To subject the retrieved site samples to systematic laboratory testing protocols at DYPCET, Kolhapur, to establish index and engineering design values. This involves evaluating Atterberg Limits (LL, PL, PI), Free Swell Index (FSI), Specific Gravity, and Direct Shear strength parameters, while experimentally analyzing the physical changes and mud-loss vulnerabilities that occur when water-based bentonite-polymer drilling slurries interface with the active clay matrix.

3. Suitability Matrix Categorization and Formulation of Design Guidelines

To synthesize the collected laboratory and field case study data into an engineering classification matrix that categorizes soil zones into 'Suitable', 'Conditionally Suitable', or 'Unsuitable' profiles relative to HDD technical capacities. Based on this categorization, the objective is to formulate practical site recommendations covering drilling fluid adjustments, optimal mud pressures, precise tool configurations, and chemical stabilization methods to ensure stable trenchless operations.

IV. METHODOLOGY

The empirical evaluation and field verification framework of this research encompass two distinct geographic and geological construction zones in Maharashtra, India:

1. Inland Expansive Zone:

Sangli-Madhavnagar Geographic Parameters: Located within the southern segment of the Deccan Trap geological province, this urban utility corridor is characterized by semi-arid conditions.

Geotechnical Stratum: The subgrade consists of a deep, highly uniform layer of weathered basaltic Black Cotton Soil (BCS) extending to depths of 3.5 m to 8.0 m. This location features high clay concentrations, significant plasticity indexes, and strong shrink-swell behaviors, making it an ideal field baseline for monitoring borehole deformation, tool-clogging, and steering deviations.

2. Coastal Interfacial Zone:

Mumbai-Uran (Pirwadi Beach) Geographic Parameters: Situated along the high-dynamic Konkan coastal strip, interfacing directly with marine deltaic and beach infrastructure alignments.

Geotechnical Stratum: This site presents a challenging, highly stratified matrix that transitions rapidly from loose, high-permeability intertidal sand beds to heavy marine alluvial clays. With a shallow water table fluctuating close to the surface (0.5 m to 1.8 m), this environment provides a practical framework for investigating borehole washouts, slurry dilution, and dynamic fluid backpressures.

V. RESULTS

Experimental Findings and Data

Synthesis The laboratory tracking program executed at the Geotechnical Engineering Laboratory of D.Y. Patil College of Engineering and Technology (DYPCET), Kolhapur, systematically monitored the consistency limit shifts of the host formations under varying drilling fluid boundaries. The consolidated empirical milestones derived from multi-point Casagrande impact blows and handrolling crumbling threads are structured in the table below.

Table 1: Atterberg Limits of Both Soil Samples under Varying Bentonite Concentrations

Parameter	0% (Water Only)	5% Bentonite	7% Bentonite	10% Bentonite
Sangli-Madhavnagar Black Cotton Soil (Inland — CH Classification)				
Liquid Limit (LL) %	82.50	93.40	101.80	111.25
Plastic Limit (PL) %	39.15	42.60	45.50	42.85
Plasticity Index (PI) %	43.35	50.80	56.30	68.40
Mumbai-Uran (Pirwadi Beach) Coastal Interfacial Soil (Sandy-Clay)				
Liquid Limit (LL) %	31.40	43.20	52.70	61.14
Plastic Limit (PL) %	22.22	26.80	31.40	34.50
Plasticity Index (PI) %	9.18	16.40	21.30	26.64

Fluid-Induced Plasticity Alterations

The consolidated experimental data demonstrates that progressive additions of sodium bentonite directly increase both the Liquid Limit (LL) and Plasticity Index (PI) values across both geological study areas. This occurs because sodium bentonite contains highly active clay fractions with high specific surface areas. Introducing these particles expands the soil's moisture holding framework, shifting the Atterberg consistency boundaries upward.

Sangli CH Soil Cohesion Performance

The inland Sangli black cotton soil displays classic high-plasticity clay (CH) behavior. Laboratory observations recorded highly uniform mixing, stable sample configurations, and smooth Casagrande groove closures across all bentonite steps. This high cohesive behavior provides a structural advantage by helping support open borehole paths during directional drilling. However, it also introduces operational risks: as highly cohesive clay cuttings disperse into the drilling mud, they can cause viscosity spikes (up to 111.25% at 10% concentrations), leading to tool balling and high rotational torque resistance.

Mumbai Coastal Interfacial Breakdown

In contrast, the Mumbai intertidal soil sample behaves differently. While it exhibits workability at high moisture levels, drying causes the sample to break down into a loose, sandy texture. This lack of cohesion made manual thread rolling and groove alignment difficult in the laboratory, resulting in variable blow counts. For real-time HDD execution under shallow coastal water tables, this non-cohesive behavior indicates a high vulnerability to borehole washouts and sand collapses. Managing these conditions requires specialized polymer drilling fluids to control fluid loss and deposit a stabilizing filter cake along the borehole path.

High Squeezing Profile — Sangli

Soil The native soil from the Sangli-Madhavnagar zone belongs to the high-plasticity clay (CH) category. Throughout all laboratory evaluations, the soil sample displayed excellent plasticity and high cohesive strength. The Casagrande groove channel closed smoothly and uniformly, reflecting steady structural binding characteristics. For directional drilling projects, this high binding capacity indicates that the borehole walls have sufficient cohesive strength to support themselves initially. However, as the liquid limit rises to 111.25% under slurry contact, the active clay matrix expands rapidly. This volume expansion can exert intense inward squeezing forces against the rotating boring pipes. Furthermore, when these highly plastic clay cuttings disperse into the drilling fluid, they cause mud viscosity to rise sharply. This leads to severe bit-balling on the reamers, high rotational torque resistance, and risks of complete downhole tool immobilization if circulation pressures are not carefully controlled.

Non-Cohesive Washout Mechanism — Mumbai Site

The Mumbai-Uran (Pirwadi Beach) coastal intertidal sample displays lower consistency limits, reflecting its high sand fraction. Laboratory observations noted that while the soil appears workable at high moisture contents, drying causes it to lose cohesion quickly and break down into a loose, sandy texture. This low cohesion made manual thread rolling difficult, leading to premature cracking and inconsistent results. In real-time horizontal operations under shallow coastal water tables, this poor binding capacity presents severe challenges. The unconstrained borehole path cannot support its own overburden pressure, making it highly vulnerable to sand sliding, fluid loss, and complete tunnel washout. To mitigate these risks, the drilling mud requires a higher concentration of bentonite (7% to 10%) combined with specialized Carboxymethylcellulose (CMC) polymer modifiers. This polymer blend helps control fluid loss and deposits a durable, stabilizing filter cake that seals the permeable sand layers and maintains the designed borehole profile.

VI. CONCLUSION AND FUTURE SCOPE

Based on the detailed laboratory investigation, experimental calculations, and comparative geotechnical interpretation carried out during this research, it can be concluded that sodium bentonite drilling slurry has a major influence on the engineering behavior of subsurface soils encountered during trenchless HDD operations. The study clearly demonstrates that the addition of bentonite significantly increases the Liquid Limit and Plasticity Index values of soils because of the high montmorillonite content, strong hydration characteristics, and swelling capacity of sodium bentonite particles. The Sangli-Madhavnagar black cotton soil consistently exhibited the characteristics of a high-plasticity clay (CH) formation. The soil possessed high cohesion, strong moisture retention capacity, and excellent plastic behavior throughout all stages of testing. As bentonite concentration increased, the soil became progressively more cohesive and viscous, eventually reaching extremely high consistency limits at the 10% slurry concentration. From a trenchless HDD perspective, this behavior presents both engineering benefits and operational risks. The strong cohesive structure of the soil can help support open borehole walls and reduce immediate collapse risks. However, the same high plasticity also creates severe challenges such as swelling pressure development, bit-balling on reamers, high rotational torque resistance, increased pullback loads, and possible downhole tool immobilization if slurry circulation is not controlled properly. The Mumbai-Uran coastal soil displayed a completely different engineering response. The high sandy particle fraction and low natural clay content resulted in weak cohesion and low consistency limits under native conditions. Although bentonite addition improved the plasticity and moisture retention characteristics of the soil, the formation still remained highly vulnerable to instability. During laboratory testing, the soil rapidly lost cohesion after drying and behaved like loose beach sand, creating substantial difficulties during groove closure and plastic thread rolling procedures. These observations accurately represent the conditions likely to occur during HDD operations in coastal sandy formations. Under shallow groundwater environments, such soils are highly susceptible to borehole washouts, slurry loss, sand sliding, and tunnel collapse. Therefore, maintaining borehole stability in coastal regions requires higher bentonite concentrations combined with polymer modifiers such as Carboxymethylcellulose (CMC) to reduce filtration losses and create a durable stabilizing filter cake.

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