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Design of Embankment on Soft Ground Conditions

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Abstract

Designing embankments on soft ground presents significant engineering challenges due to low shear strength, high compressibility, and potential risk for long-term settlement. This case study of Dohazari Cox's Bazar Railway Project (DCRP) investigates the design of an embankment constructed on soft soil conditions, focusing on geotechnical assessment, ground improvement strategies, and risk assessment. Detailed site investigations revealed the presence of soft clay layers with low bearing capacity, necessitating the adoption of specialized ground improvement techniques such as prefabricated vertical drains (PVDs), staged construction, and preloading to accelerate consolidation and enhance stability. High strength geotextiles are also used for the stability purpose. Numerical modeling and stability analyses were conducted to optimize the design parameters, ensuring safety against slope failure and excessive deformation. Instrumentation data collected during and after construction validated the design approach and confirmed the effectiveness of the mitigation measures. This study provides practical insights and design recommendations for engineers and practitioners dealing with infrastructure development on soft subsoil, emphasizing the importance of adaptive and evidence-based engineering in soft ground environments.

Keywords

Case Study, Geotechnical Design, Embankment, Soft Soil

1. Introduction

Embankments over soft ground present unique geotechnical challenges due to the low bearing capacity, high compressibility, and long-term settlement behavior of such soils. A successful design must ensure both short-term stability during construction and long-term serviceability. The integration of conservative assumptions, observational approaches, and adaptive construction practices is essential to mitigate risks associated with soil variability and ensure the safety and effectiveness of the embankment system [1].

Chu *et al.* (2012) detailed various ground improvement techniques, including vertical drains, vacuum consolidation, and geosynthetic-reinforced column/pile supported embankment systems [2]. They stressed the importance of adaptability to site-specific conditions. Low & Tang (1997) developed reliability-based methods for estimating reinforcement force requirements in soft ground embankments [3]. Their probabilistic approach improved design precision under uncertainty. Chai *et al.* (1994) analyzed stress contours to assess embankment stability and settlement behavior [4]. Their case study linked numerical predictions to field observations. Mamat *et al.* (2019) reviewed stability issues, construction constraints, and recent innovations in soft ground embankment design [5]. The paper provided a synthesis of practical lessons from Southeast Asia. Balasubramaniam *et al.* (2010) analyzed long-term settlement behavior and geotechnical responses under embankments built in Southeast Asia [6].

Ensuring embankment stability on soft ground is critical. Kirby (1972) established the two primary requirements for embankments on soft soil: ensuring stability (no bearing failure) and limiting settlement within acceptable limits [7]. The study emphasized preloading and staged construction to control consolidation. The use of limit equilibrium methods, such as Bishop's simplified method, remains prevalent for assessing slope stability (Duncan *et al.*, 2014) [8]. However, finite element modeling (FEM) has become increasingly popular for analyzing complex soil-structure interactions. Chai *et al.* (2021) demonstrated that FEM can predict failure mechanisms in soft clay embankments with greater accuracy [9]. Recent advancements include the incorporation of probabilistic approaches to account for soil variability (Griffiths & Fenton, 2023) [10].

Accurate settlement prediction is essential for long-term performance. Terzaghi's one-dimensional consolidation theory (1943) remains a cornerstone, but its limitations in capturing three-dimensional effects have led to the use of advanced models like the Biot consolidation theory (Biot, 1941) and numerical simulations (e.g., PLAXIS) [11]. Indraratna *et al.* (2022) highlighted the importance of considering creep effects in organic soils, which can lead to significant secondary consolidation over time [12]. Machine learning models for settlement prediction are emerging, with Wang *et al.* (2023) demonstrating improved accuracy in complex soil conditions [13].

To mitigate instability and excessive settlements, various ground improvement techniques are employed, such as Preloading with surcharge, Prefabricated vertical drains (PVDs), Geosynthetic reinforcement, lightweight fill materials, Deep Soil Mixing and Jet Grouting, etc. Preloading with surcharge accelerates consolidation by applying temporary loads. Kelly & Na (2019) reported that preloading combined with vertical drains can reduce consolidation time by up to 70% [14].

Prefabricated vertical drains (PVDs) are widely used to enhance drainage and accelerate consolidation. Chu *et al.* (2020) demonstrated that PVDs, when properly spaced, can reduce settlement time significantly in soft marine clays [15]. Geosynthetic reinforcement, such as geotextiles or geogrids, improves stability and reduces lateral spreading. Bonaparte & Christopher (1987) analyzed the behavior of embankments reinforced with geosynthetics, especially in marine clays [16]. Their study demonstrated improved stability and reduction of lateral displacement through reinforcement. Bush *et al.* (1990) introduced the use of geocell foundation mattresses to enhance the bearing capacity of soft soils under embankments, marking a shift towards lightweight and flexible reinforcement [17]. Zheng *et al.* (2009) further evaluated the performance of geosynthetics and pile walls combined, showing superior results in terms of settlement and load distribution [18]. Rowe & Li (2021) found that basal reinforcement with geogrids can increase the factor of safety by 20% - 30% [19]. Briançon & Simon (2012) conducted full-scale experiments on pile-supported embankments. Their method improved differential settlement control and increased construction speed [20]. Poulos (2007) provided design charts for pile-embankment systems on soft clay, integrating various loading and settlement conditions [21]. Using lightweight materials like expanded polystyrene (EPS) or lightweight aggregates reduces the load on soft ground. Horvath (2023) noted that EPS geofoam can reduce settlements by up to 50% compared to traditional fills [22]. These techniques improve soil strength by mixing cement or lime with soft soil. Shen *et al.* (2022) reported that deep soil mixing can increase bearing capacity by 2 - 3 times in soft clays [23]. Construction on soft ground requires careful sequencing and monitoring. Staged construction, where the embankment is built in layers to allow consolidation between stages, is a common practice (Tavenas & Leroueil, 1980) [24]. Instrumentation, such as piezometers and settlement plates, is critical for monitoring pore pressure and deformation during construction (Bo *et al.*, 2021) [25]. Recent advancements include real-time monitoring using IoT-based sensors for early detection of instability (Zhang *et al.*, 2023) [26]. Indraratna *et al.* (2020) documented the use of PVDs and vacuum preloading to construct a highway embankment on soft Bangkok clay, achieving 90% consolidation within 6 months [27]. Lightweight fill and geosynthetic reinforcement were used to minimize settlements on soft estuarine soils, as reported by Wong & Muttuvel (2022) [28]. Deep soil mixing and staged construction were employed to stabilize embankments on soft marine clay, reducing settlements to acceptable levels (Han *et al.*, 2021) [29]. Challenges include predicting long-term creep, managing soil variability, and addressing environmental concerns like carbon emissions from cement-based stabilization. Emerging research explores sustainable alternatives, such as microbial-induced calcite precipitation (DeJong *et al.*, 2023) [30], and machine learning for predictive modeling (Stark *et al.*, 2020) [31]. Climate change impacts, such as rising groundwater levels, necessitate adaptive design strategies.

This literature review synthesizes key findings from recent studies and established works on the design and construction of embankments on soft ground, focusing on soil characterization, stability analysis, settlement prediction, ground improvement techniques, and construction practices. This case study of Dohazari Cox's Bazar Railway Project (DCRP) outlines key aspects of embankment design over soft soils, including geotechnical characterization, settlement and stability assessment, ground improvement methods, construction staging, and risk assessment.

2. Design Criteria

2.1. Engineering Standards and Guidelines

There is no specific engineering standard or guideline formally nominated in the Project Design Criteria. Consequently, the earthwork design has been developed based on drawing upon past project experience, recognized industry best practices, and, where relevant, established guidelines published by the **Ministry of Railways, Government of India.** These reference documents have been selectively applied to enhance the performance and reliability of the proposed design.

- Government of India Ministry of Railways, Guidelines for Earthwork in Railway Projects (Guideline NO. GE: G-1).
- Government of India Ministry of Railways, Guidelines for Cuttings in Railway Formations (Guideline NO. GE: G-2).
- Government of India Ministry of Railways, Guidelines on Soft Soils-Stage Construction Method (Guideline NO. GE: G-5).

Table 1. Key design criteria.

Item	Description of Criteria	Criteria	Reference
1	Design life of embankments	Design Life = 100 years	As agreed with Stakeholders.
2	Long term stability for the whole batter, part thereof, or individual batters between benches	Factor of Safety ≥ 1.4	Guidelines for Earthwork in Railway Projects Guideline No. GE: G-1, July 2003, Ministry of Railway, Government of India.
3	Short term stability for the whole batter, part thereof, or individual batters between benches	Factor of Safety ≥ 1.2	Guidelines for Earthwork in Railway Projects Guideline No. GE: G-1, July 2003, Ministry of Railway, Government of India.
4	Seismic stability for the whole batter, part thereof, or individual batters between benches	Factor of Safety ≥ 1.0	Designer nominated as per Industry practice
5	Post construction settlement following track opened for public	40 mm per year	As agreed with Stakeholders.
6	Total post construction settlements settlement at bridge approach and culvert following 100 years after track opened for public	150 mm	As agreed with Stakeholders.

2.2. Design and Performance Criteria

The key design and performance criteria for embankments, as agreed upon with the stakeholders, are summarized in Table 1. These criteria align with the relevant guidelines issued by the **Ministry of Railways, Government of India,** ensuring consistency with national best practices and facilitating long-term performance and durability of the earthwork structures.

3. Geology and Geotechnical Aspects

3.1. Seismicity and Tectonic Setting

The Historical seismicity data for Bangladesh and its adjoining regions indicate that the country is seismically vulnerable. This vulnerability stems from the tectonic interaction between the northward-moving Indian Plate and the Eurasian Plate, resulting in active geological deformation across the region. Over the past 100 years, more than 1000 earthquakes with a magnitude (M) ≥ 4.0 have been recorded within Bangladesh and nearby areas, highlighting the region's significant seismic activity. According to the Earthquake Zoning Map provided in the Bangladesh National Building Code (BNBC-1993), study project is situated within Seismic Zone 2 (Figure 1), indicating a moderate level of seismic risk that must be considered in the engineering design and structural detailing of project components.

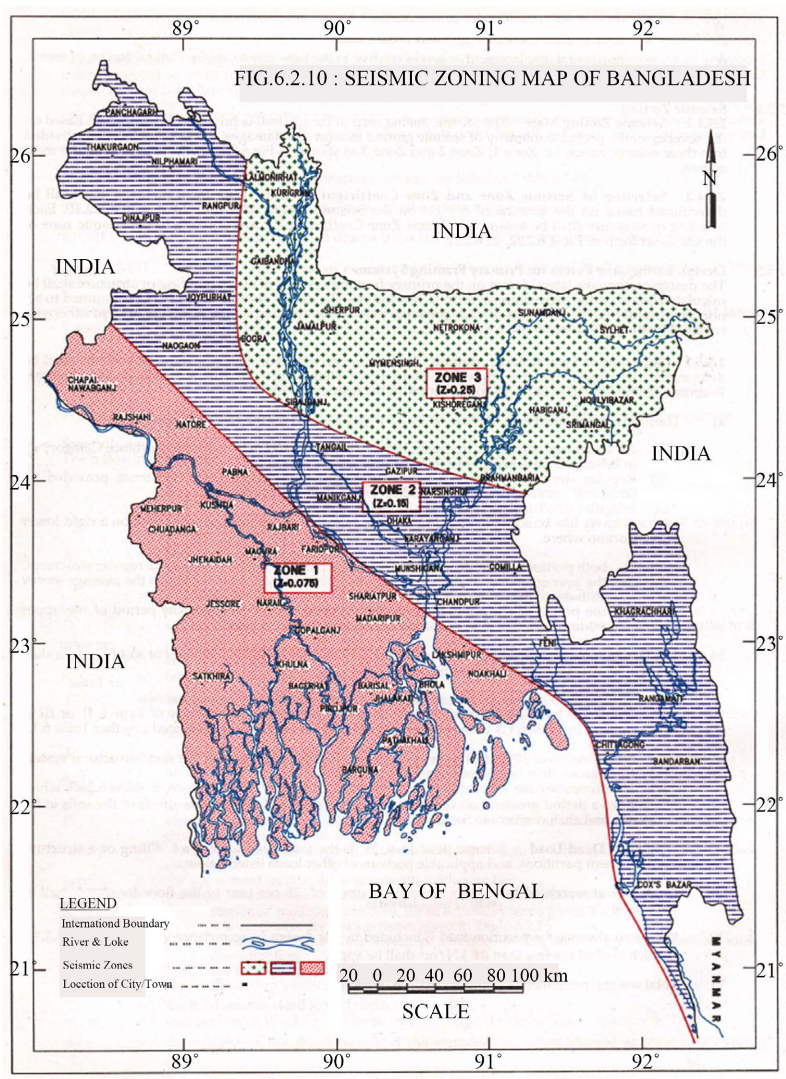

Figure 1. Seismic zoning map of Bangladesh (BNBC-1993) [32].

It is widely recognized in both international and national geotechnical engineering practice that flexible structures—such as earth embankments, soil nail walls, and mechanically stabilized earth (MSE) systems—are capable of accommodating lateral displacements without significant structural distress. Consequently, the horizontal seismic design coefficient for such structures is typically taken as half of the peak horizontal ground acceleration (PGA), in accordance with established guidelines such as those from the Federal Highway Administration (FHWA) and Australian Standard AS 5100.2.

Based on this principle, and considering the PGA value of 0.17 g for the project site (as per BNBC-1993), the adopted horizontal seismic design coefficient for embankment stability analysis is:

$$k_h = 0.5 \times 0.17\ \text{g} = 0.085\ \text{g} \quad (1)$$

This reduced coefficient reflects the deformable nature of the embankment structure while ensuring compliance with recognized seismic design approaches for geotechnical systems.

3.2. Basic Characteristics of Soils

The earthwork design presented in this report has been developed based on borehole logs and laboratory test results available at the time of design. The subsoils encountered along the proposed alignment have been classified primarily on the basis of mechanical particle-size grading, index properties, and Standard Penetration Test (SPT-N) values. The mechanical grading and plasticity characteristics of the subsurface materials have been derived from laboratory testing, and the material descriptions are consistent with those presented in the borehole logs. Sub-soil investigations were conducted through 378 boreholes, with depths ranging from 16 m to 35.5 m along the alignment. The predominant strata encountered comprise Clayey Silt, Silty Clay, and Sand, with compressible layers typically varying between 5 m and 10 m in thickness. A series of laboratory tests was carried out, including moisture content, specific gravity, grain size distribution, hydrometer analysis, Atterberg limits, and relative density. In addition, strength and stiffness characteristics were evaluated through Unconfined Compression (UC), Consolidated Drained Direct Shear (DS), Unconsolidated Undrained Triaxial (UU), Consolidated Undrained Triaxial (CU), and One-Dimensional Consolidation tests. While the classification of soils based on mechanical grading and index testing may appear elementary, these tests capture the key geotechnical properties that govern soil behavior in practical engineering contexts. It is acknowledged that the mineralogical, chemical, and geological origin of soils can influence their mechanical response. However, as supported by the foundational work of Schofield and Wroth (1968), these effects are generally reflected adequately in index test results, which are widely accepted as reliable indicators of engineering behavior in design practice. Based on the one-dimensional consolidation tests, the design values of C_v, C_{ce}, and C_{re} are obtained. Parameters estimated using empirical correlations with average initial void ratio

(e_0), moisture content (MC), and Atterberg limits (liquid limit, LL, and plasticity index, PI) are also investigated and compared for the setting of adopted design values. Secondary compression/creep consists of the residual primary consolidation settlement together with the subsequent creep settlement. The modified secondary compression index adopted in this project is based on the average value recommended by Mesri and Godlewski (1977), *i.e.*, $C_{\alpha\varepsilon}$ (NC) = 0.03 × $C_{c\varepsilon}$. To comply with the design performance criteria, long-term creep settlement was mitigated through the application of an additional surcharge load to the foundation soils. Geotechnical design parameters are provided in Table 2 in accordance with NAVFAC [33].

Table 2. Geotechnical design parameters.

Soil/Material Type	Consistency/ Relative Density	SPT-N	C_u	γ	ν	c	ϕ'	E'	C_v	C_{ce}	C_{re}	$C_{\alpha\varepsilon(NC)}$
			(kPa)	(kN/m³)	-	(kPa)	(⁰)	(MPa)	(m²/yr)			
Fine Grained Non-Organic Soil (Sandy CLAY, Silty Clay, Sandy SILT, Clayey SILT)	Very Soft	0 - 2	6 N	18.5	-	0 - 1	24	-	5	0.18	0.027	0.005
	Soft	2 - 4	6 N	19.0	-	1 - 2		-	5			
	Firm	4 - 8	6 N	19.0	-	1 - 4		-	8			
	Stiff	8 - 16	6 N	19.0	-	2 - 8		-	8			
	Very Stiff	16 - 32	6 N	19.0	-	4 - 16		-	10			
	Hard	>32	6 N	20.0	-	4 - 16		-	10			
Coarse Grained Soil (Fluvial Sand)	Very Loose	0 - 4	-	18.5	0.3	0	28	2 N	-	-	-	-
	Loose	4 - 10	-	19.0	0.3	0	30	2 N	-	-	-	-
	Medium Dense	10 - 30	-	20.0	0.3	0	34	2 N	-	-	-	-
	Dense	30 - 50	-	21.0	0.3	0	37	2 N	-	-	-	-
	Very Dense	>50	-	21.0	0.3	0	40	2 N	-	-	-	-
Drainage Blanket	-	-	-	21	0.3	-	35	50	-	-	-	-
Embankment Fill	-	-	-	20	0.3	5	30	30	-	-	-	-
Subgrade	-	-	-	21	0.3	-	40	60	-	-	-	-

Groundwater has been observed at or near the existing ground surface across the project site. This condition is primarily attributed to the extensive network of canals and water bodies in the vicinity, which exerts a significant influence on the local groundwater regime. Given this observation, and in the absence of data indicating sustained seasonal variation, the groundwater level is conservatively assumed to coincide with the existing ground level for the purpose of the embankment design. This approach ensures that the design remains robust under potentially saturated conditions, particularly in stability and settlement assessments.

4. Design Methodology

4.1. Nomenclature of Embankment Design

The following nomenclature (Figure 2) has been adopted throughout this report to describe the key components, parameters, and features associated with the embankment design over soft ground conditions:

- H = Fill height (surcharge, embankment) from EGL to surcharge level.
- H_s = Surcharge thickness.
- H_E = Fill height from EGL to finished surface level.
- H_T = Total fill thickness (surcharge, embankment, and settlement).
- H_F = Total fill thickness including settlement.

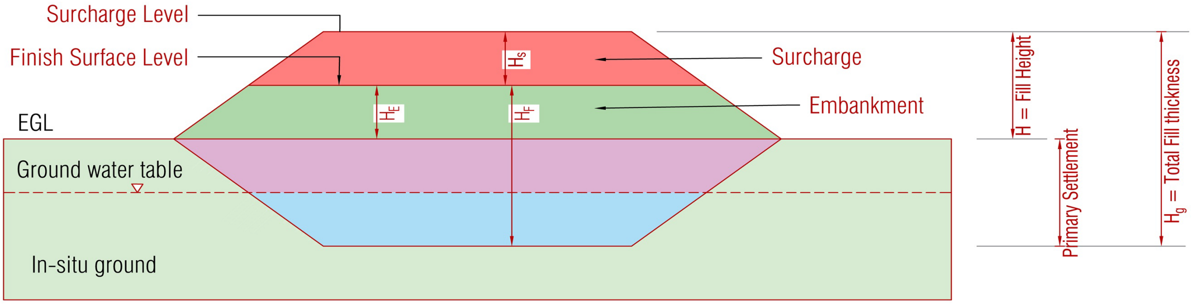

Figure 2. Nomenclature of preload embankment.

4.2. Primary Settlement

The assessment of embankment-induced settlement has been conducted using established one-dimensional consolidation theory, with the choice of method tailored to the soil type and its stress-strain response characteristics. Two analytical approaches are considered, based on the relationship between the final effective stress (σ'_f) and the pre-consolidation pressure (σ'_p):

1) m_v Method (Elastic Compression Method)

This approach is applicable to:

- Coarse-grained soils, and
- Very stiff to hard clayey materials, where the stress-strain behavior is predominantly elastic, and $\sigma'_f < \sigma'_p$.

Settlement is estimated using:

- Coefficient of Volume Compressibility (m_v), or
- Elastic Modulus (E').

This method assumes minimal plastic deformation and is typically used in overconsolidated soils or conditions where applied loads remain within the elastic range of the soil structure.

2) $C_{c\varepsilon}$-$C_{r\varepsilon}$-OCR Method (Elasto-Plastic Compression Method)

This approach is suitable for:

- Clayey soils, particularly normally consolidated or lightly over-consolidated clays, where the stress-strain response includes both elastic and plastic behavior and $\sigma'_f > \sigma'_p$.

Settlement is evaluated using:

- Modified Compression Index ($C_{c\varepsilon}$).
- Modified Recompression Index ($C_{r\varepsilon}$).

- Over-Consolidation Ratio (OCR).

This method accounts for pre-consolidation effects and is generally applied in soft compressible soils where significant plastic deformation is expected under the applied loading.

4.3. Global Stability

The global stability of the approach embankments has been evaluated under both temporary and permanent loading conditions, considering the various stages of construction and anticipated soil strength development. The stability assessments address the following critical scenarios:

- Construction/Fill Placement Stage: Evaluated both with and without short-term strength gains from consolidation.
- Surcharge Stage: Considered with strength improvement due to primary consolidation and time-dependent gain in undrained shear strength.
- Final Construction Stage: Assessed at the Finished Surface Level (FSL) incorporating estimated long-term strength gains.

To ensure compliance with the required factors of safety (FoS), reinforcement measures such as high-strength geotextiles and/or stabilizing berms may be employed. In cases where higher tensile capacity is required, multiple geotextile layers can be incorporated into the design.

The global stability analysis was performed using a limit equilibrium approach, implemented via SLOPE/W (Version 2007), a commercial geotechnical analysis software. The analysis involves:

- Calculation of FoS for multiple trial slip surfaces, using both circular and composite geometries.
- Identification of the critical slip surface—defined as the slip surface that yields the minimum FoS under the given conditions.
- The Entry and Exit method is primarily used to define potential failure zones, and results are cross-validated using the Auto Locate slip surface function for reliability.
- The reinforcement effect of high-strength geotextiles is simulated in SLOPE/W using the "fabric element" feature, with necessary input parameters.
- The geotextile strength values used in the analysis correspond to working stress conditions—*i.e.*, no safety factors are applied within the SLOPE/W model.
- Appropriate partial material factors, specific to the geotextile product used, shall be applied externally to determine the required ultimate tensile strength in accordance with design standards (e.g., BS 8006 or ISO 10318).

The minimum calculated Factor of Safety for each design condition must meet or exceed the values stipulated in the Project Design Criteria, ensuring both short-term and long-term embankment stability.

The ultimate tensile capacity of the geotextile reinforcement is determined as twice the working (allowable) load, in accordance with conventional geotechnical design practice. Material properties of embankment are shown in Table 3.

Table 3. Material properties—embankment.

Layer	Value
Embankment	Density; not less than 16 kN/m^3 EV2 = 20 MPa CBR = 4 to 5 Compaction of 97% of MDD, for sand 98% of MDD
Dredge Sand	Clean sand having 4 days soaked CBR ≥ 6 Compaction; 98% of MDD.
Existing Ground after Stripping	Density, not less than 17.5 kN/m^3 Minimum CBR = 6 EV2 = 20 MPa Compaction was 98% of MDD
Sand Blanket	Minimum F.M. = 1.65

4.4. Soil Liquefaction

Liquefaction is the sudden, temporary loss of shear strength in saturated, loose to medium dense, granular sediments subjected to ground shaking. Liquefaction generally occurs when seismically induced ground shaking causes pore water pressure to increase to a point equal to the overburden pressure. Liquefaction can cause foundation failure of buildings and other facilities due to the reduction of foundation bearing strength. The potential for liquefaction depends on the duration and intensity of earthquake shaking, particle size distribution of the soil, density of the soil, and elevation of the groundwater. Areas at risk due to the effects of liquefaction are typified by a high groundwater table and underlying loose to medium-dense, granular sediments, particularly younger alluvium and artificial fill. Due to presence of loose to very loose sand along the project alignment and high-water level, liquefaction potential for ground under seismic loads has been evaluated. The liquefaction potential assessments presented in the factual report on Geotechnical Investigation works were adopted. The permanent ground deformation due to liquefaction was assessed based on Hynes-Griffin and Franklin (1984). In this method, the yield acceleration is first estimated, then the permanent displacement of the embankment is calculated.

4.5. Design Considerations

4.5.1. General Embankment Fill

General embankment fill refers to the material layer positioned beneath the prepared sub-grade. It is classified as an open specification material, meaning it is not rigidly defined but should be locally sourced and possess adequate strength and stability. The material must be capable of being compacted to meet the required density and California Bearing Ratio (CBR) standards. Importantly, it must be free from any unsuitable materials outlined in Section 4.5.4, which are strictly prohibited from use in embankment construction. Material properties of separator geotextile and high strength geotextile are shown in Table 4 and Table 5.

Table 4. Material properties—separator geotextile.

Parameter	Test Standard	Unit	Test Result	Test Result Average
Thickness (under 2 kPa pressure)	ASTM D5199	mm	2.83 to 3.14	2.97
CBR Puncture Resistance	ASTM D6241	N	4202 to 5286	---
Effective Opening Size (EOS)	ASTM D4751	µm	EOS < 75	EOS < 75
Vertical Permeability (under 2 kPa pressure)	DIN 53936	10^{-3} m/s (at 20˚C)	2.98 to 3.14	3.07
Horizontal Permeability (under 2 kPa pressure)	ASTM D4716	10^{-3} m/s (at 20˚C)	4.5 to 4.56	4.52
Grab Tensile Strength (x-dir)	ASTM D4632	N	1649 to 1888	1769
Grab Tensile Elongation (x-dir)	ASTM D4632	%	44 to 51	46
Grab Tensile Strength (y-dir)	ASTM D4632	N	1818 to 2086	1937
Grab Tensile Elongation (y-dir)	ASTM D4632	%	51 to 57	54
Strip Tensile Strength (x-dir)	ASTM D4595	kN/m	27 to 30.1	28.4
Strip Tensile Elongation (x-dir)	ASTM D4595	%	59 to 78	-
Strip Tensile Strength (y-dir)	ASTM D4595	kN/m	25.9 to 32.4	-
Strip Tensile Elongation (y-dir)	ASTM D4595	%	46 to 64	---

4.5.2. Drainage Arrangement in Embankments

Drainage is a critical factor in maintaining the stability of embankments and cuttings in railway construction. Proper management of rainwater, particularly during the monsoon season, is essential to protect the embankment from potential failure. Water must not be allowed to flow along the track, as this can lead to ballast contamination and erosion of the formation. Prolonged water stagnation on the formation is also undesirable. Therefore, the drainage system must be designed to efficiently prevent water accumulation and ensure rapid water discharge. The sub-ballast layer is constructed with a transverse slope to facilitate the runoff of surface water toward the sides and down the embankment. Longitudinal drains are installed at the toe of the embankment to channel the water toward the nearest natural watercourses. Typical cross-sections for embankment are shown from Figures 3-5.

Table 5. Material properties—high strength geotextile.

Parameter	Test Standard	Unit	Test Result	Test Result Average*
Effective Opening Size (EOS)	ASTM D4751*	μm	EOS < 75	EOS < 75
Vertical Permittivity (for head loss of 50 mm)	ASTM D4491	sec^{-1} (at 20˚C)	0.02 to 0.023	---
Strip Tensile Strength (x-dir)	ASTM D4595	kN/m	>71.5	>71.5
Strip Tensile Elongation (x-dir)	ASTM D4595	%	4 to 10	-
Strip Tensile Strength (y-dir)	ASTM D4595	kN/m	39.6 to 44.8	41.5
Strip Tensile Elongation (y-dir)	ASTM D4595	%	5 to 11	-

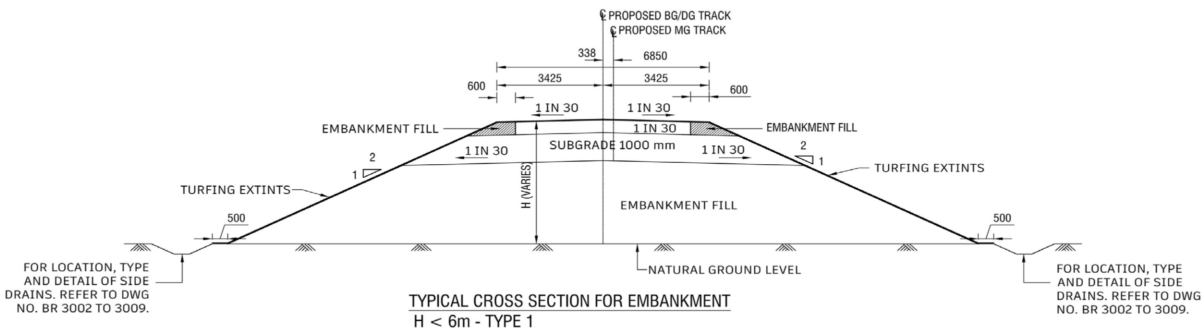

Figure 3. Typical cross section for embankment height less than 6 m (Type 1).

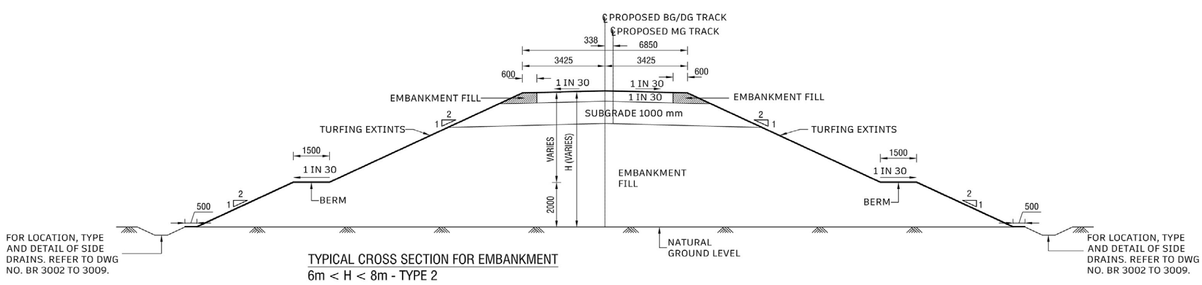

Figure 4. Typical cross section for embankment height 6 m to 8 m (Type 2).

4.5.3. Erosion Control of Embankment Slopes

Exposed sloping surfaces are vulnerable to surficial erosion caused by surface runoff, which can lead to the formation of erosion gullies. These gullies may compromise the soil matrix, reduce the excess width, and result in the steepening of slopes. The severity of erosion depends on several factors, including soil type, climatic conditions, topography, and slope length. To mitigate such erosion, two categories of control measures are typically considered:

- Engineered Systems
- Bio-Technical Solutions

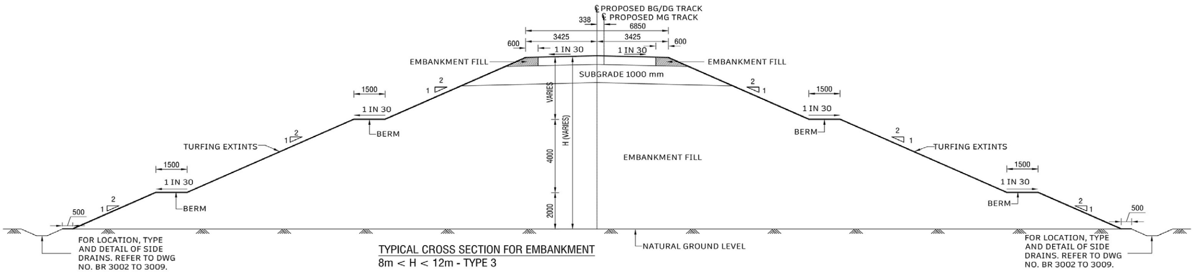

Figure 5. Typical cross section for embankment height 8 m to 12 m (Type 3).

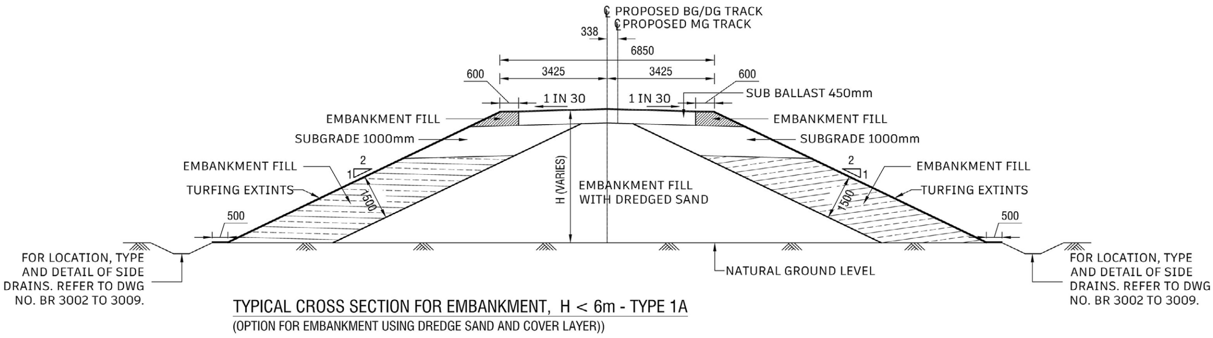

Figure 6. Typical cross section for embankment height less than 6 m (Type 1A).

Engineered Systems

Among various engineered solutions, the commonly employed methods include geojute, polymer grids, and hydroseeding. This section focuses on geojute, which is recognized as the most cost-effective and economical option. Geojute, a biodegradable material made from jute yarn with a coarse, open-mesh structure, is especially suited for areas experiencing significant erosion. As it degrades, geojute promotes the establishment of vegetation, enhancing slope stability. When applied during the dry season, initial watering should be ensured to support seed germination and plant growth. Typical cross-sections for embankment considering dredge sand are shown in **Figures 6-8**.

Bio-Technical Solutions

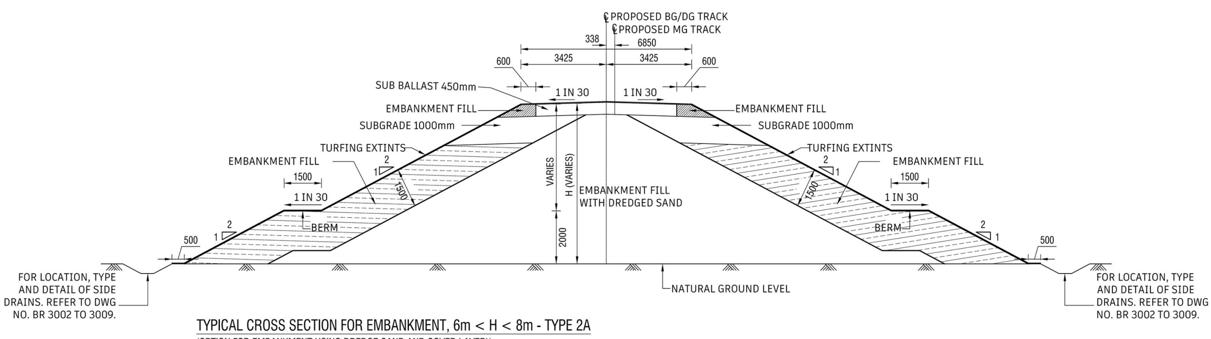

Figure 7. Typical cross section for embankment height 6 m to 8 m (Type 2A).

This method involves establishing vegetation on exposed slopes, making it particularly suitable for soil types containing a clay fraction. The approach includes grading the slope to prepare it for sowing seeds or planting root strips of locally available creeping grasses. These grasses typically develop roots penetrating 50 - 75 mm into the slope, acting as natural soil anchors and significantly enhancing resistance to erosion. For existing embankments, turfing and planting have been adopted. Following discussions with Bangladesh Railway (BR) officials, and based on the observed absence of significant erosion on current embankments, this method has been selected. Turfing and planting will be incorporated into the design drawings accordingly.

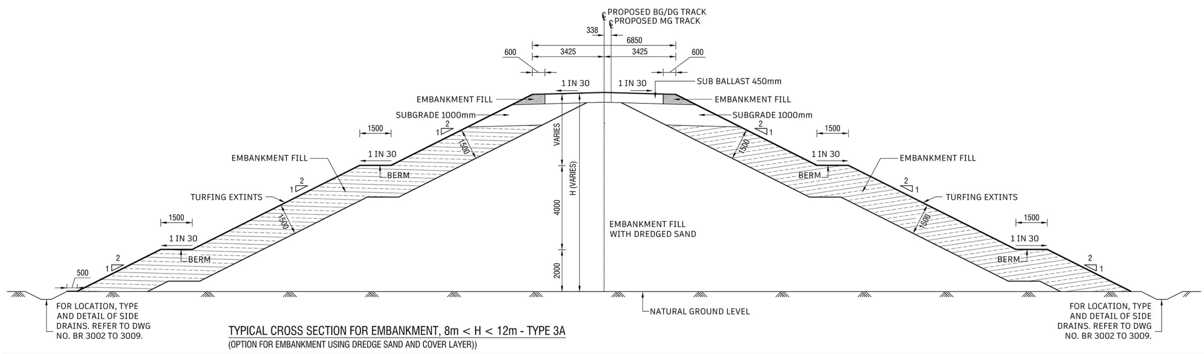

Figure 8. Typical cross section for embankment height 8 m to 12 m (Type 3A).

4.5.4. Unsuitable Materials

Materials classified as unsuitable shall not be used in the construction of embankment fill. Unsuitable materials include topsoil, peat, and other highly organic soils; logs, stumps, and combustible materials; as well as soluble substances such as gypsum and rock salt. Additionally, expansive soils, free-draining materials prone to scouring, very fine sands, cohesionless silts, organic clays, and highly dispersive soils are also deemed inappropriate. Any material exhibiting a free swell index greater than 3%, soluble content exceeding 3%, or organic matter exceeding 5% by weight of dry soil is considered unsuitable for embankment construction. Furthermore, collapsible soils present in the foundation are classified as unsuitable and must be appropriately treated prior to embankment placement. Typical cross-sections for cutting section are shown in **Figure 9** and **Figure 10**.

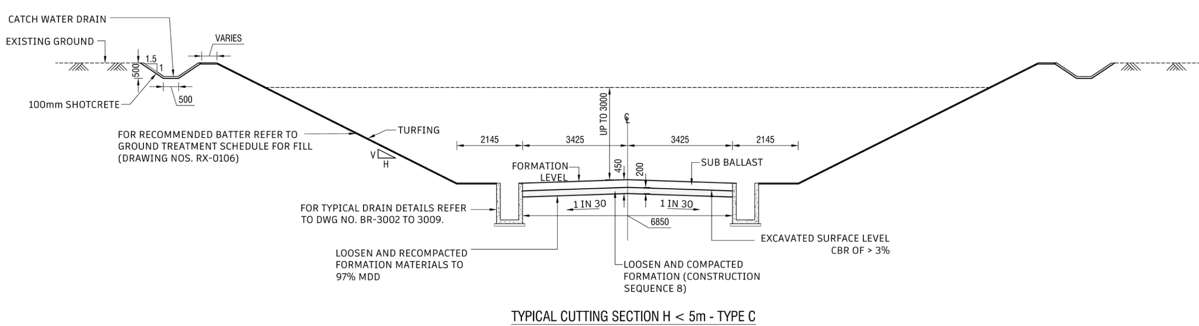

Figure 9. Typical cutting section for height less than 5 m (Type C).

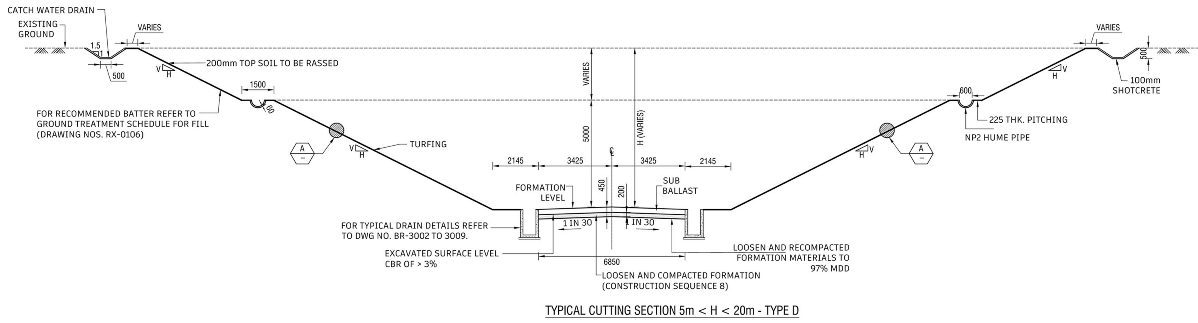

Figure 10. Typical cutting section for height 5 m to 20 m (Type D).

4.6. Ground Treatment Consideration

The presence of a compressible silty clay layer at the embankment foundation along the project alignment necessitates ground improvement measures to mitigate post-construction settlement and to ensure slope stability both during and after construction. The proposed ground improvement methods include surcharge loading (preloading), with the use of prefabricated vertical drains (PVDs) to expedite the consolidation of soft clay layers. Two distinct types of ground treatment have been proposed, as detailed below.

4.6.1. Type A Treatment

Type A ground treatment is designed for areas where embankments are to be constructed over weak, compressible layers of soft to firm clay or silty clay, which are underlain by stiff clay or medium-dense sand. These untreated compressible soils are inadequate for supporting embankments and would result in excessive settlement.

This treatment involves the installation of Prefabricated Vertical Drains (PVDs) arranged in a triangular grid at 2.0-meter center-to-center spacing, extending to a depth of up to 16 meters. A geotextile-wrapped sand drainage blanket will be placed at the base of the embankment to collect groundwater expelled during soil consolidation under surcharge loading. The collected water will be directed to low points and removed via designated drains.

Type A ground treatment is designed to achieve a minimum of 95% primary consolidation through preloading before the railway tracks are opened to traffic. The rate of embankment fill placement will be controlled to allow for gradual strength gain in the compressible subsoil. To ensure embankment stability during construction, additional stabilization measures, including high-strength geotextile reinforcement and temporary berms, have been implemented.

4.6.2. Type B Treatment

Type B ground treatment is applicable in areas where:

- Embankments are to be constructed over sand or sandy soils, where ground movements resulting from embankment loading are expected to occur over a relatively short duration.
- The subsoil consists of a thin layer of weak, compressible material underlain

by medium-dense sand.

Table 6. Material properties—PVD.

Sample Description	Sample No.	Tensile Strength @ 10% Strain	Average Tensile Strength @ 10% Strain	Tensile Strength	Average Tensile Strength	Elongation at Break (GL = 100 mm)	Average Elongation at Break (GL = 100 mm)
		kN	kN	kN	kN	%	%
PVD (TDF-WP-B)	1	1.95	1.8	2.45	2.4	55	48
	2	1.85		2.35		50	
	3	1.8		2.4		40	

In this case, the use of Prefabricated Vertical Drains (PVDs) is not required. However, a drainage blanket enclosed within a separator geotextile will be provided to ensure effective drainage and facilitate the discharge of groundwater generated during the consolidation process. Material properties of PVD are shown in **Table 6**.

4.7. Geotechnical Model

Representative geotechnical models for each design section were developed based on the following considerations:

- Settlement Assessment: The in-situ ground conditions were evaluated using available borehole data from each design section along the project alignment. The boreholes exhibiting the most critical (*i.e.*, weakest) soil conditions were selected as representative for the settlement analysis.
- Stability Assessment: Embankment stability is primarily influenced by the strength and thickness of the clay layer directly beneath the embankment. Borehole data across the alignment were analyzed to determine the thickness and consistency of soft to firm clay layers in conjunction with corresponding embankment heights. Based on this assessment, typical design sections were classified, and detailed stability evaluations were conducted for each section. Summary of stability analysis is shown in **Table 7**.

Table 7. Summary of slope stability analysis results for cuts.

Cut Hight	Subsoil Condition	Recommended Cut Batter	Achieved Factor of Safety (FOS)		
			Long Term	Short Term	Seismic
5 m - 20 m	Firm to Stiff Clay or Medium Dense Sand	3 H: 1 V	1.5	1.2	1
	Stiff Clay or Dense Sand or Better	2.5 H: 1 V	1.8	1.5	1.4
<5	Firm to Stiff Clay or Medium Dense Sand	2.5 H: 1 V	1.5	2	1.5
	Stiff Clay or Dense Sand or Better	2.0 H: 1 V	1.5	1.4	1.1

Cutting Conditions: Due to the limited subsurface data available for cut sections, two generalized ground profiles were assumed for design purposes: 1) firm clay or medium dense sand, and 2) stiff clay or dense sand.

5. Construction Sequence and Hold Point

Due to the initially low undrained shear strength of the existing soft clay soils, the construction of high embankments must be carefully staged and cannot proceed rapidly. To maintain stability, the rate of embankment construction should be limited to a maximum of 1.0 meter per seven days for general embankments, and 0.5 meter per seven days for culvert and bridge approaches, unless otherwise approved by the Consultant. These construction rates may be further refined based on data obtained from instrumentation and monitoring during construction. Additionally, intermediate preloading stages will be necessary to ensure compliance with the design requirements and to promote controlled settlement and consolidation.

6. Risks and Opportunities

The design has been developed under the assumption that there are no abrupt variations in soil stratigraphy between boreholes. Consequently, it does not explicitly account for the inherent spatial variability of subsurface conditions. Except for the bridge and its approaches, borehole data were generally spaced at intervals ranging from 500 to 1000 meters. This wide spacing introduces considerable uncertainty and risk in the ground improvement design, as outlined below:

- Uncertainty in Layer Boundaries: The interface between weak compressible soils and stronger, competent layers cannot be precisely determined due to the large distances between adjacent boreholes. Accurate estimation of the soft-to-firm clay layer thickness is essential in areas where prefabricated vertical drains (PVDs) are employed to accelerate consolidation. To address this, the design conservatively adopted the weakest ground conditions. However, if localized lenses of medium dense to dense soil are encountered within the soft-to-firm clay zone, premature termination of PVD installation may occur. This discrepancy between actual and intended installation depth could extend the required preloading period to meet the Primary Consolidation Settlement (PCS) criteria.
- Variability in Strength Gain: The design incorporates anticipated strength gains in soft soils based on estimated consolidation rates. In practice, the rate of consolidation is influenced by various site-specific factors, including natural soil variability, potential clogging and reduced discharge capacity of PVDs, and smear effects—all of which are difficult to quantify accurately and may impact the effectiveness of the proposed design.
- Post-Construction Settlement: PVDs are typically ineffective in penetrating thick, stiff to very stiff clay layers. If consolidation within these layers is not completed during the designated preloading period, post-construction set-

tlement may continue. The settlement rate in such cases will depend heavily on the permeability of these layers.

Given these uncertainties, it is essential to implement robust risk mitigation strategies during construction and monitoring. The following measures are recommended:

- Verification of PVD Depth: The installed depth of PVDs should be reviewed and cross-checked against nearby borehole data by a geotechnical engineer. Where significant deviations are observed between design and actual conditions, additional subsurface investigation using cone penetration tests (CPTs) or supplementary boreholes is advised.
- Adherence to Construction Rates: The construction sequence and rate specified in the design must be strictly followed to maintain slope stability and avoid triggering failure.
- Instrumentation and Monitoring: Regular monitoring of instrumentation data is critical to verify construction performance and stability. These data should be analyzed continuously to inform ongoing decision-making.
- Back Analysis: Post-construction back analysis should be conducted to validate key design assumptions and refine geotechnical models.

An observational approach is strongly recommended for projects involving soft ground, due to the inherent variability and uncertainty of subsurface conditions. This methodology is embedded within the overall instrumentation and monitoring framework and serves as an integral component of the design process. Monitoring results should be rigorously analyzed to update and calibrate geotechnical models, enabling better prediction of long-term embankment performance.

7. Conclusion

The design and construction of embankments on soft ground require a multidisciplinary approach, integrating detailed geotechnical investigation, appropriate ground improvement techniques, and continuous monitoring [34]. This case study on the design aspects of embankment of Dohazari Cox's Bazar Railway Project (DCRP) has demonstrated how the use of prefabricated vertical drains (PVDs), staged loading, application of high strength geotextiles, and preloading strategies can effectively mitigate the challenges posed by low shear strength and high compressibility of soft soils. The incorporation of numerical modeling and field instrumentation played a vital role in validating design assumptions and ensuring performance within acceptable limits. Lessons from the design aspects of this project emphasize the critical importance of site-specific analysis, adaptive design, and real-time data in achieving stability, durability, and cost-efficiency [35]. The step-by-step detailed description of the design procedures contributes to a growing body of knowledge in soft ground engineering and offers a valuable reference for future infrastructure projects facing similar or nearly similar geotechnical conditions.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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