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# Geotechnical Challenges in Embankment Construction on Soft Ground

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## Abstract

The construction of embankments over soft ground poses various geotechnical challenges, including settlement, stability problems, and financial impacts. This review paper presents a comprehensive case study of three projects, each demonstrating different approaches to mitigating these challenges. The first case study examines the use of wick drains and counterweight fills at Salamanga in Mozambique to evaluate their effectiveness in accelerating consolidation and improving stability. The second case study investigates the performance of geosynthetic reinforcement combined with floating pile walls in Egypt, focusing on settlement reduction and economic savings through design optimization. The third case study explores the application of lightweight fill materials and preloading techniques for shallow soil strata in an urban environment. A comparative assessment is provided, analyzing these methods in terms of feasibility, applicability, cost-effectiveness, and geotechnical performance. The paper concludes with a critical discussion offering practical insights into the most effective strategies for constructing embankments on soft ground, thereby guiding future projects.

**Keywords:** Embankment, Soft Ground, Settlement, Stability, Geosynthetics

## Introduction

One of the most challenging areas in geotechnical engineering is the construction of embankments on soft ground, as the inherent properties of soft soils are quite unfavourable. Most soft soils are in low-lying areas and have low shear strength, are highly compressible, and drain poorly. All these conditions pose severe risks to infrastructure projects because soft soils normally undergo excessive settlement and instability under load, often leading to structural failure. This can compromise the safety and longevity of facilities such as roads, railways and levees. The problems of the soft soil require innovation in solutions and advanced knowledge in geotechnical behaviour. Common methods used in the improvement of properties in soils are preloading, use of vertical drains, vacuum consolidation, and soil stabilization. In addition, there are the geosynthetics, lightweight fills, and deep foundations, which include pile-supported embankments that also play an important role in the mitigation of risks. Advanced techniques, in combination with thorough analysis, allow engineers to construct embankments on soft ground safely and effectively while minimizing risks. In this respect, comprehensive site investigations, including soil tests and numerical modelling, are needed to capture issues like time-dependent settlement and soil-structure interaction. All considered, advanced techniques, when included in thorough analysis, enable engineers to construct embankments on soft ground safely and effectively while minimizing risks [1-5].

Soft ground normally exists in floodplains, coastal areas, and other areas that contain extensive alluvial deposits. Traditional construction methods generally fail in such an environment since soft soils cannot bear heavy loads. Besides, the high water table and low permeability add to the difficulty because these two factors reduce efficient drainage and cause longer consolidation times. Hence, special solutions should be considered to ensure stability, reduce settlement, and shorten the time for construction [6-13].

Various new techniques have been developed to address these problems. The use of PVDs with preloading, for instance, can shorten the drainage distance of pore water and, hence, reduce the consolidation time drastically. This technique has found widespread application in those projects in which speed in construction plays a significant role, such as highways and railways. Another effective alternative for the improvement of the bearing capacity and the stability of soft soils are by using geosynthetic reinforcements and floating pile wall systems. Such systems offer a host of advantages: more homogeneous distribution of loads, smaller differential settlements, and better performance of the structure in general The use of lightweight fill materials-lightweight aggregates, EPS blocks-is another alternative that has been investigated. These materials reduce the total embankment weight and, hence, the vertical stress on soft soils. Lightweight fills with preloading can be effective for settlement control and providing a stable construction platform. However, the high initial cost and requirement of special equipment have kept their application limited to a few cases only [14-30].

In this paper, three case studies are reviewed to show the application of these techniques in real situations. The first case review discusses the use of wick drains together with counterweight fills at Salamanga in Mozambique for a 9.6-meter high embankment which was supported by a 39-meter-thick soft clay layer. The second case review discusses a project executed in Egypt where the problem of constructing a highway embankment on soft ground was solved by the use of geosynthetic reinforcement-float pile walls. The third case review will discuss the applications in an urban area and how effective they can be in minimizing settlement and distributing the loads more uniformly [6],[31-33].

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This paper compares these approaches with an aim to analyze their various strengths and limitations comprehensively. In establishing the most feasible solutions for embankment construction on soft ground, feasibility, cost efficiency, and geotechnical performance shall be analyzed critically. This review shall thus be expected to guide engineers and decision-makers on appropriate techniques for the selection of future projects, keeping the issues of safety and sustainability in mind.

## Case Studies

### Case Study 1: Wick Drains and Counterweight Fills in Salamanga, Mozambique

Construction of the 9.6 meters high embankment at Salamanga, Mozambique, on the 39 meters thick compressible clay presented serious problems (Figure 1). This is essentially a flood plain project which required an innovative way of achieving stability with minimal settlement to meet the design requirements. It was described by an extensive geotechnical investigation into the soil's very low permeability and consequently its poor shear strength. It therefore made it very inappropriate for normal methods of construction [31], [34-36].

Wick Drains: PVDs were installed in triangular patterns to increase the soil consolidation by reducing the path of pore water. This will increase the probability of quicker dissipation of excess pore pressure, therefore reducing the actual consolidation period remarkably [37].

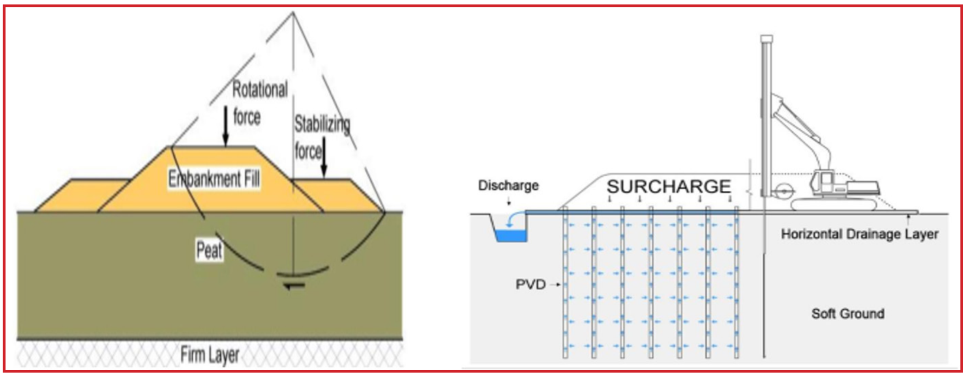


**Figure 1.** Preloading embankment combined with wick drains [31].

Counterweight Fills: Low shear strength of the foundation soil required the implementation of counterweight fills or berms were placed alongside the embankment. These counterweights redistributed the load in such a way that it averted shear failure and improved stability throughout the embankment construction in stages [38-39].

Instrumentation and monitoring were crucial for the success of the project. The installation of settlement plates, piezometers, and inclinometers allowed the monitoring of soil behavior during construction to enable real-time adjustments in design. The performance at the embankment showed that residual settlements within the acceptable limits were achieved, as expected from the design [37], [40].

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### Performance and Observations

Viability: Wick drains with counterweight fills were found to work well against deep and highly compressive soils.

Applicability: Projects that are often executed in floodplains or areas underlain by soft soil deposits in a wide area.

Cost-Effectiveness: Although the costs related to detailed geotechnical investigations and monitoring of instrumentation were high, it was worth the cost considering the long-term benefits in terms of lower settlement and reduced maintenance.

### Case History 2: Geosynthetic Reinforcement and Floating Pile Walls in Egypt

An embankment for a highway was built in Egypt at a problematic site featuring a 27.5-m-thick soft clay layer, underlain by silty sand (Figure 2). The key project requirements were to improve the stability of the embankment, decrease its settlement, and minimize the costs through the use of geosynthetic materials and floating pile wall.

Geogrid Reinforcement: The embankment design had to be supported by horizontal geogrid layers that distributed loads and reduced differential settlements. These layers improved the foundation soil while decreasing vertical displacement [18],[26],[41-43].

The concrete piles were installed to act as a vertical support resisting any lateral movement; spaced 3 meters apart, the length of the piles was optimized to reach an equilibrium between costs and performance. Numerical modeling has shown that introducing pile walls reduces the settlement by 94% compared to the unreinforced scenario [18],[43].

A two-dimensional finite element model is used to simulate the soil-structure interactions in predicting the performance of embankments under different loading conditions. This predictive modeling was important in the optimization of design parameters and to ensure stability during construction [37].

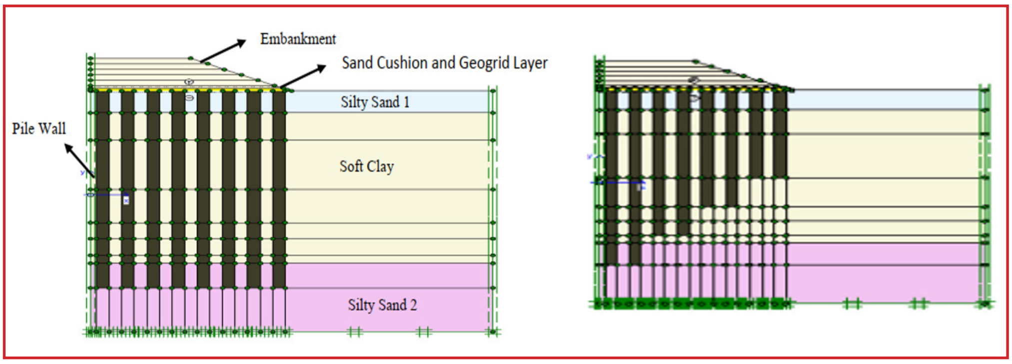


**Figure 2.** (a) Finite Element Idealization Mesh and Boundary Condition (b) Floating Pile Wall and Geogrid layer

### Performance and Observations

Feasibility: Geosynthetic and Floating Pile Wall system was highly effective for sites with thick clay deposits and high settlement potential.

Applications: This method is ideal for highway and railway embankments, particularly in areas requiring enhanced stability and reduced settlement.

Cost Efficiency: Optimizing pile lengths resulted in a 37.5% reduction in concrete volume, significantly lowering project costs without compromising structural integrity [44].

### Case Study 3: Lightweight Fill and Preloading Techniques

Lightweight fill materials and preloading techniques were applied in a project to solve the settlement problems of shallow soft soils in an urban area. In this case, the technique was used to reduce the overall weight of the embankment and speed up consolidation [45].

Lightweight Fill: EPS blocks and lightweight aggregates were used as fill materials. These materials significantly reduced the stress applied to the soft foundation soils, which in turn reduced settlement.

Preloading: Temporary surcharge loads were placed on the embankment to allow consolidation before the placing of the permanent structure. This improved the strength and stiffness of the underlying soils, reducing the potential for settlement after construction [35],[46].

Extensive monitoring of soil behavior, through settlement plates and pore pressure gauges during preloading, allowed for verification and improvement in design, fulfilling all requirements by the settlement criteria [47].

### Performance and Observations

Feasibility: The settlement-controlled lightweight fill with preloading provides good alternatives in situations when working space is low and stringent settlement limits exist in urban projects.

Application: Wherever shallow soft soils render other more conventional methods impossible or economically unfeasible.

Cost Efficiency: While lightweight materials involve high initial costs, their long-term benefits in terms of reducing maintenance requirements and improving pavement performance justify the capital investment [6].

## Comparative Analysis

A comparative assessment of three embankment construction techniques is an essential basis for determining their suitability under different geotechnical conditions. The rating of the effectiveness of each method is based on factors including feasibility, applicability range, cost-effectiveness, and overall performance in dealing with common geotechnical issues such as settlement and stability problems. The following presents a detailed comparison of these approaches on major engineering and economic parameters.

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### *Feasibility*

The viability of each technique is assessed based on its relevance to various soil conditions and site limitations:

Wick Drains and Counterweight Fills: This approach is particularly effective for initiatives that necessitate addressing deep layers of soft soil characterized by considerable compressibility. The implementation of wick drains notably enhances the rate of soil consolidation, rendering it appropriate for extensive projects, including road embankments situated in regions susceptible to flooding[13],[43].

Geosynthetics and Floating Pile Walls: This technique is especially suited for areas with significant deposits of clay and also for sites that require high load-carrying capacities. The use of geogrid reinforcement in combination with pile walls dramatically enhances structural stability, making it highly feasible for embankments related to highways and railways [48].

Lightweight Fill & Preloading: This is most effective for shallow soft soils where additional weight from embankment loads may increase the settlement problems. It is particularly advantageous in urban areas where available space is limited, constraining other methods of stabilization [45].

### *Application Scope*

Each method has different applications depending on the type of project and site conditions:

Wicks drains and counterweight fills are especially suited for large infrastructure projects, such as highways and bridges in flood-prone areas, where rapid consolidation is needed before road construction can be started [8],[31].

Geosynthetics and floating pile walls are most suited for transportation infrastructure, including highways and railways that require high load-carrying capacity and stability over soft, compressible clay substrata [26],[47].

Lightweight Fill and Preloading: This method is particularly relevant for urban development, land reclamation efforts, and locations where it is essential to reduce further stress on underlying soft soils [6],[45].

### *Economic Viability*

Economic viability is assessed in terms of material expenditures, labor necessities, and ongoing maintenance costs:

Wick Drains and Counterweight Fills: Although the upfront costs associated with geotechnical investigations and installation are reasonable, the substantial long-term savings resulting from minimized settlement and maintenance render this approach economically advantageous.

Geosynthetics and Floating Pile Walls: Though the use of geogrid reinforcement and floating piles means the initial cost rises, the resulting improved design offers a reduction of 37.5% in consumption of concrete for the same section. The significantly longer life reduces the initial payment for this practice[49-50].

Lightweight Fill and Preloading: The high costs associated with the use of lightweight materials, such as expanded polystyrene (EPS), may be a factor in this technique. However, reduced load application onto soft soil means that there is almost negligible long-term maintenance costs associated with it, hence an economical solution for certain applications [6].

### Settlement and Stability Management Effectiveness

The effectiveness of each method at reducing settlement and enhancing stability is a key performance indicator:

Wick Drains & Counterweight Fills: Very effective in accelerating consolidation and increasing embankment stability. Counterweight fills provide lateral support, reducing the likelihood of failure in soft ground conditions [31].

Geosynthetics & Floating Pile Walls: Excellent in settlement control, with numerical models indicating a 94% reduction in settlement compared to unreinforced embankments. The inclusion of pile walls prevents lateral deformation and improves structural resilience [32],[44].

Lightweight Fill & Preloading: Reduce total and differential settlement by minimizing the overall weight of the embankment. Preloading accelerates soil consolidation before final construction, mitigating long-term settlement concerns [6],[45].

Based on comparative analysis, geosynthetics and floating pile walls are found to be more effective in controlling settlement and stability but at higher initial capital cost. In contrast, wick drains and counterweight fills offer a balance between capital cost and construction effectiveness; thus, they would suit large-scale projects. Lightweight fill and preloading methods will be suitable for projects with space restrictions and low tolerance for settlement; however, they incur high material cost.

## Discussion and Comment

Among the methods reviewed, the geosynthetic reinforcement combined with a floating pile wall system is the most comprehensive method for embankment construction on soft ground. Its ability to significantly reduce settlement and enhance stability makes it the preferred method for large projects. However, the choice of the method should depend on site-specific conditions, including soil properties, the project size as well as financial constraints.

The wick drain and counterweight fill method is still effective for deep projects with heterogeneous soil profiles, generally providing a relatively good trade-off between effectiveness and cost. Although lightweight fill and preloading can be satisfactory under certain circumstances, they fall short of the methods introduced above in both versatility and effectiveness.

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## Conclusion

The development of embankments on soft terrains necessitates the implementation of novel strategies to effectively tackle geotechnical issues. This review delineates the advantages and drawbacks of three distinct methodologies, stressing their appropriateness for various project scenarios. The geosynthetic and floating pile wall system is particularly noted as the most efficient solution, offering strong performance coupled with economic viability. By utilizing these findings, engineers are positioned to make knowledgeable decisions that enhance the design and construction of embankments on soft ground.

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## Conflicts of Interest

The authors declare no conflicts of interest.

## Author Contributions

**Abdullahi Nasir:** conceptualization, methodology. **Asad Naseem:** software, data curation. **Dayang Zulaika Abang Hasbollah:** writing- original draft preparation, supervision. **Bakhtiar Affandy Othman:** visualization, investigation. **Mohd Firdaus Md Dan @ Azlan:** writing- reviewing and editing. **Lee Hooi Chie:** validation.

## Data Availability Statement

The data used to support the findings of this study are included within the article.

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