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Effects of Moisture Content, Compaction Energy, Particle Gradation, and Rainfall-Induced Wetting on the Compaction and Settlement Behavior of Coarse-Grained Soils in High Embankments: A Malaysian Case Study

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ABSTRACT

High embankments constructed from coarse-grained soils play an important role in transportation and infrastructure development, particularly in projects requiring substantial elevation changes. The deformation behavior of such embankments is governed by the combined effects of particle gradation, moisture condition, compaction level, embankment height, and stress-dependent soil compressibility. These factors are of particular significance in tropical regions, where seasonal rainfall and repeated wetting–drying cycles can modify the hydraulic and mechanical characteristics of compacted fill materials. This study presents an integrated evaluation of the compaction and settlement behavior of coarse-grained soil used in high embankments under Malaysian climatic and engineering conditions. The analysis incorporates particle-size characterization, heavy compaction testing at nominal moisture contents of 2%, 4%, 6%, 8%, and 10%, compression-modulus measurements under vertical stresses ranging from 100 to 400 kPa, and finite-element simulations conducted for different compaction levels and embankment heights. The investigated material consists predominantly of coarse particles, with more than 80% of the particles falling within the 2–20 mm size range and a maximum particle size below 40 mm. The compaction analysis indicates an optimum moisture content of 6.2% and a maximum dry density of 2.13 g/cm³. A strong relationship is identified between compression modulus and degree of compaction, expressed as $E\_s = 1727.9x^2 - 2958x + 1308.8$, with $R^2 = 0.96$, where x denotes the degree of compaction. Finite-element results demonstrate close agreement with the corresponding settlement calculations, with differences of approximately 2% for embankment-fill compression and 5% for foundation settlement. Parametric simulations for compaction degrees ranging from 85% to 100% and embankment heights between 5 and 40 m show that settlement increases nonlinearly with embankment height, while the influence of compaction quality becomes progressively more pronounced as embankment height increases. Moisture condition is also identified as an important state variable in assessing the potential effects of rainfall-induced wetting under tropical conditions. Since rainfall intensity and duration are not independently quantified within the analysis, their effects are considered through the climatic and moisture-state interpretation rather than through direct rainfall calibration. The findings provide an integrated engineering basis for assessing the performance of high coarse-grained embankments in Malaysia and support the coordinated consideration of compaction control, moisture management, particle gradation, drainage conditions, and settlement prediction in tropical earthwork design.

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1. Introduction

High embankments are an important component of transportation infrastructure constructed across mountainous, hilly, and topographically constrained regions [1]. Unlike low embankments, high fills develop substantial self-weight stresses within their lower zones, and their deformation is therefore strongly affected by the interaction between fill height, density, compressibility, particle arrangement, and construction quality [2]. Settlement control is consequently a central issue in the long-term serviceability of airport platforms, highways, approach embankments, and other large earth structures [3].

The engineering behavior of coarse-grained soils differs substantially from that of conventional fine-grained soils [4]. Coarse particles contribute strongly to load transfer through particle contacts, rearrangement, interlocking, dilation, and particle breakage [5]. Consequently, changes in particle-size distribution can modify density, shear resistance, compressibility, and deformation characteristics [6]. Experimental and numerical investigations have demonstrated that particle gradation and stress level can substantially affect the mechanical response of coarse-grained soils [7]. Bagherzadeh-Khalkhali and Mirghasemi reported significant effects of particle size and stress level on coarse-grained soil shear behavior [8], while Fu et al. demonstrated that specimen geometry and testing configuration can influence measured shear resistance [9]. Large-scale triaxial investigations have further shown that confinement affects both the stress–strain response and particle breakage characteristics of coarse aggregates [10].

Compaction represents another fundamental control mechanism [11]. During construction, compaction reduces void space, increases dry density, improves particle contact, and generally increases stiffness while reducing subsequent compression under service loading. However, the relationship between compaction and settlement is not necessarily linear [12]. The influence of compaction becomes more pronounced as embankment height increases because deeper layers are subjected to larger overburden stresses [13]. Therefore, a modest difference in compaction quality may result in substantially different cumulative settlement in a high embankment [14].

Moisture content is closely coupled with compaction behavior [15] Water facilitates particle rearrangement during compaction up to an optimum moisture condition, after which additional water may reduce achievable dry density [16]. For coarse-grained materials with relatively low water absorption, the compaction curve may be comparatively narrow, and excessive water can make the material difficult to compact effectively [17]. The observed compaction response indicates that the material reaches its maximum dry density at approximately 6.2% moisture content, whereas increasing the water content to around 10% substantially reduces the practicality of specimen formation[18].

The moisture state is particularly important when high embankments are considered in tropical environments [19]. Malaysia experiences intense and recurrent rainfall, and infiltration can alter the moisture state of near-surface and intermediate fill zones [20]. Recent research on rainfall-affected high embankments has demonstrated that rainfall duration can modify volumetric water content, pore-water pressure, seepage behavior, and deformation response [21]. Research focused specifically on Malaysian tropical conditions has likewise emphasized the importance of rainfall infiltration into unsaturated soils and the resulting changes in hydraulic and mechanical behavior [22].

The tropical climatic conditions considered in the Malaysian context provide a relevant environmental basis for examining the influence of wetting on the settlement response of coarse-grained embankment materials [23]. In this framework, rainfall is considered as a potential environmental mechanism rather than as a directly quantified experimental parameter, since its independent effects require information such as rainfall intensity, duration, infiltration characteristics, and hydraulic boundary conditions [24]. Accordingly, the moisture content measured within the experimental framework is adopted as the principal state variable for evaluating moisture-related changes in soil behavior, while rainfall-induced wetting is considered a plausible pathway through which the material may transition toward higher moisture conditions.

Particle-size gradation is considered an important material characteristic within the analytical framework of this study. The investigated coarse-grained material is predominantly composed of particles ranging from 2 to 20 mm, while the maximum particle size remains below 40 mm. The corresponding uniformity and curvature coefficients are approximately 43.3 and 6.4, respectively, reflecting a broadly graded particle-size distribution. Since the investigation considers a defined gradation, particle-size distribution is maintained as a controlled material property rather than being introduced as an independently varied experimental parameter.

Compaction energy is incorporated into the framework as a construction-control parameter. The experimental compaction procedure employs a standardized configuration consisting of three compacted layers, with 98 blows applied to each layer. Under these controlled conditions, the resulting degree of compaction can be evaluated as part of the soil response; however, the fixed compaction regime does not provide sufficient variation to independently quantify or statistically compare the influence of alternative compaction energy levels.

The central research problem is consequently formulated around the interaction of experimentally supported and contextual variables:

Particle gradation → moisture condition → achievable dry density → compaction degree → compression modulus → embankment settlement

, with embankment height acting as a major stress-amplifying factor and rainfall-induced wetting acting as a climatic mechanism that can modify the moisture state [25].

Accordingly, the objectives of this study are to:

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1. To establish the compaction characteristics of the investigated coarse-grained fill under standardized heavy-compaction conditions;
2. quantify the relationship between moisture content and dry density;
3. evaluate the relationship between compaction degree and compression modulus;
4. establish a predictive equation for compression modulus;
5. evaluate the influence of embankment height and compaction degree on settlement;
6. validate the finite-element model against measured settlement data;
7. integrate moisture condition, particle gradation, compaction energy, and rainfall-induced wetting into a Malaysian tropical engineering framework; and
8. develop a practical interpretation framework for settlement control in high coarse-grained embankments.

2. Materials and Methods

2.1 Research framework

The research framework consists of four interconnected stages:

Stage 1: particle-size characterization and material classification;

Stage 2: heavy compaction testing under five moisture conditions;

Stage 3: compression-modulus testing under controlled compaction and loading conditions;

Stage 4: finite-element simulation of high embankments under multiple combinations of compaction degree and embankment height.

The resulting framework is extended to the Malaysian tropical environment by interpreting moisture variation as the experimentally measurable proxy for wetting and by treating rainfall-induced wetting as the climatic process that can shift the fill toward higher moisture conditions.

Table 1. Variables incorporated in the analytical framework

Variable	Role	Levels/condition
Moisture content	Primary experimental variable	2, 4, 6, 8, 10%
Dry density	Response variable	Measured
Particle gradation	Controlled material characteristic	2–20 mm dominant fraction
Maximum particle size	Material characteristic	<40 mm

Compaction energy	Controlled construction/testing condition	Heavy compaction; 98 blows/layer
Compaction degree	Primary mechanical variable	85–100% in numerical analysis
Compression modulus	Intermediate response	Calculated from compression testing
Vertical stress	Loading variable	100, 200, 300, 400 kPa
Embankment height	Main numerical variable	5–40 m
Rainfall-induced wetting	Climatic/contextual variable	Represented through moisture-state interpretation
Settlement	Principal response	FE calculated and field validated
Drainage	Engineering boundary condition	Considered in interpretation

2.2 Material characterization

The original material consists of grey gravelly soil containing rock fragments and was classified as a coarse-grained fill. Six representative samples, designated S1–S6, were subjected to particle-size analysis.

The grain-size curves show that more than 80% of the total mass lies within the 2–20 mm particle-size interval, while the maximum particle size is less than 40 mm. The resulting uniformity coefficient is approximately 43.3 and the curvature coefficient is approximately 6.4.

Table 2. Main physical characteristics of the investigated fill

Parameter	Value
Dominant particle-size range	2–20 mm
Maximum particle size	<40 mm
Uniformity coefficient, C_u	≈43.3
Curvature coefficient, C_c	≈6.4
Material classification	Coarse-grained soil
Main structural mechanism	Particle contact/interlocking
Main climatic sensitivity	Moisture-induced state change

The relatively broad particle-size distribution is important because particle arrangement and interlocking contribute substantially to the stiffness of the compacted fill. In the Malaysian application, the same gradation is considered a controlled material property, while future studies

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should investigate whether alternative gradations produce different optimum moisture contents and compression characteristics.

3. Heavy Compaction Testing

3.1 Testing procedure

Heavy compaction testing was performed using a cylindrical mold with an internal diameter of 15.2 cm, a height of 17 cm, and a volume of 2177 cm³. Five target moisture contents were considered: 2%, 4%, 6%, 8%, and 10%.

The field-recovered material was oven-dried before preparation. Approximately 8 kg of dry soil was prepared for each specimen. The required quantity of water was added according to the target moisture condition, followed by thorough mixing and a 12-h equilibration period under plastic covering.

The prepared soil was placed into the mold in three layers, with 98 blows applied to each layer. Three parallel specimens were prepared for each moisture condition, and the mean response was used to determine the compaction curve.

The testing procedure is particularly relevant to tropical construction because moisture conditioning before compaction can strongly affect particle rearrangement and achievable dry density. In a rainfall-prone environment, maintaining the fill within the specified moisture window is therefore an important construction-control requirement.

3.2 Experimental compaction results

The experimental measurements used in the present analysis are summarized below and provide the basis for the subsequent evaluation of the investigated soil behavior.

Table 3. Heavy compaction test results

Specimen	Designed water content (%)	Measured water content (%)	Wet density (g/cm³)	Dry density (g/cm³)
A-1	2.0	1.9	1.92	1.88
B-1	2.0	2.1	1.93	1.91
C-1	2.0	1.8	1.90	1.86
A-2	4.0	3.7	2.05	1.97
B-2	4.0	3.9	2.06	2.00
C-2	4.0	4.2	2.07	2.03
A-3	6.0	5.8	2.25	2.12
B-3	6.0	5.7	2.23	2.11

C-3	6.0	5.9	2.28	2.12
A-4	8.0	7.7	2.26	2.09
B-4	8.0	7.6	2.25	2.08
C-4	8.0	7.9	2.23	2.09
A-5	10.0	9.8	2.26	2.05
B-5	10.0	9.7	2.26	2.01
C-5	10.0	10.2	2.20	2.00

The measured water contents closely correspond to the target values, indicating satisfactory moisture-control accuracy. Dry density increases from the dry condition toward the optimum moisture range and subsequently decreases at higher moisture contents.

The maximum dry density is **2.13 g/cm³**, corresponding to an optimum moisture content of approximately **6.2%**. The overall trend is consistent with the characteristic shape of a compaction curve: at low moisture content, insufficient water limits particle rearrangement; near optimum moisture, water facilitates rearrangement and densification; beyond the optimum condition, increasing water occupies void space and reduces the attainable dry density.

The reduction in dry density at 8–10% moisture content is especially important for tropical construction. Although rainfall-induced wetting may increase the water content of the surface or partially exposed fill, additional water does not necessarily improve compaction. Instead, if wetting occurs after compaction, it may alter the stress–strain response without increasing dry density.

4. Moisture Content and Rainfall-Induced Wetting

The five experimental moisture states provide an experimentally supported representation of the material's mechanical response over a moisture range of approximately 2–10%.

The optimum condition at 6.2% is a critical reference state.

Three moisture regimes can therefore be conceptually identified:

- **Dry regime:** approximately 2–4%;
- **Near-optimum regime:** approximately 4–8%, centered around 6.2%;
- **Wet regime:** approximately 8–10%.

This classification should not be interpreted as a direct rainfall-intensity classification. Rather, it provides a mechanical-state framework through which rainfall-induced wetting can be interpreted.

In a Malaysian tropical setting, rainfall infiltration can increase water content within the upper and intermediate portions of an embankment. The resulting change in suction, particle contact conditions, and effective stress can modify deformation. Recent research has shown that rainfall

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duration affects water content, pore pressure, seepage, and settlement response in high embankments. [26,27,28,29]

For this reason, drainage and surface-water management should be considered integral parts of compaction control rather than separate hydraulic issues.

5. Compression Modulus Testing

5.1 Specimen preparation

Following determination of maximum dry density and optimum moisture content, compression-modulus specimens were prepared at different compaction degrees.

The specimen mass required to achieve each target compaction degree was determined from the heavy-compaction results and ring volume. Three parallel specimens were prepared for each moisture condition.

Vertical loading levels of:

- 100 kPa,
- 200 kPa,
- 300 kPa, and
- 400 kPa

were applied.

Each specimen was subjected to staged loading, and deformation was monitored during the test. After completion of the 24-h consolidation period, the void ratio–pressure relationship was determined.

6. Compression Deformation and Moisture Content

The experimental results indicate that compression deformation increases with increasing moisture content [30].

At a given moisture condition, compression deformation increases with applied stress. The difference becomes progressively more evident at higher stress levels.

At 400 kPa, the increase in compression deformation relative to 100 kPa for the five moisture conditions was reported as:

Water content	Increase in deformation from 100 to 400 kPa
2%	70.5%
4%	41.9%

6%	37.8%
8%	33.1%
10%	39.3%

These results indicate that moisture condition interacts with loading intensity rather than acting as an isolated variable.

The relatively large increase observed at the lowest moisture state suggests that the initially dry structure can undergo substantial particle rearrangement when subjected to high stress. At higher moisture conditions, the deformation response becomes more directly associated with the altered contact and pore structure.

From a tropical engineering perspective, this result indicates that a high embankment should not be evaluated solely using its nominal compaction degree. Moisture state at the time of loading and subsequent wetting should also be considered.

7. Void Ratio–Pressure Relationship

The experimental results show that the void ratio decreases as vertical pressure increases.

For each moisture condition, the $e - p$relationship provides the basis for calculating compression modulus.

The general relationship can be represented as:

$$e = f(p, w)$$

where:

- e= void ratio;
- p= applied vertical pressure;
- w= water content.

The results demonstrate that water content modifies the compression response and therefore influences the stiffness parameter subsequently used in finite-element analysis.

8. Compaction Degree and Compression Modulus

A key empirical relationship identified in the present analysis is the association between the degree of compaction and the compression modulus. This relationship provides an important basis for assessing how changes in compaction state are reflected in the compressibility characteristics of the coarse-grained fill.

The relationship between the investigated variables was represented using a second-order polynomial model, which was selected to capture the nonlinear trend observed in the experimental results.

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$$E_s = 1727.9x^2 - 2958x + 1308.8$$

with:

$$R^2 = 0.96$$

where:

- $E_s$is the compression modulus;
- $x$is the compaction degree expressed as a decimal fraction;
- $85\% \leq x \leq 100\%$.

The coefficient of determination of 0.96 indicates a strong empirical association between compaction degree and compression modulus within the tested range.

Table 4. Key compression-modulus relationship

Parameter	Value
Model form	Second-order polynomial
Equation	$E_s = 1727.9x^2 - 2958x + 1308.8$
R^2	0.96
Valid compaction range	85–100%

This relationship is central to the settlement model because compression modulus provides the mechanical bridge between construction quality and embankment deformation.

In other words:

Compaction degree → E_s → stress-dependent deformation → settlement

9. Role of Particle Gradation

Particle gradation is incorporated into the present study as a material-control parameter.

The investigated soil has a dominant particle range of 2–20 mm and a maximum particle size below 40 mm. Its high uniformity coefficient indicates a broad particle-size distribution.

The effect of gradation can be interpreted through three mechanisms:

1. **Particle packing:** a broad gradation permits smaller particles to occupy voids between larger particles.
2. **Mechanical interlocking:** coarse particles provide load-bearing contact networks.
3. **Stress redistribution:** increasing stress can produce particle rearrangement and, at sufficiently high stress levels, particle breakage.

Since the investigation considers a single defined particle-size gradation, the available observations do not provide sufficient variability to establish a statistically independent relationship between settlement and gradation. Accordingly, particle gradation is maintained as a controlled material characteristic within the analytical framework rather than being treated as an independently varying parameter.

This distinction is important. A future Malaysian experimental campaign should vary C_u, C_c, fines content, and maximum particle size independently to quantify their effects.

10. Role of Compaction Energy

The heavy-compaction procedure provides a controlled compaction-energy condition. Three layers and 98 blows per layer were used for specimen preparation.

Compaction energy is therefore incorporated into the framework as:

$$E_c = \text{constant controlled testing condition}$$

rather than as a continuously varying independent variable.

Its effect is consequently reflected indirectly through the resulting dry density and compaction degree.

For engineering implementation, the practical relationship is:

$$E_c \rightarrow \rho_d \rightarrow x \rightarrow E_s \rightarrow S$$

where:

- E_c= compaction energy;
- ρ_d= dry density;
- x= compaction degree;
- E_s= compression modulus;
- S= settlement.

This framework is especially relevant to high embankments because construction compaction should be evaluated by achieved density rather than energy input alone.

11. Finite-Element Model

A two-dimensional finite-element model was established to investigate settlement under different embankment heights and compaction degrees.

The model geometry has a base width of 100 m, while embankment height varies according to the numerical scenario.

The principal modeling parameters were:

Table 5. Finite-element model parameters

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Parameter	Value
Model type	2D finite-element model
Element type	CPS4R
Embankment base width	100 m
Embankment slope	1:2
Embankment mesh size	0.25 m
Foundation mesh size	0.50 m
Foundation compression depth	20 m
Poisson's ratio	0.35
Gravity acceleration	9.8 m/s²
Loading	Self-weight
Bottom boundary	Horizontal and vertical displacement restrained

Initial geostatic equilibrium was established before settlement calculations.

The compression modulus of the fill was assigned according to the compaction degree through Equation (1).

12. Model Verification

A 25-m-high embankment section was used to compare field observations with finite-element predictions.

Settlement monitoring was conducted at the top of the original foundation and at the top of the fill. The monitoring period covered 222 days.

The 25-m embankment was divided into nine layers with thicknesses of 0.8 m, 3.2 m, and three 7-m layers.

The upper layers had compaction degrees of 96% and 95%, while the remaining layers had a compaction degree of 93%.

Using Equation (1), the corresponding compression-modulus values were approximately:

- 61.6 MPa;
- 58.1 MPa;
- 52.3 MPa.

Table 6. Finite-element validation

Component	Measured settlement (mm)	Simulated settlement (mm)	Difference
Fill compression	59	58	2%
Foundation settlement	120	126	5%

The difference between measured and simulated fill compression is approximately 2%, while the difference for foundation settlement is approximately 5%.

The close agreement indicates that the adopted constitutive representation provides a reasonable basis for analyzing the settlement response of the investigated coarse-grained embankment.

13. Parametric Settlement Analysis

Seven compaction degrees were investigated:

$$85, 87.5, 90, 92.5, 95, 97.5, 100\%$$

Eight embankment heights were considered:

$$5, 10, 15, 20, 25, 30, 35, 40\ m$$

Thus, the numerical program comprised:

$$7 \times 8 = 56$$

simulation conditions.

This parameter matrix allows the independent and combined effects of embankment height and compaction quality to be examined.

14. Effect of Embankment Height on Settlement

The numerical results demonstrate a nonlinear relationship between embankment height and settlement.

The relationship can be expressed generally as:

$$S_x = ah^b$$

where:

- S_x= settlement at compaction degree x;
- h= embankment height;
- $a$and b= fitting parameters.

The fitted exponent was approximately:

$$b = 1.916$$

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The value being close to 2 indicates that settlement increases substantially faster than a simple linear relationship with embankment height.

This behavior has a clear mechanical explanation.

As embankment height increases, the lower portion of the fill is subjected to progressively greater self-weight stress. Consequently, deeper layers contribute increasingly to total compression.

Thus:

$$h \uparrow \Rightarrow \sigma_v \uparrow \Rightarrow \varepsilon_v \uparrow \Rightarrow S \uparrow$$

The nonlinear response also means that a compaction specification suitable for a low embankment cannot automatically be assumed adequate for a very high embankment.

15. Effect of Compaction Degree

The settlement simulations show that compaction degree has a strong influence on high-fill deformation.

At lower embankment heights, the differences among compaction levels are relatively moderate.

As the embankment becomes higher, however, the difference between highly compacted and poorly compacted fill becomes increasingly important.

This occurs because the lower fill layers are subjected to larger vertical stresses.

The practical implication is that compaction quality should be increasingly stringent as embankment height increases.

The relationship can therefore be expressed conceptually as:

$$\frac{\partial S}{\partial x} < 0$$

and:

$$\left|\frac{\partial S}{\partial x}\right| \uparrow \text{ as } h \uparrow$$

In other words, increasing compaction degree reduces settlement, while the benefit of improved compaction becomes more pronounced in taller embankments.

16. Settlement Regression Model

The settlement can initially be expressed as:

$$S = f(x, h)$$

For a given compaction degree:

$$S_x = ah^b$$

with:

$$b = 1.916$$

The coefficient $a$varies systematically with compaction degree and was represented by:

$$a = cx^d + e$$

The fitted relationships were subsequently integrated to establish an empirical formulation for predicting the settlement response of the investigated coarse-grained embankment material.

$$\boxed{S = (-0.1987x^{7.313} + 0.3501)h^{1.916}}$$

where:

- S= settlement;
- x= compaction degree expressed as a decimal fraction;
- h= embankment height.

The equation explicitly links two construction variables—compaction degree and embankment height—to settlement.

For the Malaysian context examined in this study, the proposed equation is formulated as a predictive component of the present analytical framework, with its applicability defined by the characteristics and range of the investigated dataset. It is therefore intended to support prediction within the conditions examined in the study rather than to serve as a universal design equation for all Malaysian applications.

17. Tropical Malaysian Interpretation

The Malaysian application incorporates climatic conditions as an additional contextual factor, allowing the analysis to be interpreted within the environmental setting considered in the present study.

The critical pathway is:

Rainfall → Infiltration → Moisture increase → Change in soil state
→ Compression response → Settlement

The experimentally measured moisture range of 2–10% provides a useful mechanical basis for interpreting this process.

The optimum moisture condition of 6.2% represents the density-maximizing state during compaction. However, rainfall occurring after construction does not necessarily reproduce the same mechanical condition as controlled laboratory mixing. Rainfall infiltration can be spatially

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nonuniform, and drainage, permeability, slope geometry, vegetation, surface protection, and antecedent moisture all influence the resulting hydraulic state.

Recent work on rainfall-affected high embankments demonstrates that rainfall duration can modify settlement, water content, and pore-water pressure, while Malaysian research emphasizes the role of intense tropical rainfall in changing unsaturated-soil conditions. [31,32,33]

Accordingly, rainfall-induced wetting should be treated as a **boundary-condition and moisture-state problem**, rather than simply assigning a rainfall percentage to the compaction curve.

18. Drainage Considerations

Drainage is particularly important when coarse-grained embankments are exposed to repeated rainfall.

The following engineering measures are relevant:

1. maintain positive surface drainage;
2. prevent ponding on compacted layers;
3. protect exposed embankment surfaces during prolonged rainfall;
4. ensure that drainage paths are not blocked during construction;
5. control construction traffic on excessively wet fill;
6. rework layers that have experienced significant uncontrolled

   wetting;
7. monitor moisture content before subsequent compaction;
8. maintain consistent layer thickness and compaction procedures.

The importance of maintaining moisture within acceptable construction limits is also reflected in earthwork specifications used in high-rainfall environments.

19. Integrated Conceptual Model

The developed framework can be summarized as follows:

Particle gradation► Packing and interlocking► Moisture condition► Compaction response► Dry density / compaction degree ► Compression modulus -Stress distribution with embankment height ► Vertical deformation ► Total settlement with a parallel environmental pathway: Tropical rainfall► Infiltration► Moisture-state modification► Potential change in compression response► Settlement modification

Drainage acts as a regulating mechanism between rainfall and

moisture-state change.

20. Engineering Implications

The results have several practical implications for high embankment construction.

First, moisture conditioning should be considered an essential part of compaction control. The experimentally identified optimum moisture content of approximately 6.2% provides a reference for the investigated material.

Second, compaction degree is not simply a construction-quality indicator; it is directly linked to the stiffness parameter used in settlement analysis.

Third, embankment height strongly amplifies the effect of compaction. Consequently, higher embankments require stricter control of layer density and construction uniformity.

Fourth, particle gradation should be controlled because changes in gradation can modify packing and load transfer.

Fifth, rainfall should be incorporated into construction management in tropical regions. However, rainfall effects should ideally be modeled through coupled seepage–stress analysis when field rainfall and hydraulic-property data are available.

21. Limitations

Several limitations should be recognized.

First: The present investigation is subject to several considerations that should be taken into account when interpreting the findings. The analysis is based on a defined coarse-grained soil gradation, which limits the range of particle-size distributions represented in the dataset. Consequently, the independent statistical contribution of particle gradation cannot be isolated from the effects of the other variables examined in the study.

Second, the experimental framework adopts a prescribed compaction energy under controlled laboratory conditions. This fixed-energy configuration limits the ability of the present analysis to distinguish the specific contribution of compaction energy from the effects of the other investigated parameters.

Third, rainfall intensity, rainfall duration, infiltration rate, pore-water pressure, and hydraulic conductivity were not directly measured in the original experimental program. Rainfall-induced wetting is therefore incorporated as a climatic interpretation of the experimentally measured moisture state rather than as a directly calibrated rainfall variable.

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Fourth, the finite-element analysis considers self-weight loading and does not explicitly model traffic loading, cyclic loading, seepage, or coupled hydro-mechanical processes.

Fifth, the empirical settlement equation is based on a specific material and numerical parameter range and should not be extrapolated beyond the tested conditions without independent validation.

22. Recommendations for Future Research

Future research in Malaysia should expand the present dataset by conducting controlled experiments on:

1. multiple particle-size distributions;
2. different fines contents;
3. different compaction energies;
4. repeated wetting–drying cycles;
5. rainfall-simulator experiments;
6. saturated and unsaturated hydraulic conductivity;
7. suction–water-content relationships;
8. pore-water pressure evolution;
9. cyclic traffic loading;
10. coupled seepage–deformation finite-element modeling.

A particularly useful extension would be to develop a rainfall-conditioned settlement model:

$$S = f(x, h, w, R, D)$$

where:

- S= settlement;
- x= compaction degree;
- h= embankment height;
- w= moisture content;
- R= rainfall/wetting condition;
- D= drainage condition.

Such a model would provide a more comprehensive representation of tropical high-embankment behavior.

23. Conclusions

An integrated assessment framework was established in this study to investigate the compaction characteristics and settlement behavior of coarse-grained soils in high embankments under Malaysian tropical conditions. By considering the interactions among soil properties, compaction characteristics, embankment geometry, and deformation response, the proposed framework provides a structured approach for interpreting embankment performance and supporting engineering assessment within the investigated range of conditions.

The main conclusions are as follows.

1. Material characteristics.
The investigated material is a coarse-grained fill dominated by particles between 2 and 20 mm, with a maximum particle size below 40 mm. Its uniformity coefficient and curvature coefficient are approximately 43.3 and 6.4, respectively.

2. Compaction behavior.
The heavy-compaction results demonstrate a clear dependence of dry density on moisture content. The optimum moisture content is approximately 6.2%, while the maximum dry density is approximately 2.13 g/cm³.

3. Moisture sensitivity.
Compression deformation increases with increasing moisture content under the investigated loading conditions. At 400 kPa, the increases relative to 100 kPa were 70.5%, 41.9%, 37.8%, 33.1%, and 39.3% for the five moisture conditions.

4. Compaction–stiffness relationship.
Compression modulus is strongly correlated with compaction degree and can be represented within the investigated range by:

$$E_s = 1727.9x^2 - 2958x + 1308.8$$

with $R^2 = 0.96$.

5. Numerical reliability.
The finite-element model reproduced the measured fill compression with an error of approximately 2% and foundation settlement with an error of approximately 5%.

6. Embankment height.
Settlement increases nonlinearly with embankment height and can be represented by an approximate power relationship with an exponent of 1.916.

7. Compaction degree and settlement.
The influence of compaction degree becomes increasingly important as embankment height increases. Poorly compacted lower layers can therefore make a disproportionate contribution to total settlement in high fills.

8. Integrated settlement model.
The preserved numerical dataset yields the empirical relationship:

$$S = (-0.1987x^{7.313} + 0.3501)h^{1.916}$$

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which provides a convenient preliminary estimation method within the investigated parameter range.

9. Malaysian tropical context.
Rainfall-induced wetting represents a relevant environmental factor in the Malaysian context because changes in moisture conditions may influence the mechanical behavior and deformation characteristics of compacted coarse-grained fills. Nevertheless, in the absence of direct measurements of rainfall intensity and duration, the present analysis considers rainfall as a contextual wetting mechanism rather than developing a separately calibrated quantitative relationship between rainfall and settlement.

10. Engineering application.
For Malaysian high embankments, effective settlement control requires integrated management of particle gradation, moisture condition, compaction quality, embankment height, surface drainage, and rainfall exposure.

Overall, the results demonstrate that compaction quality and embankment height are strongly coupled controls on settlement, while moisture condition provides an essential link between construction practice and tropical environmental exposure. The framework provides a foundation for subsequent Malaysian laboratory and field investigations involving direct rainfall simulation and coupled hydro-mechanical modeling.

Ethical Considerations

Not applicable. This study did not require ethical approval because it does not include human or animal subjects and does not involve any personal or sensitive data.

List of Abbrevations:

E_c= compaction energy; ρ_d= dry density; E_s= compression modulus; S= settlement; S_x= settlement at compaction degree x; h= embankment height; R= rainfall/wetting condition; D= drainage condition.

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Declaration of generative AI and AI-assisted technologies in the writing process

The authors hereby declare that no generative artificial intelligence or AI-assisted technologies were used at any stage during the preparation of this manuscript, including language editing, proofreading, or content development. The authors take full responsibility for the originality and integrity of the work presented in this publication.

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Conflicts of Interest:

"The authors declare no conflict of interest."

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