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Research Article

Conceptual analysis of seepage control for Senggarang Coastal Embankment with chemically-stabilized backfill

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Abstract

One of the common problems of coastal embankments is water seepage. The Senggarang Coastal Embankment (SCE) is examined in the present work, with the objective of proposing the improvement of the earth structure via chemical stabilization. The stabilized soil embankment was simulated and analyzed with PLAXIS 8 to identify a conceptual proposition of solution using a conventional and innovative stabilizer, i.e., lime-ZnO and cement-CSP (cockle shell powder). The base of the embankment was assumed to be bedrock, in order to eliminate the passage of water below the embankment. Stabilization was taken as 100 % for the embankment, i.e., a homogeneous earth structure made entirely of stabilized soil for seepage mitigation. Input parameters for the simulations were acquired from both field samples and past studies. Varying water levels due to tidal effect were applied in the model to determine the changes of pore pressure distribution which could potentially lead to instability of the embankment. As water level increases with the rising tide, total displacement of the original earth embankment was found to increase as the soil weakened, with decreasing effective shear stress. Replacement of the embankment backfill with cement-CSP and lime-ZnO were both observed to significantly reduce the displacements. The use of both stabilizers not only improves the SCE's engineering performance in terms of reduced water seepage and displacement, accompanied by increased strength, but the 'green' nature of the former, as derived from organic waste, also enhances the appeal of the stabilization technique.

1. Introduction

An earthen embankment is generally defined as a raised confining structure made up of compacted soil for the detention and retention of water to facilitate deep percolation while minimizing seepage. Embankment cross-sections are typically trapezoidal in shape, as shown in **Figure 1**. Note the overlying pavement on the embankment, which usually serves as a service road in such coastal earth dams. Cover for the seaward side protection is often of rock armor or other forms of protection schemes against tidal impact. On the other hand, seepage is one of the most common failures that occur in earth embankments. Seepage can occur due to hydraulic failure, seepage failure, piping through the dam body, and structural failure due to earthquakes.

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Soil stabilization is the process of adding a special soil, cementing material, or other chemical materials to a natural soil to improve one or more of its properties (Afrin, 2017). When stabilizing agents are admixed with an originally weak soil, the chemical reactions can effectively increase inter-particle cohesion for cementing and waterproofing purposes (Kalkan, 2020). Supplementary cementing materials, such as zinc oxide (ZnO) and cockle shell powder (CSP), help to further improve the effectiveness of the binder in term of strength (Jit et al., 2021; Md. Nujid et al., 2020; Nochaiya et al., 2015). The present proposition examined the efficacy of lime-ZnO and cement-CSP as stabilizing agents for strengthening an earth structure against seepage.

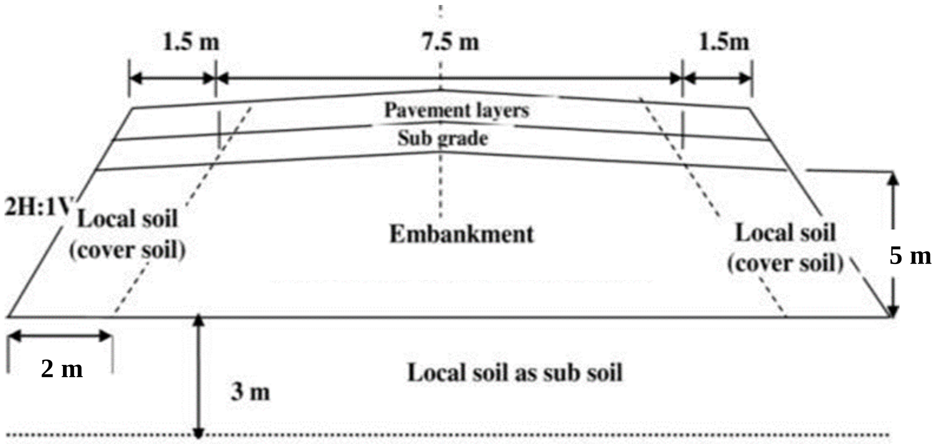

Figure 1 Typical cross-section of an embankment; actual dimensions are dependent on site conditions and design requirements (adapted from Yang et al., 2019).

There is a major seepage problem at the Senggarang Coastal Embankment (SCE), as shown in **Figure 2**. The embankment is over 20 years old, with a semi-paved service road for access. Bordering the sea and oil palm plantations, with a narrow buffer zone in between, the SCE shows apparent signs of water emigrating inland (**Figure 3**). Backfills with poor engineering properties of low strength and high compressibility could have resulted in both a low bearing capacity and high permeability of the earth structure, leading to the current severe seepage issues. As such, the present study aimed to explore the possibility of using chemical stabilized backfill soil to specifically improve the embankment's engineering properties against seepage.

Figure 2 The Senggarang Coastal Embankment (SCE), bordering the sea and inland agriculture allotments.

Figure 3 Evident seepage problem: Inundated inland buffer zone between the SCE and an oil palm plantation.

This study was carried out to investigate the SCE seepage problem with a focus on the adoption of chemically-stabilized backfills for enhanced engineering properties of the earth structure for seepage mitigation. The conceptual analysis was conducted using PLAXIS 8, a commercially-available software for the simulation and examination of geotechnical problems, including the safety of embankments such as this (Yang et al., 2019).

2. Materials and methods

The SCE is located at 1°43'01.7"N 103°02'59.1"E. The type of soil found as the base material for the existing embankment is a silty clay. The foundation of the embankment was assumed to be bedrock for two purposes, i.e., (1) to provide stability for the self-weight of the earth structure, and (2) to prevent seepage through the embankment's foundation, both of which are factors that could complicate the examination process.

Soil properties of the embankment were inputs in the PLAXIS material data sets (**Table 1**), while the geometric model of the SCE was derived based on the actual dimensions of the embankment (**Figure 4**). Three distinct water levels, namely, 1, 2, and 3 meters (m), were simulated in the analysis to determine the tidal effect on the seepage dynamics.

The phases of embankment construction in the program were defined as per the sequential calculation stages. Computation for the modelling analysis was divided into five stages, where the initial conditions and stress fields were defined in the early parts, followed by load application in the third stage. Note that the load applied was 1.79kN/m^2, equivalent to the traffic load on the single-lane service road overlying the embankment. The dimensions of the embankment as simulated are shown in **Figure 4**.

Table 1 Material properties of the embankment and subsoil (Khodaparast et al., 2021; Mohd Noh & Chan, 2021).

Parameter	Name	Unit	Bedrock	Untreated silty clay	Treated silty-clay (Cement-CSP)	Treated silty-clay (Lime-ZnO)
Model	-	-	Linear elastic	Mohr-coulomb	Mohr-coulomb	Mohr-coulomb
Drainage type	-	-	Undrained	Drained	Drained	Drained
Dry unit weight	γ unsaturated	kN/m^3	26.0	16.0	17.2	16.5
Bulk unit weight	Γ saturated	kN/m^3	26.0	17.0	19.5	18.0
Friction angle	φ	o	50.0	34.0	38.7	40
Cohesion	c_{ref}	kN/m^2	100	14	520	74
Poisson ratio	υ	-	0.3	0.34	0.15	0.25
Young modulus	E_{ref}	kN/m^2	85400	1300	187353	22000
Horizontal permeability	k_x	m/day	0.6	0.778	0.034	0.078
Vertical permeability	k_y	m/day	0.6	0.778	0.034	0.078

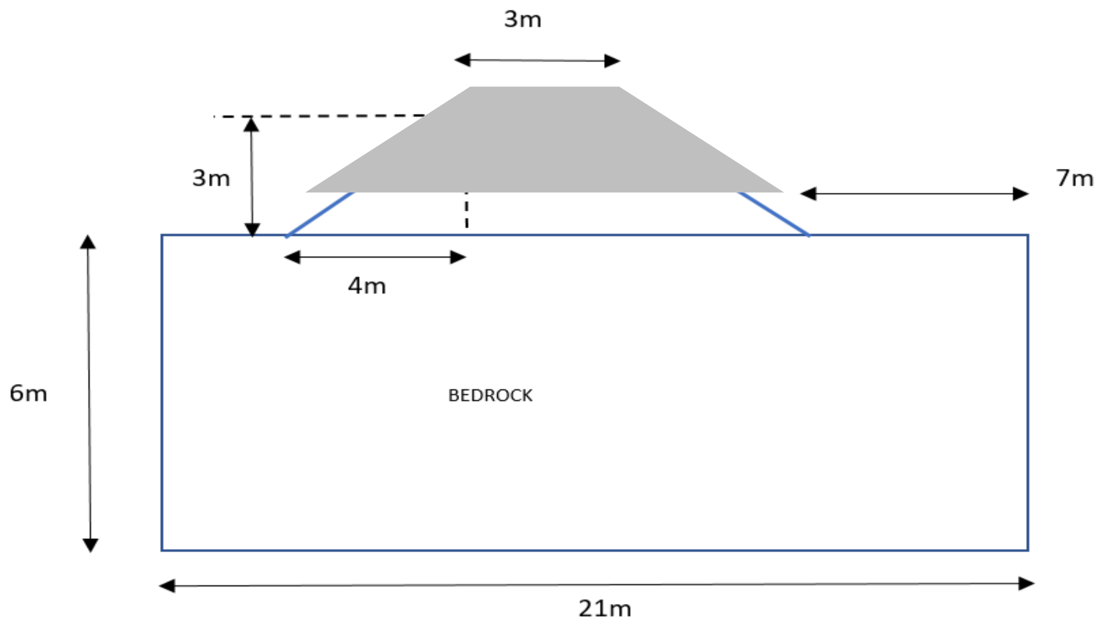

Figure 4 Simulated embankment model in PLAXIS.

3. Results and discussions

The following discussions are directed at the analytical results for total displacement, effective stress, excess pore pressure, and discharge of seepage.

3.1 Total displacement

Figure 5 shows the water level vs. total displacement plots for the untreated silty clay and stabilized silty clay with cement-CSP and lime-ZnO. The untreated silty clay had a much larger total displacement than the treated soils. The differences could also be noted to increase with rising water level, where the untreated soil underwent an approximately linear 100 % increment in displacement with every 1 m of rising water. On the contrary, the treated soils recorded remarkably small displacement, i.e., ranging from about 0.4 to 1.5 mm, as the water level was raised from 1 to 3

m. This significant improvement in terms of strength of the embankment resisting deformation with increased lateral force from the water level, as well as increased pore pressure, can be attributed to the greater cohesion of the treated soils, i.e., cohesion was found to be 520 kN/m^2 and 74 kN/m^2 for the cement-CSP and lime-ZnO admixed soils, respectively. This is indicative that cement-CSP was far more effective in improving the soil's strength in comparison with lime-ZnO, though both were viable stabilizing agents for the embankment's soil.

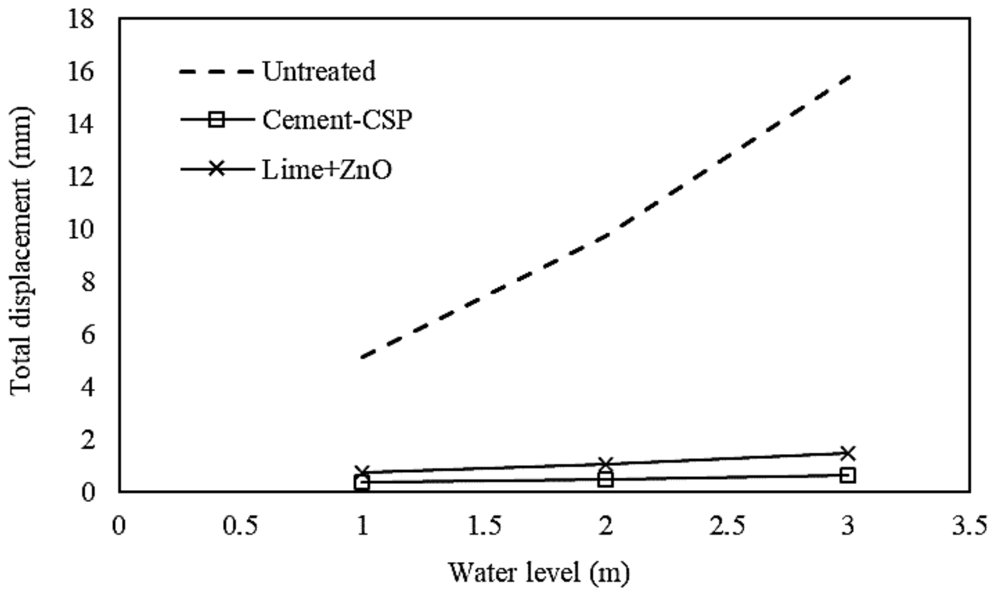

Figure 5 Changes of total displacement with water level.

3.2 Effective stress

Table 2 summarizes the effective stress changes with water level, which at first glance showed negligible differences in the values recorded. Nonetheless, it is apparent that stabilization did raise the effective stress at all water levels, ranging from 2.4 to 4.9 % in comparison with the untreated soil. This is suggestive of the enhanced strength of the stabilized soil as the water level rose, enabling the embankment to have better load-bearing capacity. Also worth noting is the slightly higher effective stress recorded for the cement-CSP-treated soil, regardless of the water level. This is in corroboration with the displacement pattern (**Figure 6**), where the untreated soil underwent the most significant deformation, while the soil stabilized with cement-CSP succumbed the least under load.

Also, it can be seen from **Table 3** that the change in effective stress for the treated silty clay was smaller than for the untreated silty clay. For example, effective stress increase for the soil treated with cement-CSP was 4.8 kN/m^2, clearly smaller than that of the untreated silty clay, at 6.2 kN/m^2. This, in turn, points to the fact that settlement of the cement-CSP-treated soil would be less than that of the untreated silty clay. Note, too, that the addition of cement-CSP could improve the strength of the silty clay more effectively than lime-ZnO, resulting in greater load resistance and less displacement. The overall reduced susceptibility of the stabilized soil of the embankment towards the combined effect of loading and rising water level suggests marked improvement of the SCE's stability, highlighting the potential of stabilization technique for seepage mitigation.

Table 2 Effective stress in the embankment at various water levels.

Water level (m)	Soil types	Effective stress (kN/m^2)
1	Untreated silty clay	122.7
	Treated silty clay (cement-CSP)	123.8
	Treated silty clay (lime-ZnO)	123.5
2	Untreated silty clay	118.9
	Treated silty clay (cement-CSP)	120.8
	Treated silty clay (lime-ZnO)	120.4
3	Untreated silty clay	116.5
	Treated silty clay (cement-CSP)	119.0
	Treated silty clay (lime-ZnO)	117.9

Table 3 Change of effective stress with water level.

Soil types	Increase of effective stress for 1 to 3 m water level (kN/m^2)
Untreated silty-clay	6.2
Treated silty clay (lime-ZnO)	5.6
Treated silty clay (cement-CSP)	4.8

3.3 Excess pore pressure

Figure 6 shows the relationship between excess pore pressure and water level for the simulated embankment. It is immediately apparent that the cement-CSP-treated soil was barely affected by the rising water level in terms of pore pressure, an indicator of the low hydraulic conductivity and porosity of the material. This is advantageous indeed for the coastal geostructure in constant contact with water on the seaward slope, where tidal fluctuations have minimal impact on water migration into the embankment, leading to seepage. As for the lime-ZnO admixed soil, the seemingly parallel rise of excess pore pressure with that of the untreated soil as the water level rose suggests the presence of voids within the soil mass, as well as the susceptibility to water ingress. The increased pore pressure with tidal rise can potentially lead to partial breakdown of the soil's structure, with ensuing reduction in strength and stiffness. It follows that stabilization of the embankment backfill with lime-ZnO should be carried out with caution and monitoring of pore pressure changes upon loading at various stages of the incoming tide. This would help avoid unknown inherent destabilization of the embankment, while external displacement records may demonstrate limited changes, i.e., **Figure 5**.

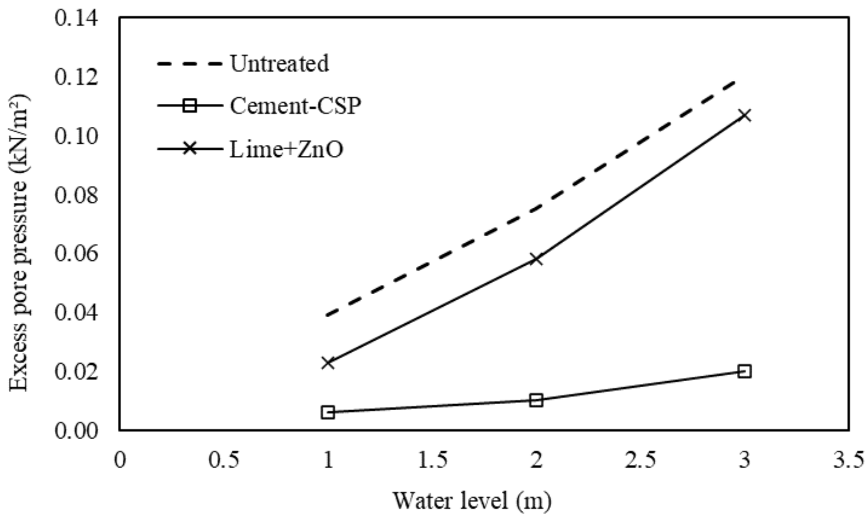

Figure 6 Water level vs. excess pore pressure.

3.4 Seepage analysis

The seepage discharge rate is summarized in **Table 5** for all backfill types at various water levels. It is evident that seepage is very severe for the existing embankment, with water inflow rising to almost 500×10^{-3} m^3/day at 3 m tide level. In fact, the seepage increased by 4.5 times as water level rose from 1 to 2 m, followed by an overwhelming 4.5 times increment as the water level rose to 3 m. This seepage rate - water level correlation explains the inland flooding observed on site, where excessive water inflow via the embankment kept the buffer zone inundated for most of the time. It also serves as a risk indicator of an imminent collapse of the embankment due to loss of fine-grained soils from the backfill.

On the other hand, stabilization with cement-CSP and lime-ZnO significantly reduced the seepage rate. However, water migration through the embankment was not totally eliminated, especially with rising water levels accompanying the incoming tide (**Table 5**). The stabilized soils recorded a seepage rate of almost 10 times lower than that of the original, untreated soil at every water level in an ascending manner. The cement-CSP-stabilized soil provided far more remarkable resistance against seepage, recording 140 % greater efficiency than the soil admixed with lime-ZnO. The difference in efficiency was consistent at all water levels, pointing to the improved soil's fabric being unperturbed by the rising water level and tidal impact.

Table 5 Discharge of seepage at various water levels.

Water level (m)	**Soil types**	**Discharge of seepage (m^3/day), ×10^{-3}**
1	Untreated silty clay	38.08
	Treated silty clay (cement-CSP)	1.78
	Treated silty clay (lime-ZnO)	3.95
2	Untreated silty clay	170.90
	Treated silty clay (cement-CSP)	7.21
	Treated silty clay (lime-ZnO)	16.77
3	Untreated silty clay	485.80
	Treated silty clay (cement-CSP)	21.34
	Treated silty clay (lime-ZnO)	49.68

Figure 7 depicts the relationship between displacement and seepage for the cement-CSP-stabilized soil. Vertical displacement remained largely unchanged, even when seepage discharge increased by almost 20 times. This is in contrast with the horizontal displacement, which rose in proportion to the water discharge rate, suggestive of the negative impact seepage force has on the embankment as a whole. Excessive deformation of the geostructure could compromise the stability of the embankment, with gradual safety factor reduction leading to total failure or collapse. Considering that the SCE is the last frontier protecting the Senggarang township from deluge and seawater intrusion, it is, therefore, imperative that in situ displacements of the existing embankment are regularly monitored while awaiting mitigation measures. The correlation captured in **Figure 7** makes a cautionary note on the risks faced by the SCE in its current condition and exposure, which is conservative at best.

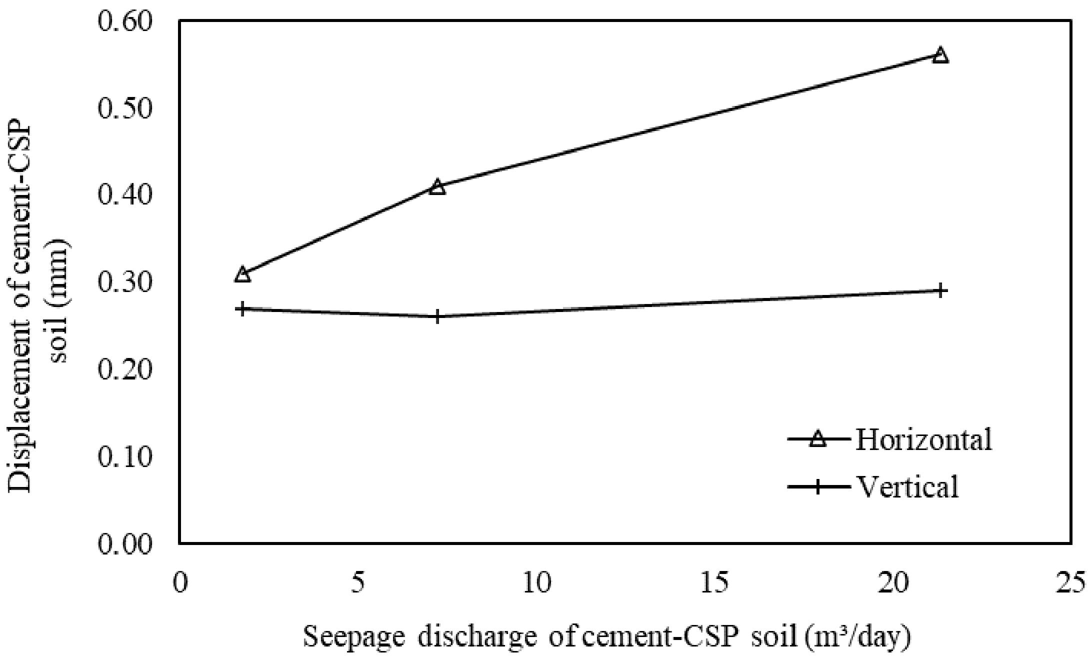

Figure 7 Displacement vs. seepage discharge.

4. Conclusions

The conceptual analysis of the Senggarang Coastal Embankment (SCE) with representative backfills of original untreated soil, and soils stabilized with cement-CSP and lime-ZnO, respectively was carried out. With changing water levels between 1 - 3 m simulating the tidal effect, displacement was noted to be effectively constrained with stabilization, though cement-CSP could enhance shear strength of the soil by up to 7 times that of the lime-ZnO-treated soil. Also, stabilization was found to raise the effective stress by 2.4 to 4.9 % compared to the original soil, a significant improvement for load-bearing, as corroborated by the small overall displacement of the embankment. Interestingly, admixing the soil with lime-ZnO had a marginal effect on porosity and susceptibility towards water ingress, where the excess pore pressure increased with the water level. Stabilization significantly reduced seepage discharge through the embankment, with cement-CSP showing far more superior water stoppage capacity. Overall, the conceptual analysis gives useful insight into the feasibility of incorporating soil stabilization in the rehabilitation of the deteriorating coastal embankment, with potentially better long-term durability, stability, and cost-effectiveness.

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