Behavioral Study of Soft Soil Beneath the Embankment Improved by Columns Derived from Recycled Concrete Aggregate and High-Calcium Fly Ash-Based Geopolymer

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***Abstract*— Soft clay poses geotechnical challenges, not only due to its high water content, but also caused by high compressibility, low permeability, low bearing capacity, and low shear parameters, which might damage the upper structure of the building. Although column reinforcement methods, such as deep soil mixing, bottom ash columns, and cement soil columns, have been widely used for ground improvement, the performance of geopolymer concrete column (GCC) with recycled concrete aggregate remains under explored. This study aims to analyze embankment behavior on soft soil by reviewing settlement, the embankment safety factor, and the time required to reach a 90% degree of consolidation, both before and after reinforcement with geopolymer columns. Numerical simulations were conducted using a two-dimensional finite element method (FEM) in PLAXIS 2D software under plane-strain conditions. The parameters used in the modeling were soil parameters and geopolymer column (GPC) reinforcement adopted from previous research. The FEM analysis showed that GPCs can reduce consolidation settlement, accelerate consolidation rates, and increase the overall stability safety factor of the embankment system.**

Keywords— Embankment, RCA, Geopolymer, Safety factor, FEM, Road construction.

I. INTRODUCTION

In geotechnical engineering, soft soil is one of the most challenging soil types because it contains high moisture content, high compressibility, low permeability, low bearing capacity, and low shear parameters [1]. Generally, soft soil characteristics are influenced by two major factors: macroscopic and microscopic. Macroscopic factors include load, drainage conditions, consolidation time, and thickness. Meanwhile, microscopic factors include cohesion, internal friction angle, and shear strength [2], [3]. The increasing need for facilities and infrastructure and the limited availability of adequate land has resulted in construction activities being carried out on weak deposits. Often the presence of soft soils causes foundation instability and settlement of embankments, and ground surfaces that occur during the construction process. Therefore, soil improvement is required to overcome these problems [4].

The selection of soil improvement methods depends on the field condition and takes into account several factors, such as time, cost, and adverse geotechnical conditions. A frequently used method is stabilization using cement to increase the soil's bearing capacity and reduce the plasticity index [5]. Other methods include rigid inclusion of micropiles and pressurized cement grout injections with the jet-grouting system. Among them, column reinforcement techniques, such as stone columns or deep cement mixing columns (DCMC), are widely implemented to increase soil bearing capacity, reduce embankment settlement, and accelerate consolidation rates. These methods have been widely used in countries such as Thailand, Japan, Singapore, China, and Sweden [6], [7]. Farouk and Shahien [8] investigated the performance of soil-cement columns (SCCs) produced by the deep mixing method in soft soil. The results revealed that the use of SCC reduced subsidence by up to 80%. Similarly, Hasan and Canakci [5] studied the application of self-compacting concrete (SCC) via jet grouting. They observed that increasing the grouting pressure decreased the SCC's compressive strength due to a decrease in cement concentration caused by machine pressure. The presence of SCC reduces the vertical deformation of the embankment without affecting the expected stress distribution within it [9].

Despite their mechanical performance, heavy reliance on Portland cement (OPC) as the main binder in DCMC leads to environmental degradation. The production of cement is highly energy-intensive because it releases CO2, which contributes to global warming through the greenhouse effect. As of 2013, OPC production accounted for 5-7% of CO2 emissions [10]. Therefore, eco-friendly substitute binder materials, such as lime (L), fly ash (FA), bottom ash (BA), magnesite mine tailings, biomass ash blends, and geopolymers, are used as the primary material for reinforcing columns [11], [12].

Geopolymers have emerged as an effective material in the geotechnical field, especially as a cement column, and base/subbase material [13]. The material is classified as eco-friendly because it does not require much energy and is categorized as a low-carbon material [14]. Geopolymers also have resistance to heat and fire as well as environmental conditions with a wide range of chemical exposure [15]. Recent studies demonstrated the effectiveness of an alternative material, bottom ash (BA), for column reinforcement. Ullah et al. [16] examined the BA-based geopolymer column (BAGC) and found that the embankment bearing capacity increased with a smaller spacing/diameter (s/d) ratio and a larger

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length/diameter (L/d) ratio. Therefore, BAGC can be used to improve soft soils and provide environmental benefits. Furthermor, Ullah et al. [17] observed that increasing the replacement area ratio (Ar) enhances the embankment's bearing capacity up to 1.83 times more than an unreinforced embankment. This is supported by numerical analysis conducted by Abbil et al. [18], which revealed that changes in time to settlement and pore water pressure depend on Ar and increases in column length. A higher Ar value significantly reduces the settlement value by increasing bearing capacity.

The above descriptions confirm that column reinforcement using cement, fly ash, and bottom ash significantly reduces settlement and increases the embankment's bearing capacity. However, the effect of geopolymer concrete columns incorporating Recycled Concrete Aggregate (RCA) beneath embankment on soft soil is rarely investigated. To address this research gap, this study aims to perform a finite element analysis to evaluate the geotechnical performance of soft clay reinforced with recycled fly ash-based geopolymer columns. Specifically, it analyzes embankment behavior by examining settlement, the embankment safety factor, and the time required to reach 90% consolidation, both before and after reinforcement with geopolymer columns.

II. Research Method and Geotechnical Properties

A. Finite Element Analysis

Numerical analysis in this study was conducted using the finite element method (FEM) implemented in Plaxis 2D V20 software. This software allows performing analyses that consider the sequence of construction stages. FEM is one of the most effective numerical analysis methods and provides a theoretical approach to soil stability. In practice, it is used for embankment analysis in road and rail construction, as well as for probabilistic embankment stability analysis in soft soil and slope stability analysis [19], [20], [21]. The finite element method (FEM) can perform plastic analyses to interpret the well-known first-approximation model of soil behavior: the linear elastic perfectly plastic (LEPP) model, also known as the Mohr-Coulomb (MC) model. The MC model's main linear elastic aspect relies on isotropic elasticity and Hooke's law, while the perfectly plastic aspect relies on failure criteria. Plastic analysis is typically used to evaluate elastic-plastic deformations calculated using small deformation theory. In normal plastic computations, the stiffness matrix is based on the original, undeformed shape. Therefore, this type of calculation is suitable for most geotechnical applications. Meanwhile, embankment modeling uses the Mohr-Coulomb material model because its materials are considered stable [22], [23].

In addition to material model selection and parameter input, discretization or meshing affects the analytical accuracy of FEM analysis. In this study, the embankment was modeled using a 15-noded triangular element because it provides more accurate results compared to the 6-noded triangular element [24]. Furthermore, the modeling method was plane-strain because the plane-strain model is a simplification of 3D numerical analysis, in which the embankment geometry is modeled in 2D to determine deformation based on input soil parameters and external loads [25]. Therefore, it is suitable for slope stability analysis. This plain-strain modeling assumes that deformation occurs only in two directions—the X and Y—, with zero deformation in the longitudinal Z direction [26] [27]. At the same time, the mesh size is the medium element distribution listed in Plaxis 2D. The embankment model and soil layers are shown in **Error! Reference source not found.**.

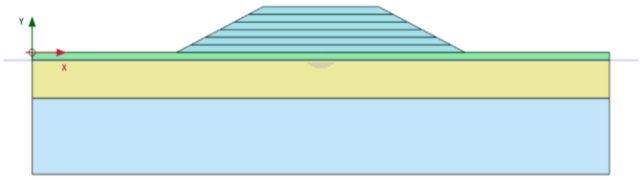


Fig. 1. Embankment model in PLAXIS 2D

B. Consolidation Behavior of Soil Under an Embankment

Consolidation is the process of dissipating excess pore water pressure caused by external loads. In this context, the external loads were the surcharge and traffic loads. In practice, the fill is modeled as accurately as possible to determine its consolidation behavior, such as consolidation settlement, consolidation duration, and the safety factor of the embankment. Factors that influence consolidation behavior include soil type, which is determined by soil permeability, drainage pathways, compressibility, void ratio, and time [28]. Furthermore, the approach to consolidation behavior is based on the one-dimensional nonlinear consolidation theory as suggested by Omar et al. [29].

In this study, the evaluation compares two structural schemes: an unreinforced embankment (control model) and an embankment stabilized with vertical geopolymer concrete columns (GCC). The analysis was performed using the finite element method (FEM) implemented in Plaxis 2D software [30]. The results were synthesized to calculate total consolidation settlement, time required to achieve 90% consolidation, and the effect of consolidation settlement on the embankment's safety factor.

C. Embankment Model

The embankment was built on crust, soft clay, and stiff clay at depths of 1.00, 5.00, and 10.00 meters, respectively. The groundwater table was located 1 m below the ground surface. The embankment was divided into six 1-meter-high segments. The total width of the cross section under review is 80.00 m, with bottom and top widths of 40.00 m and 16.00 m, respectively. The embankment has a horizontal-to-vertical slope ratio of 2:1 and a total height of 6 m [30]. **Fig. 2**. shows the cross-section of the embankment and the soil profile without geopolymer column (GPC) reinforcement. Meanwhile, the illustration showing the embankment reinforced with (GPC) is shown in **Fig. 3**. Based on previous research, the diameter used to reinforce the embankment is 1.0 m, and the ratio of the GPC installation distance to the diameter is 2.0 [31]. Physical and mechanical parameters of the soil were obtained from research conducted by Tan et al. [32] are shown in Table I.

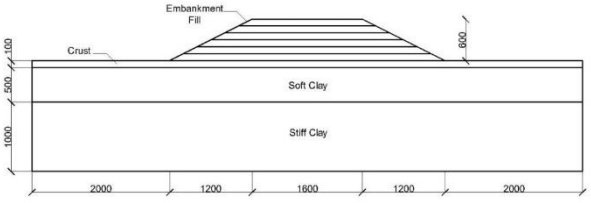


Fig. 2. Embankment cross section without geopolymer column reinforcement

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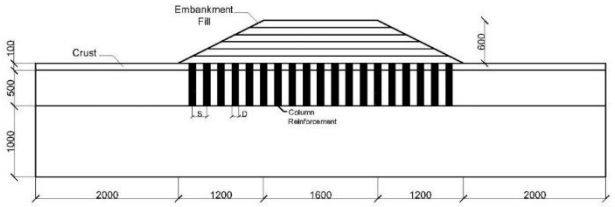


Fig. 3. Embankment cross section with geopolymer column reinforcement

D. Column Reinforcement

The reinforced column is made of recycled concrete aggregate (RCA) stabilized with high-calcium Type C fly ash (FA) geopolymer binder. RCA is a material derived from demolished building concrete that has been crushed using a milling machine [33]. Type C fly ash was chosen due to several advantages, such as a shorter binding time, increased hydration at an early age, and the absence of high temperatures during the hardening or curing process [34]. Previous research indicates that the activator used as a binder between RCA and FA is a mixture of 10M NaOH and Na_2SiO_3 solutions. This mixture was synthesized to form a new composite material [35], [36]. The use of recycled structural concrete has environmental benefits, including reducing the carbon footprint associated with RCA accumulation and eliminating greenhouse gas emissions from natural aggregate production. In addition, the long-term use of RCA results in lower production costs compared to natural aggregate [37]. The mixture of materials is tested to determine its physical and mechanical properties, which are then used in a finite element analysis (FEA). In this study, the physical and mechanical parameters were obtained from experimental testing by Irnawan et al. [38] and are shown in Table I.

TABLE I. PROPERTIES OF BASE LAYER ALTERNATIVE MATERIAL [32], [38]

Material	Embank-ment fill	Crust	Soft clay	Stiff clay	RCA-based geopolymer
Material model	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	Linear elastic
Drainage type	Undrained	Undrained	Undrained	Undrained	Non porous
Thickness (cm)	600	100	500	1000	-
Diameter (cm)	-	-	-	-	100
Dry density (kN/m^3)	18	17	15	18	22.58
Saturated density (kN/m^3)	20	18	15	20	-
Cohesion (kPa)	3	3	1	3	-
Internal friction angle, Ø (°)	33	28	20	30	-
Elasticity Modulus (kPa)	15000	15000	1100	40000	6040000
Poisson's ratio (μ)	0.3	0.3	0.3	0.3	0.35
k_h (m/s)	1.16×10^{-5}	3.47×10^{-7}	3.47×10^{-9}	3.47×10^{-9}	-
k_v (m/s)	1.16×10^{-5}	1.16×10^{-7}	1.16×10^{-9}	1.16×10^{-9}	-

E. Surcharge Load

A surcharge load on an embankment is a simplified representation of the load of a passing vehicle. The amount of load used depends on the standards set by each country or authorized association. Previous studies applied live loads ranging from 10 to 30 kPa [39], [40], [41]. In this research, the road planning is classified into the Class I Road group, which has the highest daily traffic count and the largest axis load among other road classes. Therefore, based on the standards set by the Ministry of Public Works and Housing, the present research used a uniform 15 kPa surcharge traffic load to calculate embankment stability on Class I Road. The load spreads across the embankment cross-section [42]. The surcharge load standards on various road classifications are detailed in Table II.

TABLE II. SURCHARGE LOAD [42]

Road class	Load (kPa)
I	15
II	12
III	12
IV	12

III. RESULTS AND DISCUSSION

A. Safety Factor of Embankment

The reliability of the embankment is quantified through the safety factor (SF) value. The minimum required SF thresholds stipulated by the Ministry of Public Works and Housing, Indonesia [42] are shown. **In Table III.** The safety factor values of the embankment were obtained from finite element analysis using Plaxis 2D. The safety values of the unreinforced embankment and after reinforced with geopolymer columns are shown in Table IV.

TABLE III. SAFETY FACTOR REQUIREMENT OF ROAD EMBANKMENT [42]

Road class	Safety factor
I	1.4
II	1.4
III	1.3
IV	1.3

TABLE IV. SAFETY FACTOR OF ROAD EMBANKMENT FROM FINITE ELEMENT ANALYSIS

Stage construction	Safety factor		
	Unreinforced embankment	Reinforced with GPC	Deviation (%)
Stage 1 (embankment layer 1)	2.957	3.208	8.49
Stage 2 (embankment layer 2)	1.946	2.453	26.05
Stage 3 (embankment layer 3)	1.602	2.099	3.02
Stage 4 (embankment layer 4)	1.430	1.968	37.62
Stage 5 (embankment layer 5)	1.323	1.746	31.97
Stage 6 (embankment layer 6)	1.255	1.586	26.37
Stage 7 (static loading)	1.211	1.464	20.89

Improving the internal strength of soft soil through column reinforcement increases the safety factor value of the embankment. The FEM analysis of GPC reinforcement in the embankment above the soft soil indicates that the presence of GPC increases the safety factor value of the embankment. As argued by by Munawir et al. [21], the use of pile reinforcement can increase the FS value and soil bearing capacity on critical slopes. As shown in Table IV and Fig. 4, the FS values of the unreinforced embankment at stages 1-4 are above the threshold.

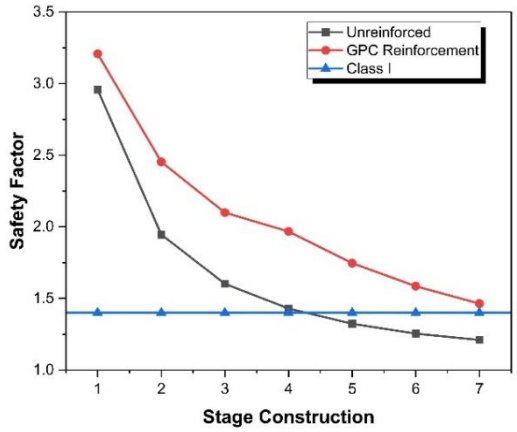


Fig. 4. Safety factor value of embankment

However, as embankment height increases during stages 5-7 of construction, the unreinforced FS values decline below the mandatory Class I road standard (SF=1.40). Meanwhile, the FS values of GPC-reinforced embankment at all stages were above the minimum 1.40 standard, as shown in Table 3. The utilization of GPC reinforcement increased the FS value by 20.89%, compared to GPC unreinforcement. However, the FS value decreased during the embankment's stage construction phase due to the embankment's increased level and the application of vehicle loads. Nevertheless, the FS value remains above the standard stipulated by the Ministry of Public Works and Housing.

B. Settlement and Consolidation Time

Subsidence is caused by loads transmitted from the top of a building or infrastructure to the bottom of the soil surface layer during the construction period until it is put into use. The increase in stress from the combined weight of the building and the soil causes increased settlement. Total settlement is determined by adding instantaneous, primary consolidation, and secondary consolidation settlements [43]. Consolidation settlement occurs when the soil reaches 90% consolidation, a degree that is affected by soil permeability, the thickness of the clay layer, and drainage conditions [44]. Table V presents the finite element analysis using Plaxis 2D.

TABLE V. CONSOLIDATION SETTLEMENT OF ROAD EMBANKMENT FROM FINITE ELEMENT ANALYSIS

Stage construction	Consolidation settlement (m)		
	Unreinforced embankment	Reinforced embankment	Deviation (%)
Stage 1 (embankment layer 1)	0.06493	0.005582	91.40
Stage 2 (embankment layer 2)	0.1332	0.01296	90.27
Stage 3 (embankment layer 3)	0.2056	0.01986	90.34
Stage 4 (embankment layer 4)	0.2820	0.02859	89.86
Stage 5 (embankment layer 5)	0.3633	0.04006	88.97
Stage 6 (embankment layer 6)	0.4623	0.05490	88.12
Stage 7 (static loading)	0.5447	0.06910	87.31

As shown in Table V and Fig. 5, increasing the stage of embankment construction results in an increase in the value of soil consolidation settlement, although it occurred slowly. This increase in value was observed in both models, under both unreinforced conditions and conditions with GPC reinforcement. This is because the pore water pressure was dissipated during the consolidation process of the soft soil layer beneath the fill.

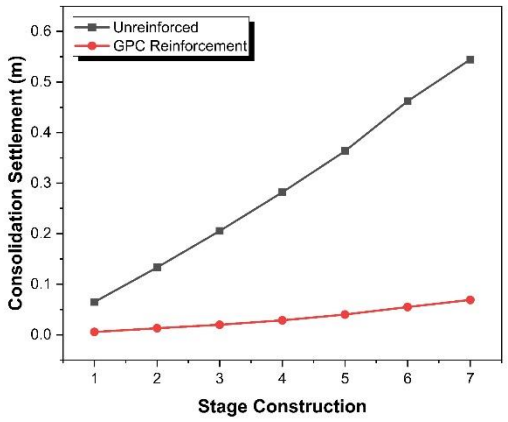


Fig. 5. Consolidation settlement of embankment

As a result, the soil underwent significant vertical deformation [45]. The largest consolidation settlement occurs in embankments that are not reinforced with GPC. The use of GPC can reduce the soil consolidation settlement by 87.31% until the vehicle load is applied when compared to an unreinforced embankment. This is due to the high composite elasticity modulus of soil around the GPC, which increases the soil's stiffness and prevents both vertical and lateral deformation [46].

In addition to magnitude reduction, column installation significantly accelerates consolidation rates. Table VI outlines the consolidation time required to achieve a 90% degree of consolidation. It reveals that the largest consolidation time occurs in unreinforced soil. Meanwhile, the smallest consolidation time occurs in soil reinforced with GPC.

TABLE VI. CONSOLIDATION TIME OF ROAD EMBANKMENT FROM FINITE ELEMENT ANALYSIS

Stage construction	Consolidation time (days)		
	Unreinforced embankment	Reinforced embankment	Deviation (%)
Stage 1 (embankment layer 1)	2205	39.34	98.22
Stage 2 (embankment layer 2)	4623	283.6	93.87
Stage 3 (embankment layer 3)	7060	424.4	93.99
Stage 4 (embankment layer 4)	8871	536.2	93.96
Stage 5 (embankment layer 5)	10870	598.4	94.49
Stage 6 (embankment layer 6)	12780	681.2	94.67
Stage 7 (static loading)	14210	755.7	94.68

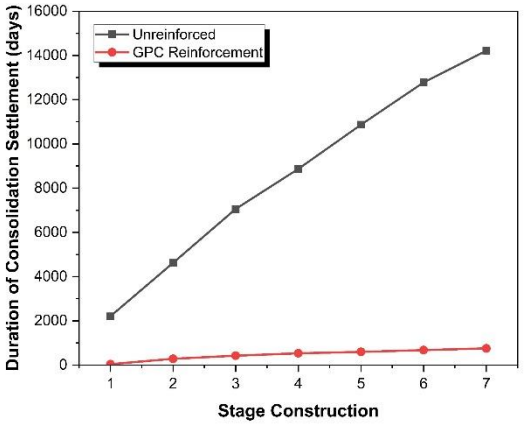


Fig. 6. Consolidation time of embankment

Fig. 6 shows that increasing the stage of embankment construction increases the soil consolidation time. The

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presence of GPC in soft soil can reduce and accelerate soil consolidation time up to 94.68% until vehicle load is applied. This finding confirms the results of Nguyen & Nguyen [40], which show that the use of reinforcing columns can reduce settlement and accelerate consolidation time.

As shown in Fig. 7, the use of GPC helps distribute the above-ground load to deeper, stiffer soil layers by utilizing the friction between the piles and the soil [47], [48]. Meanwhile, Fig. 8 shows an embankment and surcharge loads rest directly on soft soil without any load distribution. This creates the potential for settlement and collapse [29]. These figures indicate that the smallest deformation occurs at the edges of the embankment, while the greatest occurs at its center. This is because the load at the center of the embankment exceeds that at the edge of the embankment, which is consistent with research by Soomro et al. [49].

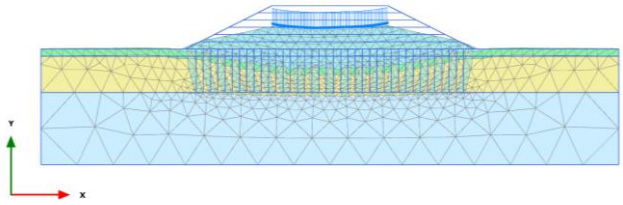


Fig. 7. Deformed mesh of embankment using GPC reinforcement

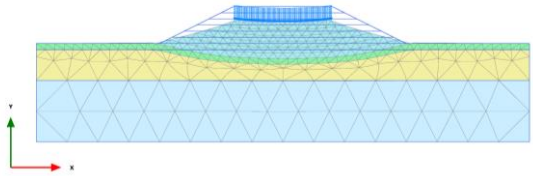


Fig. 8. Deformed mesh of embankment without GPC reinforcement

IV. Conclusion

Based on several finite element method (FEM) analyses, it is concluded that embankment stabilization of soft soil using geopolymer column (GPC) can reduce consolidation settlement, accelerate consolidation, and increase embankment safety factors. This is due to increased stiffness, which enhances the soil's bearing capacity to withstand external loads such as embankments and traffic loads on top of the embankment. The safety factor value increased up to 37%. In addition, column reinforcement is an effective solution for overcoming consolidation settlement problems up to 91%. Furthermore, the use of GPC can reduce consolidation time by up to 98%.

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