Stability Analysis of Embankment using Finite Element Method Constructed over Treated Soil with Anionic Polyacrylamide

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ABSTRACT: Landfill materials composed of weak soil are closely related to stability problems. To minimise this problem, various stabilisation techniques are often used, one of which is the addition of polyacrylamide anionic polymer (APAM). In this paper, soil behaviour before and after adding APAM in the West Bandung area, Indonesia, has been analysed. It has been done with different variables by considering the landfill's geometry and the soil material's properties. Several models were analysed to determine the slope height and angle that are safe for soil stabilisation. The modelling was done using the finite element method based on the soil hardening criteria model and Mohr-Coulomb. The analysis results show that with the increase in height and slope, the safety factor (FS) decreases, and the deformation increases. Conversely, if the height and slope decrease, the FS increases, and the deformation decreases. It is observed that the soil with the highest percentage of APAM (1%) has produced the highest shear strength parameters and the lowest deformation. This study found that weak soil treated with APAM can be used as a backfill material, but the potential for collapse is more significant.

KEYWORDS: Anionic Polyacrylamide, Embankment, Finite Element Method, and Deformation.

1. INTRODUCTION

Soil is an essential material for any construction work. However, soil stabilisation in geotechnical engineering requires discovering soils with saturated conditions or high plasticity. (Daraei et al., 2018). Currently, around the world, many flexible and rigid pavements are constructed. (Amena, 2022). Most of these pavements are constructed on weak soils with low bearing capacity and saturated soils. (Arsyad et al., 2020; Dewi et al., 2023; Lu et al., 2020; Pooni et al., 2022; Wani & Mir, 2021). Pavement construction on weak soils is usually preceded by embankment construction. (Ifediniru & Ekeocha, 2022). The pavements need to have stable embankments. Embankments over weak soils have been exposed to slope instability and large deformations, which are mainly caused by construction failure and load applied to it (Al-Jeznawi et al., 2019; Deshpande et al., 2021; Gu et al., 2021; Ifediniru & Ekeocha, 2022; Tsige et al., 2022; Xueying & Shunfu, 2020). Most of these pavements are constructed on weak soils with low bearing capacity and saturated soils or what is commonly known as foundations. The foundation is the most essential part of every construction; it supports the structure above it. If the foundation is not designed or constructed correctly, it can pose severe risks to residents and the surrounding environment. Foundations often encounter complex challenges because they must contend with vertical and lateral loads, such as surcharge, moving traffic, and earth pressure. (Lateh et al., 2023; Kaewjuea et al., 2022). It can cause structural damage during implementation and throughout the project's life (Tiwari & Tiwari, 2016). This may need more cost in maintenance and improvement in a later step of construction (Chompoorat et al., 2021; Louzada et al., 2019; Zhou et al., 2021).

Geotechnical engineers usually have two alternatives, specifically soil improvement and the usage of soil reinforcement (Karkush & Jabbar, 2022; Prakash & Krishnamoorthy, 2022). Por et al. (2015) suggested that bentonite mixing can improve soft clay's engineering and physical properties. Chompoorat et al. (2021) also mentioned that adding cement with fly ash can reduce the swell-shrink behavior of lakebed sediment. In addition, for deep soil mixing, cement combined with fly ash is also effective in reducing the shrinkage of clayey soils (Chompoorat et al., 2022). Mase et al. (2023) mentioned the importance of liquefaction countermeasures. Recently, Indhanu et al. (2023) mentioned that geotextile infiltration could reduce the liquefaction potential in sandy soils.

Increasing population growth and technological advances in developing countries have resulted in the need for infrastructure development, such as roads in the highlands where the soil type is usually weak. Building this structure requires suitable foundation soil and adapts to the needs of road users. However, weak soils are unsuitable for such purposes due to their low bearing capacity and excessive settlement. Therefore, soil improvements must be made before this weak soil can be constructed. To achieve this goal, engineers in academia and the construction industry must find ways to improve weak soils, which can be used as foundation materials through various soil improvement methods. Soil conditions that could be better for construction present challenges for civil engineers. To overcome the problem, soil improvement is essential to modify and repair the soil's characteristics and strengths.

Continuous growth of the world's population, especially in developing countries, and technological advances have led to the need to construct tall buildings and other infrastructure, such as roads and bridges in highlands, where the soil type is usually weak. Building this structure requires suitable foundation soil. However, weak soils are unsuitable for such purposes due to their low bearing capacity and excessive settlement. Therefore, soil improvement is required before this weak soil can be constructed. To achieve this goal, engineers in academia and the construction industry must find ways to improve weak soils, which can be used as foundation materials through various soil improvement methods (Saleh et al., 2019).

Over the years, the development of soil improvement has significantly increased. Techniques to improve soil properties can increase the soil strength, making it readily used for construction. The characteristics and strengths modifications of so from soil improvement using various techniques have a long history, and they have evolved constantly with the innovation of new materials (Goh et al., 2020; Kulanthaivel et al., 2021; Latifi et al., 2017).

One of the most accessible soil improvement techniques to implement is soil stabilisation. Soil stabilisation was carried out using various stabilisers to overcome the unstable behaviour of weak soil using materials (Firoozi et al., 2017). For the stabiliser, different materials such as soil-cement, lime cement, plastic waste, and soil polymer have been proposed in the past (Adetayo et al., 2019; Adeyanju & Okeke, 2019; Consoli et al., 2020; Emarah & Seleem, 2018; Gao, Yanhua Xue Mingxing Feilong, 2021; Soltani-Jigheh et al., 2019; Tavakol et al., 2019; Tiwari & Tiwari, 2016; Yang et al., 2019; Zhou et al., 2021; Zukri, 2013). For embankment, the selection of materials should be carefully considered. Overusing materials such as plastic waste and overuse of cement as soil stabilisation can result in environmental pollution. Therefore, many pieces of research are conducted to investigate the merits and the demerits of using those materials (Amena, 2022; Karimiazar et al., 2022; Saloma et al., 2015).

Much research has been conducted on the best way to avoid environmental pollution. Previous studies have compared and evaluated the effectiveness of traditional chemical stabilisers and commercially available polymers in reducing the high plasticity soils (Taher et al., 2020). It has been concluded that synthetic polymers can reduce water content by forming new structures (Georgees & Hassan, 2019; Jia et al., 2023; Soltani-Jigheh & Bagheri, 2021). One of the various synthetic polymers is anionic polyacrylamide (PAM) (Chen et al., 2016; Frutaz et al., 2023; Georgees & Hassan, 2022; Huang et al., 2021; Mamedov et al., 2021). In addition, using local materials with high shear strength is the best option.

Several areas in Indonesia have low soil bearing capacity and high plasticity soil properties, one of which is in West Bandung Regency, Indonesia. These conditions are vulnerable to disasters related to ground movement (Yuda et al., 2021). A preliminary investigation found weak soil with an NSPT value < 2 and high water content (Dewi et al., 2024). Based on these characteristics, soil is proven to have an unstable tendency. This has been explained in previous research, which proved the occurrence of landslides in 2020. Amalia et al. (2023) suggested that soil improvement using APAM could increase the bearing capacity of soil by reducing the void in clayey soils. The interaction between APAM and soil particles could reduce the crack potential and void ratio. Therefore, the smaller void ratio could improve the soil density.

Slope stability analysis is critical to ascertain the stability of the embankment (Zewdu, 2020). Factors of safety and deformation are critical parameters for evaluating stability in saturated soils. These parameters need to be reviewed during the construction period until the end of the embankment construction to measure their stability. The stability analysis of the embankment should consider saturated soils as a large deformation continuum approximation.

Many studies in the last five years have been carried out to investigate slope stability using the finite element method with a reduction approach (Habtemariam et al., 2022; Xu et al., 2022). FEM is considered the best numerical analysis technique that can describe and provide solutions to soil stability. Additionally, FEM has been found to provide good results in the circumstances studied (Swasdi et al., 2024). The finite element method (FEM) provides the most theoretically sound approach for the modelling of the embankment (Arsyad et al., 2020; Luo et al., 2020; Tyagi et al., 2018). For the specific problems in clay, several studies conducted by Likitlersuang et al. (2018) for the stability of embankment railway, Hsiung et al. (2021) for the impacts of plane strain ratio on excavation in soft alluvium deposits, Nguyen et al. (2022) for the probabilistic analysis of embankment stability on soft ground, and Roeun et al. (2024) for underground deep excavation in Phnom Penh City, Cambodia have presented the implementation of finite element. For other stability problems, such as deep excavation and slope stability, studies conducted by Huynh et al. (2022) and Mase et al. (2022a; 2022b) showed the reliability of the finite element method.

This study is extended from the authors' previous studies, i.e., Dewi et al. (2024) and Amalia et al. (2023), that successfully implemented APAM to improve soil strength. This study, as a contribution, investigates the strength improvement of weak local soil from West Bandung Regency, Indonesia, with 0.2%, 0.4%, 0.6%, 0.8%, and 1% APAM by analysing the factor of safety and deformation of safety improvement of embankment founded on weak soil. This research could help assess the performance and validity of embankment analysis with soil stabilisation.

2. METHOD OF ANALYSIS

2.1 Geometry Model

For this study, a road embankment with a horizontal width of 70 m and different heights varying from 1.5 m to 3 m (H1 = 1.5 m, H2 = 2 m, and H3 = 3 m) was modelled. In addition, the embankment was modelled with varying side slopes (S1 = 1V:1H, S2 = 1V:1.5H, and S3 = 1V: 2H). The geometry of the road embankment is shown in Figure 1.

The geometric model consists of five levels of existing soil with a 2 m, 10 m, and 4 m thickness. The groundwater level is 5 m from the ground surface. The embankment was constructed from APAM-treated soil and a flexible pavement arrangement. The surcharge load of 12 kPa was considered a traffic load.

2.2 Material Modelling and Material Properties

In this study, finite element modelling is performed to observe the stability of the embankment under traffic. The material model selection and input parameters should be carefully considered for finite element modelling. Surarak et al. (2012), Likitlersuang et al. (2013), and Sukkarak et al. (2021) suggested the experimental test to justify determining input parameters such as stiffness and strength parameters. In line with those previous studies, the procedure to determine input parameters in this study is based on the experimental test.

An embankment geometry has been modelled using 15-node triangular elements and a plane strain condition. The Mohr-Coulomb model is used for embankment soil, and the hardening and softening soil models were used for existing soils. The embankment is categorised as stable granular materials. Mohr-Coulomb is suitable for construction planning and the availability of data obtained from lab testing. In this research, embankment material modelling used Mohr-coulomb because embankment material is considered stable. The hardening soil model describes an approach to actual conditions of stress-strain behaviour in hyperbolic elastoplastic conditions in the soil. This model is used on soils of stiff to hard consistency because of the relatively large modulus value of Mohr-Coulomb. The hardening soil model is used for existing soils because the existing soil is under pressure due to traffic loads and backfills, which makes the existing soil stiffer. Existing soils are dominated by clay, and the consolidation effect affects the term's strength. Therefore, a Hardening Soil Model is suitable for the existing soils. For near-surface existing soils, the material is still soft. Therefore, the model used for this soil is the softening soil model.

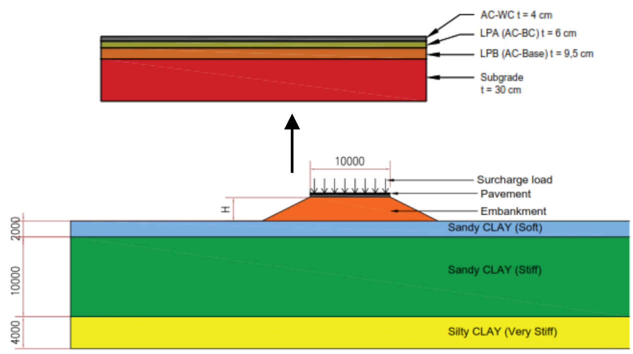


Figure 1 Modelled Geometry of Road Embankment

Based on the results of soil investigations, it was found that the soil type existing layers 1 to 3 are cohesive soils, where cohesive soil tends to have a higher practical cohesion value than the effective friction angle. In addition, other references have classified the range of cohesive soil with the value of the effective friction angle (Look, 2007). This study selects a critical effective friction angle because this value represents the critical condition in numerical simulations.

The required parameters for the existing soils are Modified compression index (λ*), Modified swelling index (κ*), density (γ), triaxial loading stiffness (E_{50}^{ref}), oedometer loading stiffness (E_{50}^{re}), triaxial unloading stiffness, E_{ur}^{ref}, cohesion (c), friction angle (φ), Poisson's ratio (ν), and Young's modulus (E), as shown in Table 1.

The finite element analysis was performed for each embankment construction sequence.

Properties of treated soil were used as embankments with a thickness of 3 m. It was obtained from a soil testing laboratory, as shown in Table 2. The table's parameters include density (γ), *E*, ν, *c'*, and effective friction angle. The increase in soil strength and elastic modulus is generally consistent with the parameter suggested by Look (2007). The initial soil is stabilised by APAM. APAM is manually stabilised with initial soil with percentages of 0.2%, 0.4%, 0.6%, 0.8%, and 1%. The optimum amount of water required to treat the initial soil for this study is 36.6%. Adding APAM significantly improved strength parameters, such as CBR, triaxial, and unconfined compressive strength. It should be noted that the engineering properties of layers are based on the authors' previous study, i.e., Dewi et al. (2024). The APAM tends to bond the soil particles, making the soil more compacted, as investigated under the Scanning Electron Microscope (SEM) presented in Amalia et al. (2023). Therefore, the soil strength parameters, such as soil cohesion, are significantly improved.

The analysis also considers the pavement at the top surface of the soil. In this study, the pavement is assumed to be flexible pavement. The material properties of the pavement are presented in Table 3. The material properties in Table 3 are obtained based on the American Association of State Highway and Transportation Officials or AASHTO (2013), adopted by the authorised regulation in Indonesia, i.e., Bina Marga (2017). The material models for asphalt concrete are linear elastic, whereas, for foundation layers, such as sub-base, base, and subgrade, model materials are assigned as Mohr-Coulomb. In this study, the concern is addressed, which is to inspect the safety condition of the embankment structure.

3. METHOD OF ANALYSIS

This study used finite element method analysis to investigate the embankment stability with different slope angles (30°, 33°, 45°). The required parameters for the embankment model, such as internal friction angle (φ), cohesion (c), density (γ), Poisson's ratio (ν), and Young's modulus (E), were considered for embankment fill and soft soil. The treated soil is used as an embankment fill to assess its effect on the strength in sustaining the load above it.

Embankment on soft soils of saturated soils with high plasticity requires careful slope stability analysis. Therefore, an in-depth slope stability analysis was carried out in this study because the embankment fill material is treated soils with APAM stabiliser. In the case of embankment stability with a lower safety factor than required, the existing soil can be replaced with improved soil. Several studies proved that the application of APAM on natural slopes and embankments could effectively increase the factor of safety and minimise deformation (Frutaz et al., 2023; Liu et al., 2011).

This study simulates a total of 54 geometrical models using finite element simulation. Those models consider the variation of soil properties under the improvement using APAM based on previous studies conducted by Amalia et al. (2023) and Dewi et al. (2024). The embankment slope variations, i.e., 1:1, 1:1.5, and 1:2, are considered in this study. The slope height is constrained to be 1.5, 2, and 3 m. The well-known material models are also used in this study. Model materials such as soft soil and hardening soil models are used for embankment properties. A Mohr-Coulomb model is implemented for embankment fill properties. For pavement, the linear elastic model is assigned flexible pavement. In this study, the simulation is simulated based on several construction stages. The first is a self-weight stage, the second is under traffic load, and the last is shear strength reduction. Several outputs, such as displacement contour and factor of safety, are presented. This study also discussed the effect of APAM in improving slope stability for road embankments based on numerical analysis.

4. RESULTS AND DISCUSSIONS

4.1 Initial Condition

Figure 2 presents the displacement contours for various slope heights and slope gradients under the initial condition. In this study, only several results are selected to represent the general result tendency. Figure 2a presents the initial condition for a slope height of 1.5 m with a slope gradient of 1:1. Figure 2b presents the initial condition for height and gradient as 2 m and 1:1.5, respectively, and Figure 2c presents the initial condition with the height of 3 m and gradient of 1:2. Based on the simulation results, it can be observed that the gentle slope with a lower height tends to have a smaller displacement. In addition, the slip surface tends not to cross the middle part of the road embankment and vice versa. It indicates that a steeper slope could undergo slope failure on both sides without considering the accumulation of slope mass movement starting from the centre of the road embankment. It also implies that slope failure could happen separately or not as a system, as presented in Figures 2a and 2b. A different tendency is shown in Figure 2c, in which the slope failure mechanism tends to accumulate below the centre of the road embankment and starts to push with the gravity load. All figures showed a large displacement at the slope toe. It indicates that slope movement could start at the slope toe after shear stress reduction (Mase et al., 2022a; 2022b).

To assess the safety condition of the initial slope, the Factor of Safety (FS) is calculated from the simulation of finite elements. Figure 3 provides the information on FS for all analysed initial slopes. It can be observed that in terms of the stability condition, a gentle slope tends to provide a low gravity mass. Therefore, the potential mass movement under a gentle slope with a lower height tends to have a higher FS. Sooksatra and Jinga (2016) suggested that an FS of 1.25 is the minimum required criteria for a stable slope. In contrast, Mase et al. (2023) suggested that for areas with height environmental effects, the minimum FS should be 1.5. Referring to both studies, it can be concluded that only a slope with a height of 1.5 m and a gradient of 1.1 is relatively stable under the initial condition.

4.2 The Effect of APAM Stabilization on FS

In this section, several results are selected to present the effect of APAM stabilisation on displacement contour and FS. Figure 4 presents the displacement contour for several conditions. Figure 4a shows the displacement contour for a slope with a height of 1.5 m and a gradient of 1:1, with 0.2% APAM added. Figure 4b shows the displacement contour for a slope with a height of 2 m and a gradient of 1:1.5, with 0.6% APAM added. Figure 4a shows the displacement contour for a slope with a height of 2 m and gradient of 1:2, with 2% APAM added. Based on the figures, the tendency of failure pattern changes from the initial condition, and the embankment fill is relatively stable. The failure pattern at the slope embankment disappears. However, the possibility of failure pattern of bearing capacity could happen, especially for the first clay layer, as shown in Figures 4a and 4b. For Figure 4c, the maximum displacement distribution is generally concentrated in the middle part of the embankment. However, the total displacement from adding APAM up to 1% is relatively minor. In general, maximum total displacement decreases (from the initial condition) due to APAM adding. Dewi et al. (2024) mentioned that adding APAM could increase soil cohesion effectively. It indicates that the soil strength of the embankment increases so that the potential sliding is reduced. Regarding the bearing capacity ratio defined as California Bearing Ratio (CBR), Dewi et al. (2024) explained that APAM adding could effectively increase CBR value. Therefore, the use of APAM is not only to improve the stability of embankment but also to improve bearing capacity.

The Factor of Safety is directly proportional to ground cohesion and deep shear angle parameters. Based on the results of the triaxial research conducted on cohesive soil samples, both parameters have increased. Previous research has explained this (Dewi et al., 2024). In addition to soil parameters, the slope and height of the embankment dimension are variables in this study that also affect FS. The smaller the height and slope of the pile, the greater the FS.

Table 1 Material Properties of Existing Soils

Material	Existing soil layer 1	Existing soil layer 2	Existing soil layer 3
Model	Soft Soil	Hardening soil	Hardening soil
Modified compression index, λ^*	0.14	-	-
Modified swelling index, κ^*	0.01	-	-
The triaxial loading stiffness, E_{50}^{ref} (kPa)	-	4000	7500
The oedometer loading stiffness, E_{oed}^{ref} (kPa)	-	8000	15000
The triaxial unloading stiffness, E_{ur}^{ref} (kPa)	-	12000	22500
Saturated density, γ_s (kN/m³)	16	19	19
Poisson's ratio, ν	0.4	0.3	0.3
Effective cohesion, c′ (kPa)	7	32	88
Effective friction angle, φ (°)	10	4	4

Table 2 Embankment Fill Properties

Material	Untreated embankment fill	Treated embankment with 0.2% APAM	Treated embankment with 0.4% APAM	Treated embankment with 0.6% APAM	Treated embankment with 0.8% APAM	Treated embankment with 1% APAM
Model	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb
Saturated density, γ_{sat} (kN/m³)	16	18	18	18	19	19
Young's modulus (E) (kN/m²)	5333	8533	10456	12632	14084	17067
Poisson's ratio (ν)	0.3	0.3	0.3	0.3	0.3	0.3
Effective cohesion (c') (kN/m²)	7	59	65	71	83	101
Effective friction angle (φ) (°)	8	12	14	16	16	19

Table 3 Pavement Properties

Material	Asphalt Concrete	Sub-base	Base	Subgrade
Model	Linear elastic	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb
Thickness (h) (m)	0.04	0.06	0.095	0.3
Young's modulus (E) (kPa)	2100×10^3	100×10^3	50×10^3	20×10^3
Poisson's ratio (ν)	0.45	0.35	0.30	0.30
Dry density (γ_d) (kN/m³)	20	20	20	18
Saturated density (γ_{sat}) (kN/m³)	-	22	20	20
Cohesion (c) (kN/m²)	-	30	40	35
Friction angle (φ) (°)	-	43	14	5

Table 4 presents the recapitulation of FS based on finite element simulation. It can be observed that the improvement in using APAM effectively increases the FS of road embankments. Under the initial condition, only a slope with a height of 1.2 m and a slope gradient of 1:2 is defined as a stable slope. After adding APAM, the FS is generally increased. Dewi et al. (2024) suggested that soil strength is significantly increased due to APAM adding. Amaliah et al. (2023) explained this phenomenon using XRD observation and found that the interaction between APAM and soil could reduce the void, so the soil density becomes larger.

4.3 Discussion on the Potential of APAM as a Soil Improvement Alternative

As a material with uncertainties, soil characteristics are not easily predicted. On the other hand, the development of infrastructures should enforce the construction method. Referring to the previous studies by Dewi et al. (2023) and Amalia et al. (2023), using chemical materials like APAM seems fruitful. The characteristics of soil treated by APAM have significantly changed. The engineering properties are also improved. In terms of stability, APAM adding could also improve the stability of slope embankments.

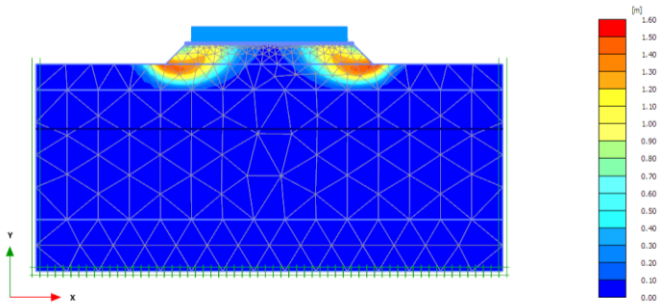
Figure 5 presents the percentage of FS increase due to APAM adding. The increase of APAM could improve FS up to 38 to 59%. Adding APAM about 0.2% to 0.6% (Figures 5a, 5b, 5c) is generally not very significant regarding the percentage of FS increase. Both treatments could improve FS up to 38 to 53%. In other words, adding 0.2% APAM or 0.4% APAM or 0.6% could improve the similar FS increment. However, adding APAM of 0.8% to 1.0% (Figures 5d and 5e) shows that the percentage of FS increase is about 44 to 59%. Adding APAM of 0.8% and 1% is generally not very significant. Therefore, based on the simulation, it can be concluded that there are two fractional options for APAM adding. The first option is to add APAM about 0.2 to 0.6%, and the second is to add APAM about 0.8 to 1%.

The results presented in this study show that in terms of numerical analysis, the improvement of soil strength, as compared to the previous experimental studies, effectively influences the stability of the embankment. However, the challenge is how the implementation of APAM adds to a large scale. Therefore, it is essential to observe the performance of APAM, adding in full scale. It will be presented in further studies.

5. CONCLUSIONS

This paper presents a stability analysis of embankment using a finite element method constructed over treated soil with Anionic Polyacrylamide (APAM). This study refers to the authors' previous studies that presented increased soil strength properties after APAM addition. The finite element simulation to various conditions in the field is modelled. Several concluding remarks can be drawn in the following:

1) considering the initial characteristics of the embankment and fill, the initial condition shows that FS generally does not fulfil the stability criteria. Therefore, adding APAM could be the solution to improve the soil strength, which also means improving embankment stability. The characteristics of APAM to improve soil strength, as presented in previous studies, have been confirmed in this study, which shows that the stability of embankment for materials is relatively improved under APAM.
2) Adding APAM of about 0.2% to 1% could effectively increase FS. There are two alternatives to selecting the APAM percentage to improve embankment stability. To improve FS by up to 53%, adding APAM of about 0.2% to 0.6% is recommended. To achieve an improvement of FS of up to 59%, adding APAM of about 0.8% to 1.0% is applicable.



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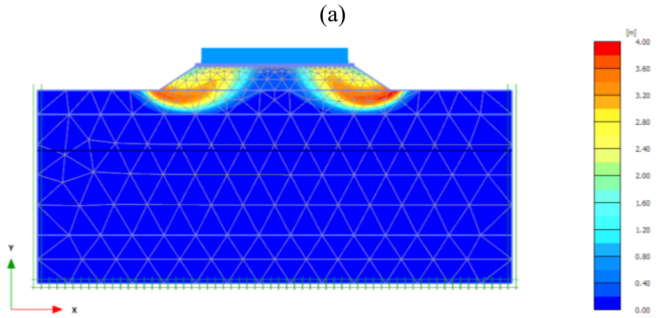

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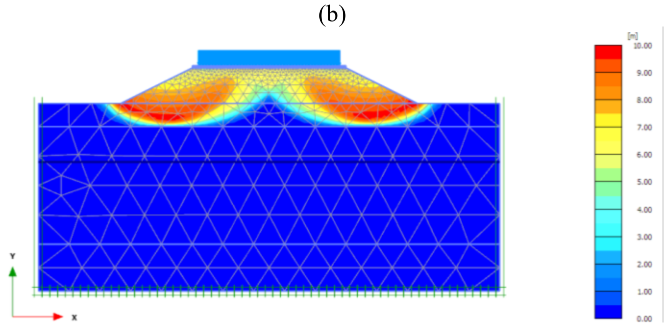


(c)

Figure 2 Displacement contour for initial condition for (a) height of 1.5 m and gradient of 1:1, (b) height of 2 m and gradient of 1:1.5, (c) height of 3 m and gradient of 1:2

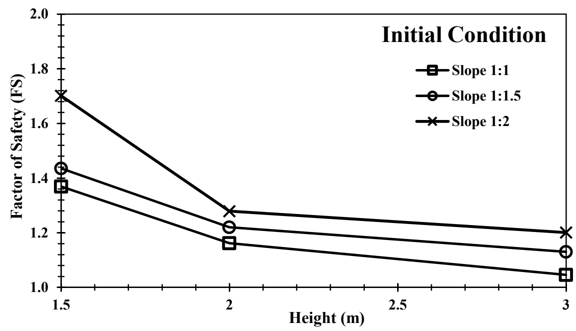
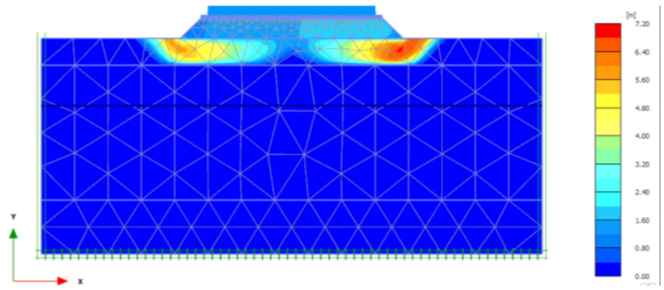


Figure 3 Displacement contour for initial condition for (a) height of 1.5 m and gradient of 1:1, (b) height of 2 m and gradient of 1:1.5, (c) height of 3 m and gradient of 1:2

3) The significant increase of FS under a small quantity of APAM could be fruitful for field implementation. However, the implementation of field applications is still ongoing. The effectiveness of the APAM application will be detailed in several general guidelines that are helpful in solving soft soils.
4) This study still focuses on numerical analysis using the finite element method to inspect embankment stability for materials improved by APAM, which are reflected based on the increased soil strength parameter. The effectiveness of APAM in a large-scale application is also the target of this study. It will be presented in further studies.



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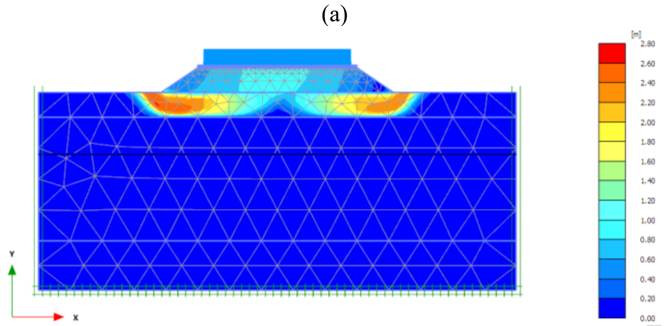

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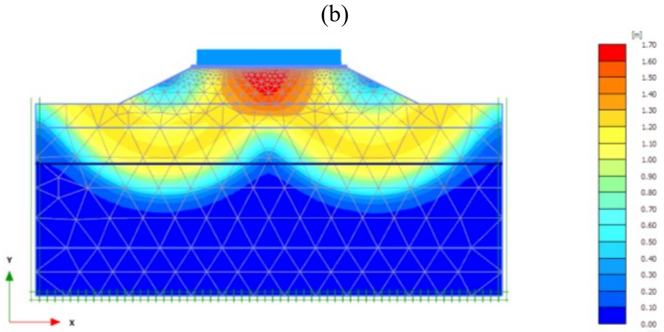

(c)

Figure 4 Displacement contour for initial condition for (a) height of 1.5 m and gradient of 1:1 with 0.2% APAM, (b) height of 2 m and gradient of 1:1.5 with 0.6% APAM, (c) height of 3 m and gradient of 1:2 with 1% APAM

Table 4 Recapitulation of FS based on finite element simulation

APAM Percentage	Slope Gradient	FS		
		Height of 1.5 m	Height of 2 m	Height of 3 m
Initial Condition	1: 1	1.369	1.162	1.046
	1: 1.5	1.435	1.220	1.130
	1: 2	1.701	1.279	1.201
0.2%	1: 1	2.210	1.950	2.051
	1: 1.5	2.347	2.102	2.239
	1: 2	2.954	2.261	2.445
0.4%	1: 1	2.214	1.970	2.104
	1: 1.5	2.373	2.132	2.293
	1: 2	3.002	2.290	2.539
0.6%	1: 1	2.227	1.983	2.152
	1: 1.5	2.395	2.155	2.348
	1: 2	3.044	2.320	2.580
0.8%	1: 1	2.418	2.519	2.243
	1: 1.5	2.647	2.717	2.452
	1: 2	3.289	2.907	2.843
1.0%	1: 1	2.440	2.555	2.275
	1: 1.5	2.684	2.778	2.544
	1: 2	3.355	2.984	2.934

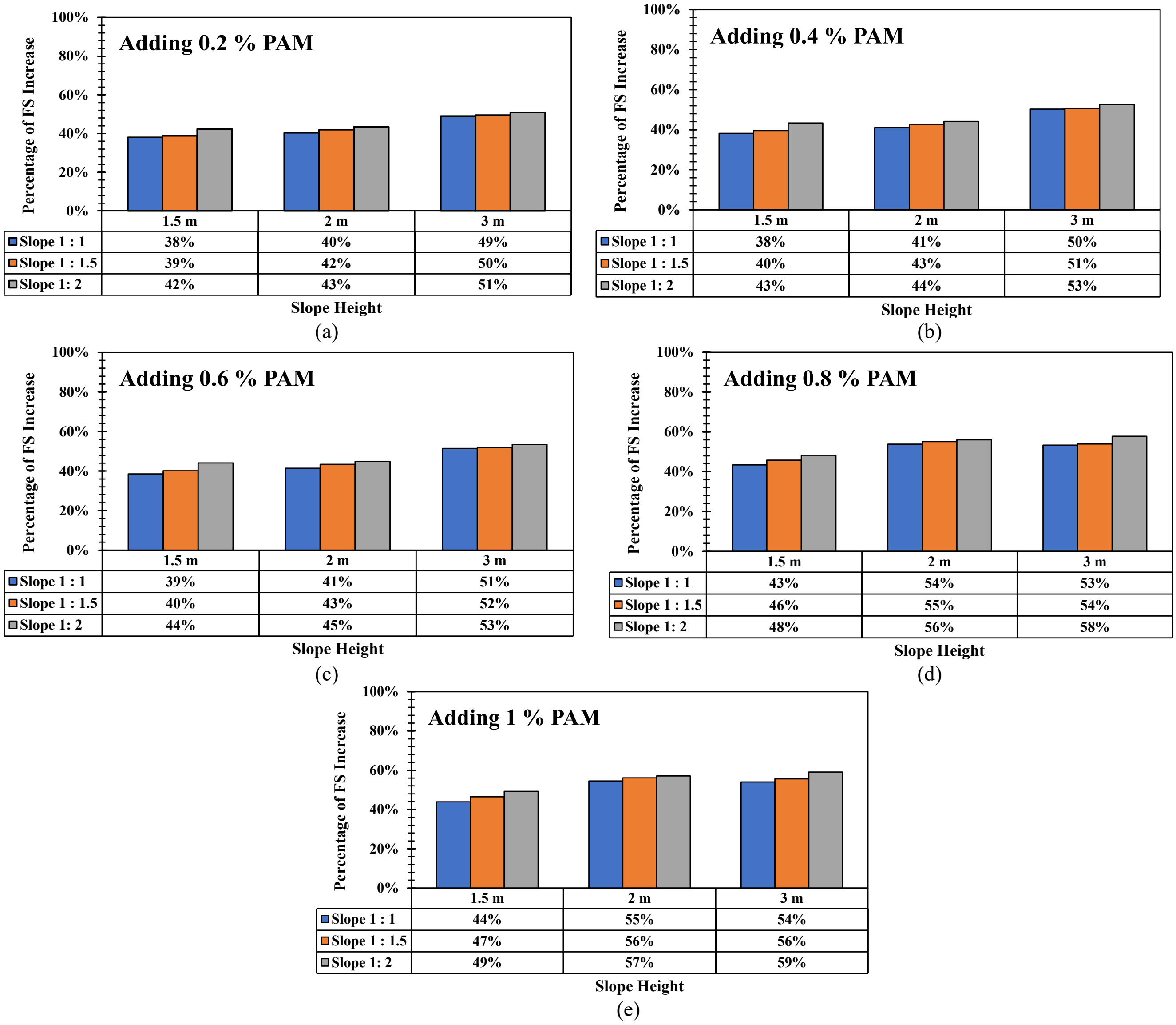

Figure 5 Percentage of FS increase due to APAM adding variations for (a) 0.2%, (b) 0.4%, (c) 0.6%, (d) 0.8%, and (e) 1%

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