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Finite Element Modeling of Soil Settlement Using Rectangular Deep Soil Mixing with Biopolymer Stabilization

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ABSTRACT

Unstable subgrade conditions often cause structural and serviceability problems in road infrastructure. To mitigate these problems, soil improvement techniques are needed, one of which is Deep Soil Mixing (DSM). This study presents a numerical investigation of rectangular DSMs with column diameters of 40 cm, 60 cm, and 80 cm. A biopolymer-based stabilization material was used to reduce subsidence and increase stability along the Karanggede–Juwangi Road, Central Java. The mechanical behavior of the soil before and after biopolymer treatment was evaluated. Numerical modeling was performed using the finite element method (FEM) implemented in PLAXIS software to analyze vertical deformation (settlement) and the factor of safety (SF) of slope stability. Biopolymers materials Consisting of chitosan (CHI), guar gum (GG), and xanthan gum (XG) were used as stabilizing agents in the DSM columns. The results show that the application of DSM combined with biopolymer significantly improves soil performance. All DSM configurations demonstrated reduced soil deformation and increased factor of safety compared to untreated soil conditions. Among the analyzed models, the 80 cm diameter DSM column exhibited the most favorable performance. The incorporation of chitosan (CHI) resulted in a reduction in soil deformation of 70.72%, while guar gum (GG) achieved a 77.55% reduction. The highest deformation reduction was obtained using xanthan gum (XG), reaching 84.88%, indicating its superior stabilization effectiveness. Furthermore, the analysis revealed a substantial improvement in slope stability, as reflected by an increase in the safety factor (SF) ranging from 76.44% to 220.30% compared to the untreated soil condition.

Keywords: deep soil mixing, biopolymer, soil settlement, finite element method, ubgrade stability.

INTRODUCTION

In general, transportation is crucial for facilitating daily human activities. In economic and service activities, land transportation has an important role in supporting economic growth in Indonesia. Therefore, road infrastructure is a crucial component in supporting national economic development [1], [2]. However, a main challenge in road infrastructure development is the failure to achieve its expected service life. One of the most common causes of road damage is a lack of subgrade stability [3]

The subgrade is a critical component of in the pavement structure, as it directly receives the stresses caused by traffic loads. Consequently, the subgrade must have adequate bearing capacity to withstand these loads and ensure structural performance [4]. Unstable subgrade can lead to various types of failures, including road settlement, slope instability, and damage to overlying infrastructure components [5]. In Indonesia, construction projects frequently encounter problems related to soft and expansive soils. Soft soils generally exhibit low bearing capacity, while certain types are characterized by high shrinkage-swelling potential, which negatively impacts pavement durability and long-term stability [6].

Based on survey data from previous research conducted by Guritno and Amalia [7] the Karanggede–Juwangi road section has experienced significant damage. Despite rehabilitation efforts, the road quickly experienced recurrent damage. Observed failures include slope instability, differential settlement, and surface cracking, indicating inadequate base course performance.

Soil stabilization is one of the most commonly applied techniques in road construction projects. Soil stabilization aims to improve the inherent properties of the soil and increase its mechanical strength. Through stabilization, soil plasticity can be reduced and swelling behavior minimized. Stabilization techniques generally involve increasing bearing capacity and shear strength, reducing soil compressibility, modifying permeability, and improving overall soil performance. Soil stabilization methods are broadly classified into soil improvement, which includes the use of chemical additives, soil regrading, dewatering, or energy-based treatments, and soil reinforcement, which involves the addition of reinforcing materials within the soil mass [8], [9], [10], [11].

Among the various soil improvement techniques, Deep Soil Mixing (DSM) has been widely applied. DSM involves on-site mixing of soil with stabilizers using specialized mixing equipment. In recent years, research into environmentally friendly construction materials has gained increasing attention, Biopolymers, derived from natural sources such as plants, algae, fungi, or bacteria and primarily composed of polysaccharides, have emerged as a promising alternative for soil stabilization. Biopolymers are characterized by low environmental impact, non-toxicity, and the absence of secondary pollution, making them a viable and cost-effective alternative to conventional chemical stabilizers [12]

This study builds on previous research by Guritno and Amalia [7] who reported significant improvements in soil properties after laboratory mixing with biopolymers such as guar gum (GG), xanthan gum (XG), and chitosan (CHI). To further evaluate the effectiveness of these materials at the field scale, this study employed numerical modeling using PLAXIS 2D with a rectangular Deep Soil Mixing configuration to assess their effects on land settlement behavior along the Karanggede–Juwangi road section.

RESEARCH METHODS

Materials

Research area is based on previous investigations conducted by Guritno and Amalia, located along the Karanggede–Juwangi road section, Boyolali Regency, as shown in Figure 1. The site is situated within a problematic claystone formation in Central Java, characterized by unfavorable geotechnical behavior, especially in terms of subgrade instability.

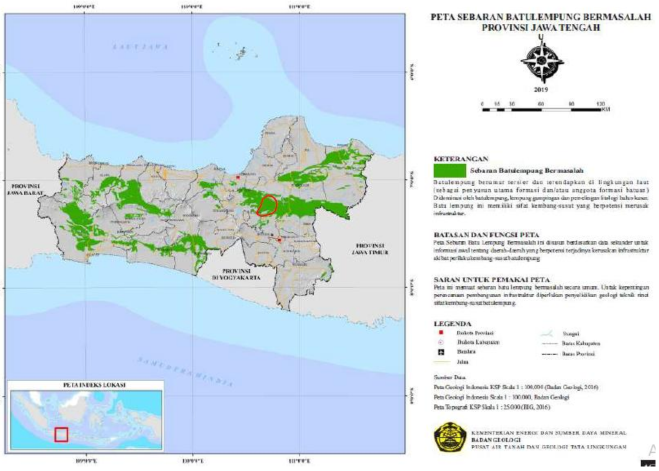


Figure 1. Distribution map of problematic claystone formations in Central Java Source: Atlas Sebaran Tanah Lunak Indonesia

The material properties and soil conditions adopted in this research are obtained from Guritno and Amalia [7] and are subsequently modeled in two-dimensional (2D) conditions using PLAXIS 2D software. The configuration of the embankment soil and natural ground conditions is illustrated in

Figure 2, which represents the actual field conditions, including both fill material and underlying natural soil layers.

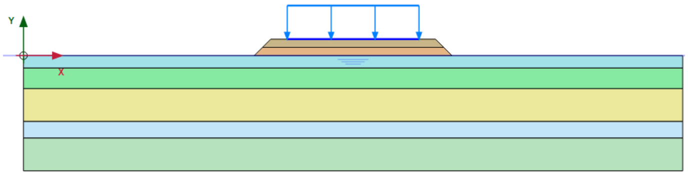


Figure 2. Soil model without ground improvement

The pavement structure consists of an asphalt concrete (AC) surface layer with a thickness of 0.075 m, an asphalt concrete binder course (AC-BC) with a thickness of 0.06 m, and an asphalt concrete wearing course (AC-WC) with a thickness of 0.05 m. The soil stratification beneath the pavement is divided into several layers based on soil type, as presented in Figure 2. The thicknesses of the soil layers are 0.75 m, 2 m, 4 m, 5 m, and 7 m, comprising clayey soil and silty clay. The groundwater table is assumed to be located at a depth of 7 m below the ground surface.

The parameters required to characterize the existing soil include the modified compression index (λ^*), modified swelling index (κ^*), unit weight (γ), cohesion (c), internal friction angle (ϕ), Poisson's ratio (ν), and elastic modulus (E). These parameters are summarized in Table 1, which presents the material properties of the soil under untreated conditions.

Table 1. Material Properties of untreated soil

Parameter	**Notation**	**Layer location and Condition**							**Unit**
		Layer 1 0m - 0,75m	**Layer 2 0,75m - 2m**	**Layer 3 2m - 4m**	**Layer 4 4m - 5m**	**Layer 5 5m - 7m**	**Embankment 1**	**Embankment 2**	
Soil Model	MC	Mohr Coloumb	Mohr Coloumb	Mohr Coloumb	Mohr Coloumb	Mohr Coloumb	Mohr Coloumb	Mohr Coloumb	-
Soil Behavior Type	type	Undrained	Undrained	Undrained	Undrained	Undrained	Drained	Drained	-
Unsaturated	Υ_{unsat}	10,8	10	10,08	10,08	10,08	22	21	kN/m3
Saturated	Υ_{sat}	15,6	15,6	10,3	10,3	10,3	23	22	kN/m3
Elastic Modulus	E	1457,14	3400	3400	1656	1656	15000	15000	kN/m2
Poisson Ratio	ν	0,3	0,3	0,3	0,3	0,3	0,3	0,3	-
Cohesion	c'	10,797	10,552	10,575	10,757	10,575	50	30	kN/m2
Angle of Internal Friction	ϕ	12,198	13,955	10,572	10,572	10,572	50	30	°
Angle of dilatacy	Ψ	-	-	-	-	-	-		°
Reduction Factor	Rinter	-	-	-	-	-	-		-

Methods

The Deep Soil Mixing (DSM) method with a rectangular configuration was modeled using three column diameters, namely 40 cm (0.4 m), 60 cm (0.6 m), and 80 cm (0.8 m), as illustrated in Figure 3. In each model, the DSM columns were filled with different biopolymer-stabilized soil mixtures. The stabilization materials consisted of chitosan (CHI), guar gum (GG), and xanthan gum (XG), which had been previously investigated through laboratory testing reported by Guritno and Amalia [7] as summarized in Table 2

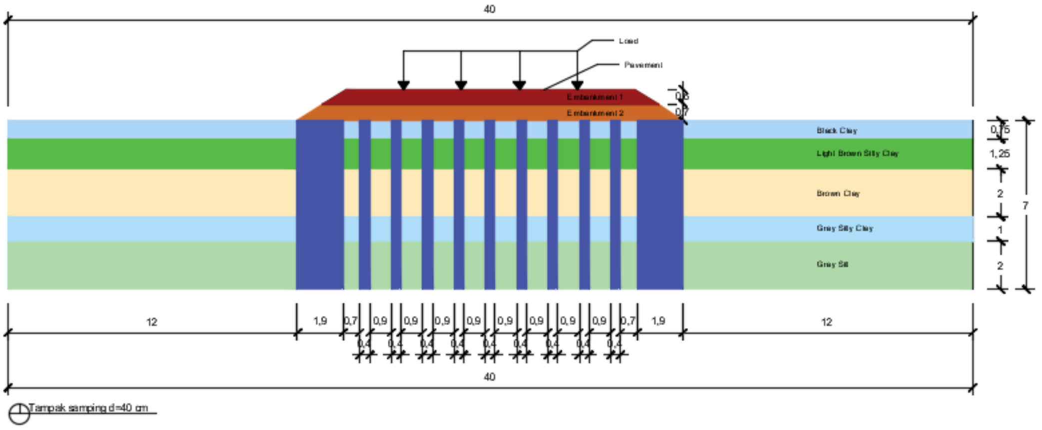


Figure 3. Soil model with Deep Soil Mixing

Table 2. Material Properties of Biopolymer Stabilized Soil

Parameter	Notation	Layer location and Condition			
		CHI	**GG**	**XG**	**Notation**
Soil Model	MC	Mohr Coloumb	Mohr Coloumb	Mohr Coloumb	-
Soil Behavior Type	type	Drained	Drained	Drained	-
Unsaturated	ϒunsat	15,80	15,80	15,80	kN/m3
Saturated	ϒsat	16,00	16,00	16,00	kN/m3
Elastic Modulus	E	3734,64	5745,60	10054,80	kN/m2
Poisson Ratio	v	0,35	0,35	0,35	-
Cohesion	c'	24,80	36,15	10,575	kN/m2
Angle of Internal Friction	ϕ	11,52	21,64	47,55	°
Angle of dilatacy	Ψ	0	0	0	°
Reduction Factor	Rinter	-	-	-	-

The numerical simulations were conducted using PLAXIS 2D, employing 15-node triangular elements under plane strain conditions. Both the embankment soil and the natural subgrade were modeled using the Mohr–Coulomb constitutive model, which is widely adopted in geotechnical engineering practice due to its suitability

In the numerical analysis, two drainage conditions were applied. A drained condition was assigned to the embankment soil and the biopolymer-stabilized soil, representing conditions where pore water can flow in or out during deformation. In contrast, the untreated natural soil was modeled under undrained conditions, where pore water movement is restricted. The undrained assumption is considered appropriate for short-term consolidation behavior [13]

The traffic load was modeled based on the Indonesian Ministry of Public Works and Housing (PUPR) regulation (2002). The Karanggede–Juwangi road is classified as a Class II road, for which a uniformly distributed live load of 12 kN/m² was applied.

Data Analysis

Based on the recommendations of FHWA (2013), finite element modeling of the Deep Soil Mixing (DSM) method requires the incorporation of isolated columns beneath the road embankment, as well as the installation of a shear wall beneath the embankment slope to prevent stability failure of the embankment [14] as illustrated in Figure 4

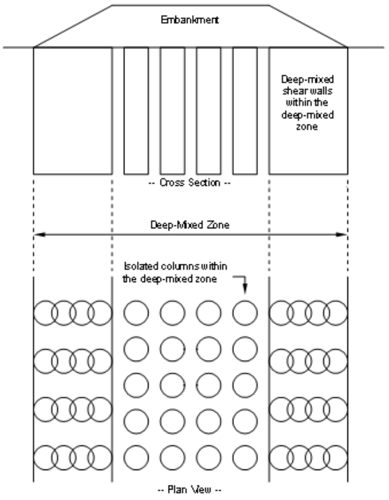


Figure 4. Soil model with Deep Soil Mixing Source: FHWA 2013

According to the study conducted by Kim Chan and Bosco Poon [21], the determination of the shear wall properties and isolated column parameters can be carried out using the equivalent strip approach, which was originally developed for modeling stone columns. This approach is based on the stress distribution mechanism between the column material and the surrounding soil. The spacing between equivalent strips is adjusted to match the actual column spacing, denoted as b. For a triangular column arrangement, the equivalent spacing is defined as √(3b/2). The equivalent Young's modulus (E_{eq}) and the equivalent cohesion (C_{eq}) of the DSM-reinforced zone can be calculated using Equation (1), as presented below.

$$E_{eq}\left(\text{or } C_{eq}\right) = \frac{E_{soil}(\text{or } C_{soil})\cdot A_{soil} + E_{coloumn}(\text{or } C_{coloumn})\cdot A_{coloumn}}{A_{soil} + A_{column}} \qquad (1)$$

The parameters A_{soil} and A_{column} represent the cross-sectional areas of the surrounding soil and the column, respectively, as illustrated in Figure 5.

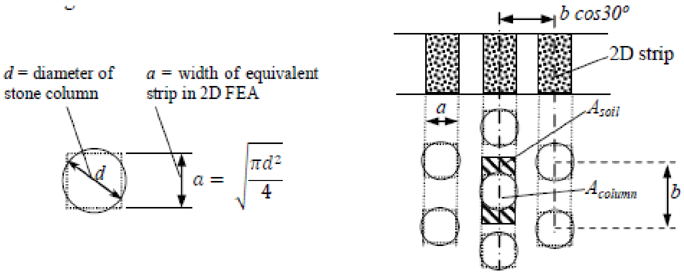


Figure 5. Two-dimensional representation of stone column strips Source: Designing Stone Columns Using 2D FEA with Equivalent Strips

To determine the equivalent internal friction angle (ϕ_{eq}), an assumed value of the stress concentration factor, denoted as n, is required. The stress concentration factor is defined as the ratio of the vertical stress carried by the column to the vertical stress carried by the surrounding soil at the same depth.

The equivalent friction angle can be calculated using Equation (2):

$$\tan_{(\phi eq)} = \frac{A_{soil}\tan_{(\phi eq)} + n \cdot A_{coloumn}\tan_{(\phi eq)}}{A_{soil} + A_{column}} \qquad (2)$$

The primary outcomes of this study include the evaluation of soil settlement reduction and the improvement of the safety factor following ground improvement using rectangular Deep Soil

Mixing (DSM). In addition, this research examines the influence of biopolymer addition on enhancing soil strength based on the results of numerical analysis.

RESULT AND DISCUSSION

In this study, numerical modeling was divided into several sequential stages. The first stage involved modeling a road embankment constructed on untreated soil. The second stage simulated an embankment constructed on improved soil using rectangular Deep Soil Mixing (DSM) with chitosan (CHI) as a stabilizer, using column diameters of 40 cm (0.4 m), 60 cm (0.6 m), and 80 cm (0.8 m). The third stage applied a rectangular DSM using guar gum (GG) with the same column diameter, and the fourth stage used a rectangular DSM stabilized with xanthan gum (XG), with the same column diameter.

Figure 2 illustrates the results of the first-stage modeling, in which the embankment was constructed on untreated soil. The input parameters for the untreated soil model used in PLAXIS 2D are presented in Table 1. The soil was modeled using the Mohr–Coulomb constitutive model, consisting of five soil layers, namely black clay, slightly silty light-brown clay, gray silty clay, and gray silt. The total model width was 28 m.

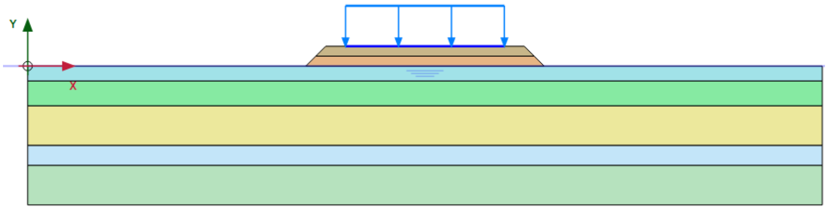
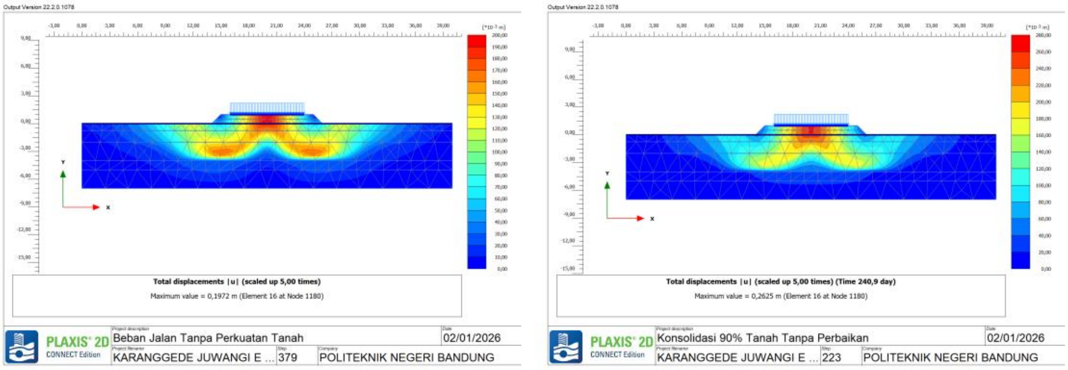


Figure 6. The untreated soil model in PLAXIS.



Total displacements |u| (scaled up 5,00 times)
Maximum value = 0,1972 m (Element 16 at Node 1180)

Project description: Beban Jalan Tanpa Perkuatan Tanah
Date: 02/01/2026
Project filename: KARANGGEDE JUWANGI E ...
Step: 379
Company: POLITEKNIK NEGERI BANDUNG

Total displacements |u| (scaled up 5,00 times) (Time 240,9 day)
Maximum value = 0,2625 m (Element 16 at Node 1180)

Project description: Konsolidasi 90% Tanah Tanpa Perbaikan
Date: 02/01/2026
Project filename: KARANGGEDE JUWANGI E ...
Step: 223
Company: POLITEKNIK NEGERI BANDUNG

(a) (b)

Figure 7. (a) presents the results of immediate settlement and slip surface analysis (b) illustrates the consolidation settlement and slip surface analysis for the untreated soil condition.

The numerical analysis yielded vertical displacements (settlement) of 0.19720 m and 0.26250 m. According to the Road Pavement Manual No. 02/M/BM/2017 [15] the allowable settlement for embankments constructed on soft soil after pavement installation is 100 mm (0.1 m). Therefore, the untreated soil condition exceeds the permissible settlement limit.

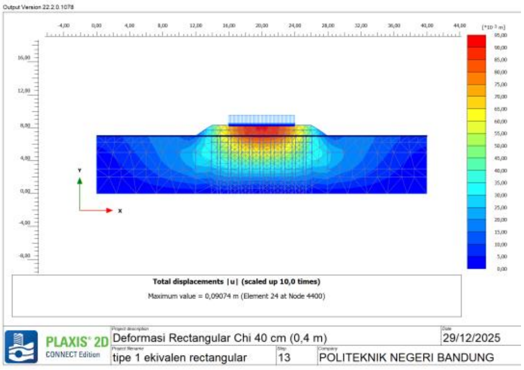
In terms of slope stability, the calculated safety factors (SF) were 1.142 and 1.473. Based on SNI 8460:2017 – Geotechnical Design Requirements [16] the minimum allowable safety factor for slope stability is 1.5. These results indicate that ground improvement is required for the Karanggede–Juwangi road section.

Soil Improvement Using CHI-Based DSM

The results of numerical analysis for soil improvement using CHI-stabilized DSM, as illustrated in Figure 8 and summarized in Tables 3 and 4, show that all improved models satisfy the allowable settlement criteria specified in the Road Pavement Manual No. 02/M/BM/2017, with settlement values less than 100 mm (0.1 m).

Among the CHI-based DSM configurations, the rectangular DSM column with a diameter of 80 cm (0.8 m) exhibited the lowest immediate settlement, with a deformation value of 0.07315 m and a corresponding safety factor of 2.501. Similarly, the consolidation settlement analysis for the same configuration yielded a settlement of 0.07686 m and a safety factor of 2.559, indicating a substantial improvement in both deformation control and slope stability.

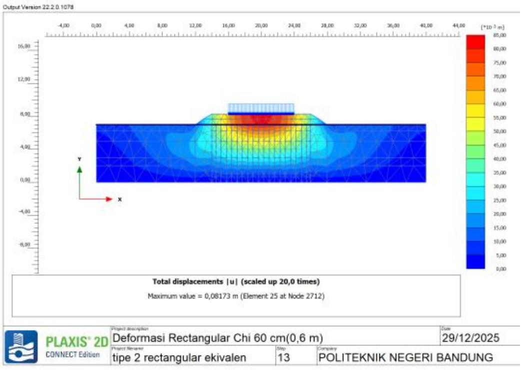
Based on both immediate and consolidation settlement analyses, the application of CHI-stabilized rectangular DSM can be considered technically feasible for ground improvement along the Karanggede-Juwangi road section. The obtained settlement values are within the allowable limits for embankments on soft soil, and the safety factors exceed the minimum criteria specified in SNI 8460:2017, confirming the effectiveness of this method.



Total displacements |u| (scaled up 10,0 times)
Maximum value = 0,09074 m (Element 24 at Node 4400)

Project description: Deformasi Rectangular Chi 40 cm (0,4 m)
Date: 29/12/2025
Project filename: tipe 1 ekivalen rectangular
Step: 13
Company: POLITEKNIK NEGERI BANDUNG

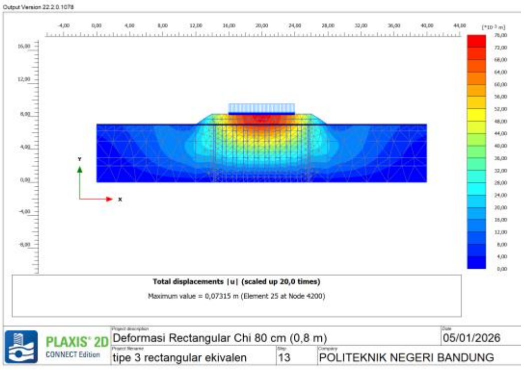
(a)



Total displacements |u| (scaled up 20,0 times)
Maximum value = 0,08173 m (Element 25 at Node 2712)

Project description: Deformasi Rectangular Chi 60 cm(0,6 m)
Date: 29/12/2025
Project filename: tipe 2 rectangular ekivalen
Step: 13
Company: POLITEKNIK NEGERI BANDUNG

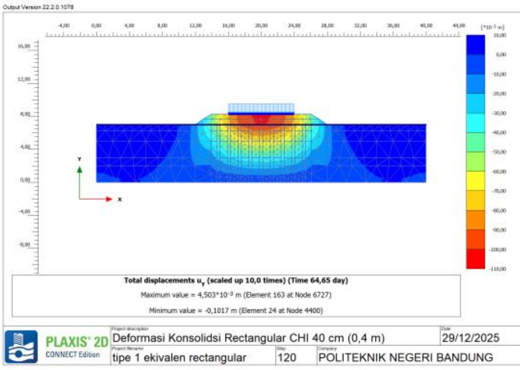
(b)



Total displacements |u| (scaled up 20,0 times)
Maximum value = 0,07315 m (Element 25 at Node 4200)

Project description: Deformasi Rectangular Chi 80 cm (0,8 m)
Date: 05/01/2026
Project filename: tipe 3 rectangular ekivalen
Step: 13
Company: POLITEKNIK NEGERI BANDUNG

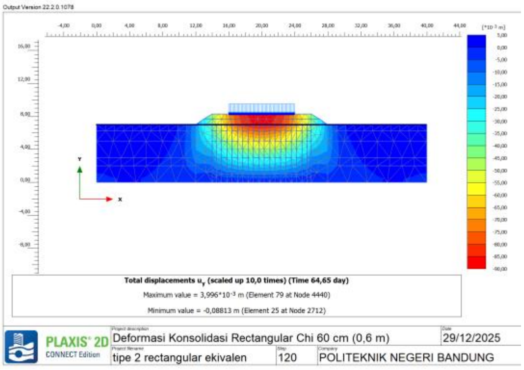
(c)



Total displacements u_y (scaled up 10,0 times) (Time 64,65 day)
Maximum value = 4,503*10^{-3} m (Element 163 at Node 6727)
Minimum value = -0,1017 m (Element 24 at Node 4400)

Project description: Deformasi Konsolidsi Rectangular CHI 40 cm (0,4 m)
Date: 29/12/2025
Project filename: tipe 1 ekivalen rectangular
Step: 120
Company: POLITEKNIK NEGERI BANDUNG

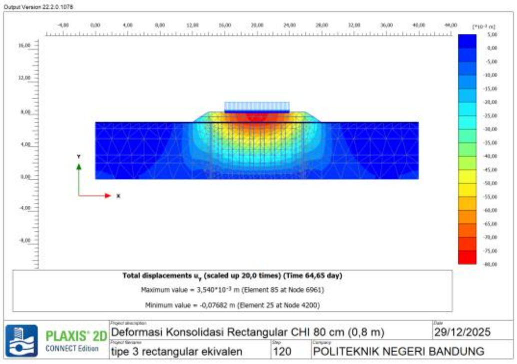
(d)



Total displacements u_y (scaled up 10,0 times) (Time 64,65 day)
Maximum value = 3,996*10^{-3} m (Element 79 at Node 4440)
Minimum value = -0,08813 m (Element 25 at Node 2712)

Project description: Deformasi Konsolidasi Rectangular Chi 60 cm (0,6 m)
Date: 29/12/2025
Project filename: tipe 2 rectangular ekivalen
Step: 120
Company: POLITEKNIK NEGERI BANDUNG

(e)

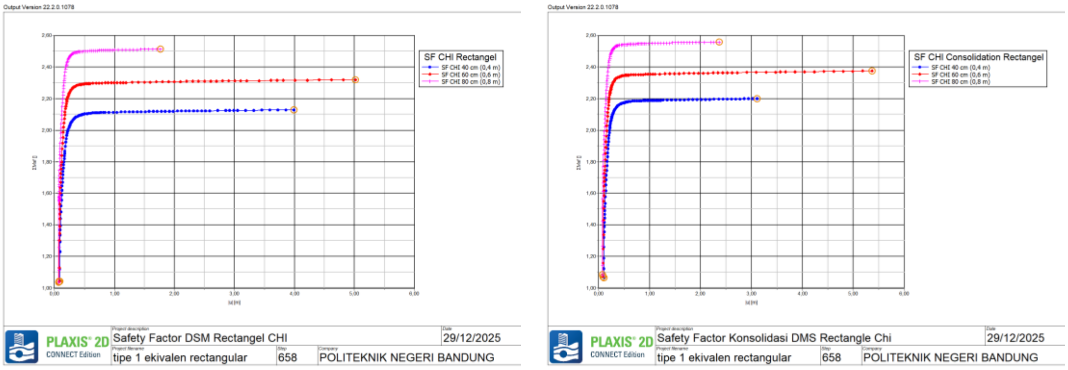


Total displacements u_y (scaled up 20,0 times) (Time 64,65 day)
Maximum value = 3,540*10^{-3} m (Element 85 at Node 6961)
Minimum value = -0,07682 m (Element 25 at Node 4200)

Project description: Deformasi Konsolidasi Rectangular CHI 80 cm (0,8 m)
Date: 29/12/2025
Project filename: tipe 3 rectangular ekivalen
Step: 120
Company: POLITEKNIK NEGERI BANDUNG

(f)

Figure 8. Results of Deformation Value Analysis Using Replacement CHI, Results of Deformation Value Analysis and Slip Angle Using Rectangular DSM Method, (a) Deep Soil Mixing CHI 40 cm (0.4 m) (b) Deep Soil Mixing CHI 60 cm (0.6 m) (c) Deep Soil Mixing CHI 80 cm (0.8 m), (d) Deep Soil Mixing Consolidation 40 cm (0.4 m), (e) Deep Soil Mixing Consolidation CHI 60 cm (0.6 m) (f) Deep Soil Mixing Consolidation CHI 80 cm (0.8 m)



(a) (b)

Figure 9. Safety factor analysis of rectangular Deep Soil Mixing (DSM) with chitosan (CHI)

Table 3. Summary of settlement and safety factor results for immediate settlement of rectangular DSM with chitosan (CHI)

No	Improvement	Deformation (m)	Safety factor
1.	DSM Rectangular CHI 40 cm	0,09074	2,199
2.	DSM Rectangular CHI 60 cm	0,08173	2,320
3.	DSM Rectangular CHI 80 cm	0,07315	2,501

Table 4 Summary of settlement and safety factor results for consolidation settlement of rectangular DSM with chitosan (CHI)

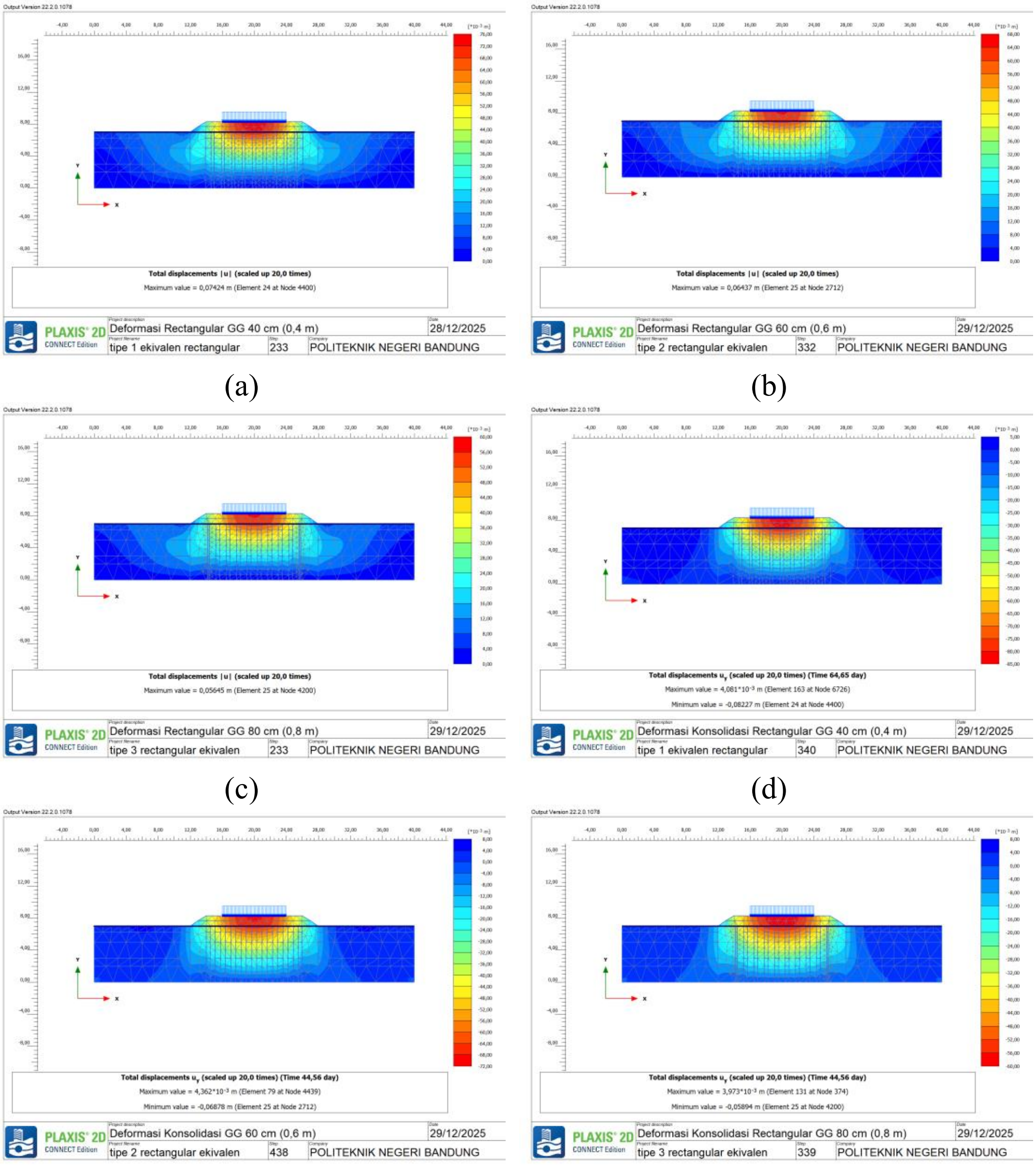
No	Improvement	Deformation (m)	Safety factor
1.	DSM Consolidation 90% Rectangular CHI 40 cm	0,1017	2,199
2.	DSM Consolidation 90% Rectangular CHI 60 cm	0,08813	2,375
3.	DSM Consolidation 90% Rectangular CHI 80 cm	0,07686	2,599

Soil Improvement Using GG-Based DSM

The results of numerical analysis for soil improvement using GG-stabilized DSM, as illustrated in Figure 10 and summarized in Tables 5 and 6, show that all improved models satisfy the allowable settlement criteria specified in the Road Pavement Manual No. 02/M/BM/2017, with settlement values less than 100 mm (0.1 m).

Among the GG-based DSM configurations, the rectangular DSM column with a diameter of 80 cm (0.8 m) exhibited the lowest immediate settlement, with a deformation value of 0,05645 m and a corresponding safety factor of 2,814. Similarly, the consolidation settlement analysis for the same configuration yielded a settlement of 0.05894 m and a safety factor of 2.819, indicating a substantial improvement in both deformation control and slope stability.

Based on both immediate and consolidation settlement analyses, the application of GG-stabilized rectangular DSM can be considered technically feasible for ground improvement along the Karanggede–Juwangi road section. The obtained settlement values are within the allowable limits for embankments on soft soil, and the safety factors exceed the minimum criteria specified in SNI 8460:2017, confirming the effectiveness of this method.



Total displacements |u| (scaled up 20,0 times)
Maximum value = 0,07424 m (Element 24 at Node 4400)
Project description: Deformasi Rectangular GG 40 cm (0,4 m)
Date: 28/12/2025
Project filename: tipe 1 ekivalen rectangular
Step: 233
Company: POLITEKNIK NEGERI BANDUNG

(a)

Total displacements |u| (scaled up 20,0 times)
Maximum value = 0,06437 m (Element 25 at Node 2712)
Project description: Deformasi Rectangular GG 60 cm (0,6 m)
Date: 29/12/2025
Project filename: tipe 2 rectangular ekivalen
Step: 332
Company: POLITEKNIK NEGERI BANDUNG

(b)

Total displacements |u| (scaled up 20,0 times)
Maximum value = 0,05645 m (Element 25 at Node 4200)
Project description: Deformasi Rectangular GG 80 cm (0,8 m)
Date: 29/12/2025
Project filename: tipe 3 rectangular ekivalen
Step: 233
Company: POLITEKNIK NEGERI BANDUNG

(c)

Total displacements u_y (scaled up 20,0 times) (Time 64,65 day)
Maximum value = $4{,}081 \cdot 10^{-3}$ m (Element 163 at Node 6726)
Minimum value = -0,08227 m (Element 24 at Node 4400)
Project description: Deformasi Konsolidasi Rectangular GG 40 cm (0,4 m)
Date: 29/12/2025
Project filename: tipe 1 ekivalen rectangular
Step: 340
Company: POLITEKNIK NEGERI BANDUNG

(d)

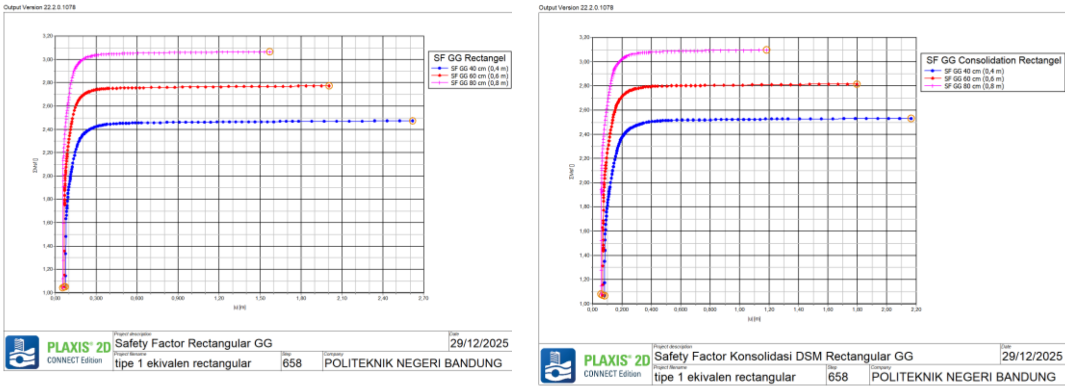
Total displacements u_y (scaled up 20,0 times) (Time 44,56 day)
Maximum value = $4{,}362 \cdot 10^{-3}$ m (Element 79 at Node 4439)
Minimum value = -0,06878 m (Element 25 at Node 2712)
Project description: Deformasi Konsolidasi GG 60 cm (0,6 m)
Date: 29/12/2025
Project filename: tipe 2 rectangular ekivalen
Step: 438
Company: POLITEKNIK NEGERI BANDUNG

(e)

Total displacements u_y (scaled up 20,0 times) (Time 44,56 day)
Maximum value = $3{,}973 \cdot 10^{-3}$ m (Element 131 at Node 374)
Minimum value = -0,05894 m (Element 25 at Node 4200)
Project description: Deformasi Konsolidasi Rectangular GG 80 cm (0,8 m)
Date: 29/12/2025
Project filename: tipe 3 rectangular ekivalen
Step: 339
Company: POLITEKNIK NEGERI BANDUNG

(f)

Figure 10. Results of Deformation Value Analysis Using Replacement GG, Results of Deformation Value Analysis and Slip Angle Using Rectangular DSM Method, (a) Deep Soil Mixing GG 40 cm (0.4 m) (b) Deep Soil Mixing GG 60 cm (0.6 m) (c) Deep Soil Mixing GG 80 cm (0.8 m), (d) Deep Soil Mixing Consolidation 40 cm (0.4 m), (e) Deep Soil Mixing Consolidation GG 60 cm (0.6 m) (f) Deep Soil Mixing Consolidation GG 80 cm (0.8 m)



(a)

(b)

Figure 11. Safety factor analysis of rectangular Deep Soil Mixing (DSM) with Guar gum (GG)

Table 5. Summary of settlement and safety factor results for immediate settlement of rectangular DSM with guar gum (GG)

No	Improvement	Deformation (m)	Safety factor
1.	DSM Rectangular GG 40 cm	0,07424	2,472
2.	DSM Rectangular GG 60 cm	0,06437	2,772
3.	DSM Rectangular GG 80 cm	0,05645	2,814

Table 6. Summary of settlement and safety factor results for consolidation settlement of rectangular DSM with guar gum (GG)

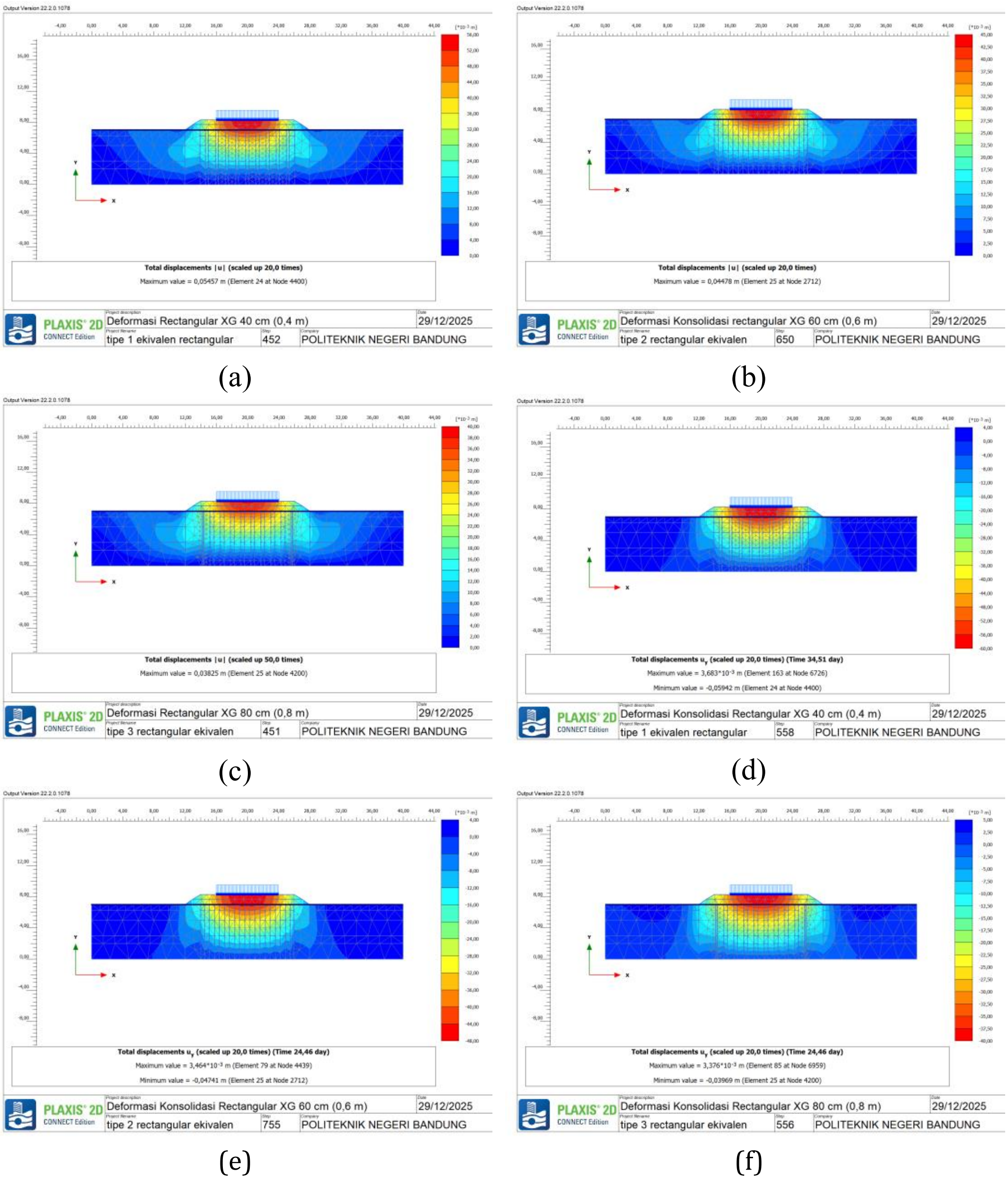
No	Improvement	Deformation (m)	Safety factor
1.	DSM Consolidation Rectangular GG 40 cm	0,08227	2,531
2.	DSM Consolidation Rectangular GG 60 cm	0,06878	2,815
3.	DSM Consolidation Rectangular GG 80 cm	0,05894	2,819

Soil Improvement Using XG-Based DSM

The results of numerical analysis for soil improvement using XG-stabilized DSM, as illustrated in Figure 12 and summarized in Tables 5 and 6, show that all improved models satisfy the allowable settlement criteria specified in the Road Pavement Manual No. 02/M/BM/2017, with settlement values less than 100 mm (0.1 m).

Among the GG-based DSM configurations, the rectangular DSM column with a diameter of 80 cm (0.8 m) exhibited the lowest immediate settlement, with a deformation value of 0,03825 m and a corresponding safety factor of 4,178. Similarly, the consolidation settlement analysis for the same configuration yielded a settlement of 0.03969 m and a safety factor of 4,718, indicating a substantial improvement in both deformation control and slope stability.

Based on both immediate and consolidation settlement analyses, the application of XG-stabilized rectangular DSM can be considered technically feasible for ground improvement along the Karanggede–Juwangi road section. The obtained settlement values are within the allowable limits for embankments on soft soil, and the safety factors exceed the minimum criteria specified in SNI 8460:2017, confirming the effectiveness of this method.



Total displacements |u| (scaled up 20,0 times)
Maximum value = 0,05457 m (Element 24 at Node 4400)
Deformasi Rectangular XG 40 cm (0,4 m) 29/12/2025
tipe 1 ekivalen rectangular 452 POLITEKNIK NEGERI BANDUNG

(a)

Total displacements |u| (scaled up 20,0 times)
Maximum value = 0,04478 m (Element 25 at Node 2712)
Deformasi Konsolidasi rectangular XG 60 cm (0,6 m) 29/12/2025
tipe 2 rectangular ekivalen 650 POLITEKNIK NEGERI BANDUNG

(b)

Total displacements |u| (scaled up 50,0 times)
Maximum value = 0,03825 m (Element 25 at Node 4200)
Deformasi Rectangular XG 80 cm (0,8 m) 29/12/2025
tipe 3 rectangular ekivalen 451 POLITEKNIK NEGERI BANDUNG

(c)

Total displacements u_y (scaled up 20,0 times) (Time 34,51 day)
Maximum value = 3,683*10^{-3} m (Element 163 at Node 6726)
Minimum value = -0,05942 m (Element 24 at Node 4400)
Deformasi Konsolidasi Rectangular XG 40 cm (0,4 m) 29/12/2025
tipe 1 ekivalen rectangular 558 POLITEKNIK NEGERI BANDUNG

(d)

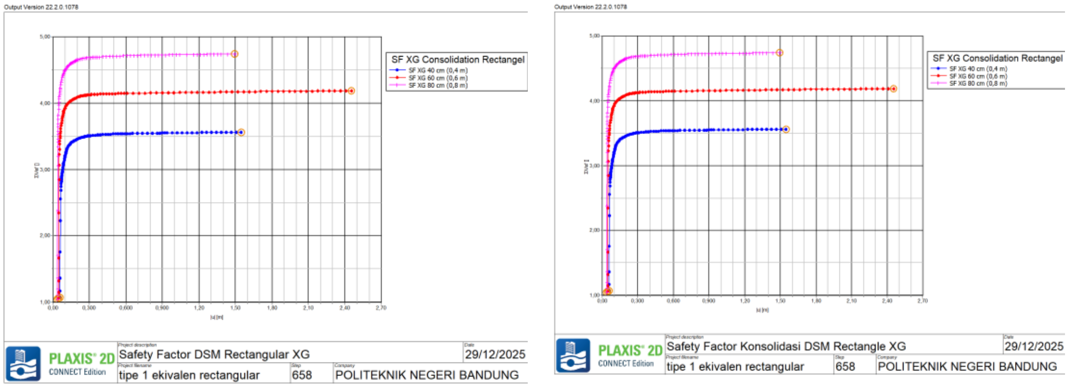
Total displacements u_y (scaled up 20,0 times) (Time 24,46 day)
Maximum value = 3,464*10^{-3} m (Element 79 at Node 4439)
Minimum value = -0,04741 m (Element 25 at Node 2712)
Deformasi Konsolidasi Rectangular XG 60 cm (0,6 m) 29/12/2025
tipe 2 rectangular ekivalen 755 POLITEKNIK NEGERI BANDUNG

(e)

Total displacements u_y (scaled up 20,0 times) (Time 24,46 day)
Maximum value = 3,376*10^{-3} m (Element 85 at Node 6959)
Minimum value = -0,03969 m (Element 25 at Node 4200)
Deformasi Konsolidasi Rectangular XG 80 cm (0,8 m) 29/12/2025
tipe 3 rectangular ekivalen 556 POLITEKNIK NEGERI BANDUNG

(f)

Figure 12. Results of Deformation Value Analysis Using Replacement XG, Results of Deformation Value Analysis and Slip Angle Using Rectangular DSM Method, (a) Deep Soil Mixing XG 40 cm (0.4 m) (b) Deep Soil Mixing XG 60 cm (0.6 m) (c) Deep Soil Mixing XG 80 cm (0.8 m), (d) Deep Soil Mixing Consolidation 40 cm (0.4 m), (e) Deep Soil Mixing Consolidation XG 60 cm (0.6 m) (f) Deep Soil Mixing Consolidation XG 80 cm (0.8 m)



(a) (b)

Figure 13. Safety factor analysis of rectangular Deep Soil Mixing (DSM) with Xhantanan gum (XG)

Table 7. Summary of settlement and safety factor results for immediate settlement of rectangular DSM with Xhantanan Gum (XG)

No	Improvement	Deformation (m)	Safety factor
1.	DSM Rectangular XG 40 cm	0,05457	3,514
2.	DSM Rectangular XG 60 cm	0,04478	4,157
3.	DSM Rectangular XG 80 cm	0,03825	4,178

Table 8. Summary of settlement and safety factor results for consolidation settlement of rectangular DSM with Xhantanan Gum (XG)

No	Improvement	Deformation (m)	Safety factor
1.	DSM Consolidation Rectangular XG 40 cm	005942	3,560
2.	DSM Consolidation Rectangular XG 60 cm	0,04741	4,185
3.	DSM Consolidation Rectangular XG 80 cm	0,03969	4,718

Several studies have demonstrated that incorporating biopolymers can significantly enhance the mechanical properties of problematic soils. Setyaningrum and Amalia [17] reported that the addition of biopolymers to peat soil increased the shear strength by up to 153.18%. These findings are consistent with the results reported by Guritno and Amalia [7], who investigated the effects of biopolymer additives based on chitosan (CHI), guar gum (GG), and xanthan gum (XG) on existing soil. Their study revealed a substantial improvement in shear strength, with the most pronounced enhancement achieved through XG treatment, which increased soil quality by up to 482%.

The improvement in shear strength directly influenced the outcomes of the numerical analysis conducted in this study. Numerical simulations indicated that biopolymer addition significantly affects soil deformation characteristics. Among the evaluated materials, XG-treated soil exhibited the lowest settlement, achieving a reduction of 84.88% relative to the consolidation settlement of untreated soil. This result highlights the superior performance of XG in enhancing soil stiffness and resistance to deformation. In addition, the effect of Deep Soil Mixing (DSM) column geometry was clearly observed. Larger column diameters result in lower deformation values, with the 80 cm (0.8 m) diameter DSM column demonstrating the most effective settlement reduction.

Overall, the findings of this study suggest that the use of biopolymers as soil strengthening agents represents a promising approach for ground stabilization in geotechnical engineering applications. Biopolymer-stabilized DSM not only improves soil strength and deformation behavior but also has the potential to enhance structural performance and extend the service life of civil engineering projects constructed on expansive or problematic soils.

CONCLUSION

Based on the results of the settlement analysis using the Deep Soil Mixing (DSM) method with a Rectangular configuration and the addition of biopolymers in the form of chitosan (CHI), guar gum (GG), and xanthan gum (XG), it can be concluded that Under the existing soil condition without improvement, the PLAXIS 2D analysis shows deformation values of 0.19720 m and 0.2625 m, with corresponding Safety Factor (SF) values of 1.142 and 1.473, respectively. Based on the numerical analysis of the Rectangular DSM model with biopolymer additives, the following conclusions can be drawn: a) All DSM modeling variations using CHI, GG, and XG biopolymers meet the allowable settlement limits specified in the Road Pavement Manual No. 02/M/BM/2017. In addition, the resulting Safety Factor values satisfy the stability requirements stipulated in SNI 8460:2017, indicating that this method is technically safe, b) The effectiveness of soil improvement is influenced by the diameter of the DSM columns. Among the diameter variations the DSM column with a diameter of 80 cm (0.8 m) produced the smallest deformation value, making it the most optimal configuration in reducing soil settlement, c) In terms of biopolymer materials, xanthan gum (XG) exhibited the best performance compared to CHI and GG. In percentage terms, CHI reduced the maximum deformation by 70.72%, GG by 77.55%, and XG by 84.88%. This indicates that XG is the most effective material in enhancing soil stiffness and bearing capacity, and therefore is the most recommended for field application, d) The Safety Factor analysis shows that the addition of biopolymers to the existing soil results in a significant improvement in stability. The increase in safety factor ranges from 76.44% to 220.30%, indicating that biopolymers play an important role in improving slope stability and overall soil safety. Soil improvement using the Rectangular Deep Soil Mixing method with the addition of biopolymers—chitosan, guar gum, and particularly xanthan gum—has been numerically proven to enhance soil strength, reduce settlement, and improve slope stability. This method has high potential for application in geotechnical and road infrastructure projects, especially under problematic soil conditions.

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