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Numerical Analysis of Flexible Pavement on Soft Soil Using Finite Element Method

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Abstract: *Road he construction of flexible pavement on soft clay subgrades faces challenges due to low bearing capacity, high compressibility, and sensitivity to moisture. This study analyzes the stress–strain response of soft clay using Finite Element Method with three water content scenarios: 19%, 36%, and 53%. The 2D model consisted of a 57 cm clay layer and a 3 cm pavement layer, with soil parameters obtained from laboratory tests and represented by the Mohr-Coulomb model. The results show that effective stress increased slightly with higher water content, from 10.57 kN/m² at 19% to 11.54 kN/m² at 53%. In contrast, displacement remained nearly constant at around 0.2046 mm. This indicates that while moisture variation affects stress distribution, it has minimal impact on soil deformation under the modeled conditions. These findings suggest that flexible pavement on soft clay may maintain stable deformation despite increased moisture, providing useful insights for pavement design on problematic soils.*

Keywords: *Finite Element Method, soft clay, effective stress, displacement, flexible pavement, water content.*

1. Introduction

The construction of road infrastructure on soft soils remains a major challenge in civil engineering, particularly in areas characterized by low bearing capacity, high compressibility, and limited shear strength. These conditions often lead to excessive deformation, settlement, and premature damage to pavement structures built on such soils [1]. In Indonesia, soft clay soils are widely distributed, especially along the northern coast of Java, the eastern coast of Sumatra, and parts of Kalimantan, covering more than 20 million hectares [2].

The expansive nature of clay soils makes them highly sensitive to changes in moisture content. Under wet conditions, the soil tends to swell and push the overlying structures upward, while during dry periods, it shrinks and causes cracking or differential settlement of the pavement [3][4]. This problem is further exacerbated by the low permeability of clay, which often traps water beneath the pavement layer, accelerating structural deterioration. In tropical regions, high rainfall intensifies these issues and increases the risk of pavement failure on soft soils [5].

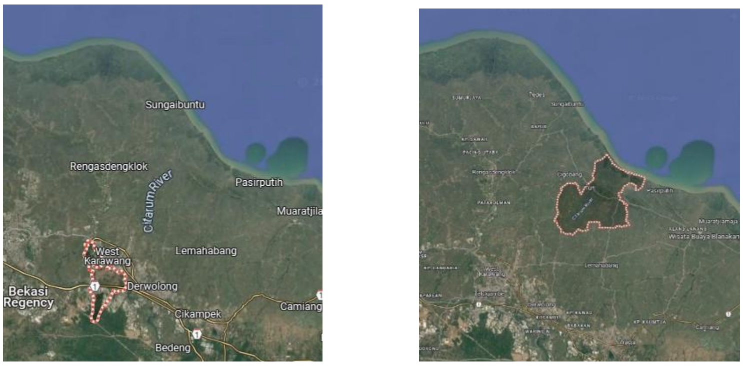
Several previous studies have employed numerical software to analyze the behavior of soft soils under traffic loads. For instance, Plaxis 2D has been widely used to model soil deformation and effective stress under saturated conditions [6] . However, an alternative approach based on finite element methods offers advantages in analyzing the stress–strain response of soils, particularly in simulating deformation under staged loading and varying moisture conditions.

This study aims to analyze the response of soft clay subgrade under traffic loads using a finite element–based numerical approach capable of simulating soil stress–strain interactions in detail. The focus of this research is to quantify deformation and stress distribution within the subgrade, thereby providing a more comprehensive understanding of potential settlement and pavement stability on soft soils. Consequently, the findings are expected to contribute to more reliable pavement design in problematic soil conditions.

2. Methods

2.1. Research location

This study was conducted in Karawang Regency, West Java, Indonesia, specifically along the distribution route between Telukjambe Barat and Tempuran Subdistricts. The area serves as an important transportation corridor connecting the Karawang New Industry City (KNIC) industrial zone in Wanajaya with the Cilamaya Port development site. Due to rapid industrial expansion, this corridor has experienced significant traffic loading, making it highly vulnerable to road damage when constructed on soft clay subgrades. The soil in this region is predominantly soft clay, characterized by low shear strength, high compressibility, and poor bearing capacity, which makes it unsuitable for supporting heavy traffic loads without reinforcement. Soil sampling was carried out at several points along the corridor to obtain both disturbed and undisturbed samples for laboratory testing and numerical modeling. These samples were essential for determining the physical and mechanical properties of the subgrade soil, including moisture content, specific gravity, unit weight, and stress–strain parameters required for the numerical analysis. Soil sampling locations can be seen in Figures 1.



(a)Telukjambe Sub-district (b) Tempuran Sub-district

Fig. 1. Soft Clay Soil Research Site

2.2. Models Field Data Collection Technique

Soil investigation in Karawang Regency was carried out through both disturbed and undisturbed sampling in accordance with the ASTM standards. Undisturbed samples were obtained using thin-walled tube samplers following ASTM D1587, and these were utilized for laboratory tests related to the physical and mechanical properties of the soil, including moisture content (ASTM D2216), specific gravity (ASTM D854), and unit weight (ASTM D7263). Disturbed samples, on the other hand, were collected for classification tests and served as representative material for numerical modeling.

2.3. Numerical Analysis using Finite Element Method

Numerical analysis was carried out using Finite Element Method to model the behavior of soft clay subgrade under traffic loads. The model geometry was constructed in 2D, consisting of a 57 cm soft clay layer overlain by a 3 cm flexible pavement layer. Boundary conditions were defined with full fixity at the base and horizontal fixity on the lateral sides. Soil parameters including cohesion, internal friction angle, elastic modulus, Poisson's ratio, and permeability were obtained from laboratory tests and applied using the Mohr-Coulomb constitutive model. The mesh was refined around the loading area to capture local deformation more accurately. The simulation was performed in sequential stages: initial stress condition, water content variation, consolidation, and traffic loading. Three infiltration scenarios were introduced with additional water contents of 19%, 36%, and 53%, modeled as an increase in pore-water pressure before the application of a 20.4 kg equivalent traffic load. The outputs, including vertical deformation, effective stress distribution, and pore pressure changes, were analyzed to evaluate the influence of varying water content on the stability of flexible pavement constructed on soft soil.

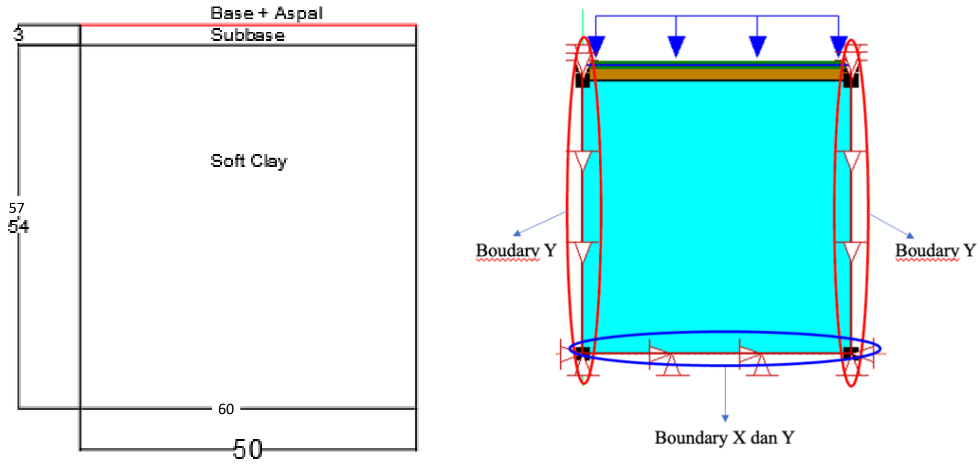
3. Result and Discussion

3.1 Stages of Numerical Modeling and Simulation of Soft Clay under Water Infiltration

Before The modeling process began with the preparation of a two-dimensional geometry consisting of a soft clay layer with a thickness of 57 cm and a flexible pavement layer of 3 cm on top. The geometry was discretized into triangular finite elements, with mesh refinement applied around the loading area to improve accuracy in capturing stress–strain responses. Initial boundary conditions were assigned with fixed displacements at the base and horizontal fixity along the vertical boundaries, while the soil constitutive behavior was defined using the Mohr-Coulomb model with parameters derived from laboratory testing.

Simulation was conducted through staged construction analysis, starting from the initialization of in-situ stresses to represent the geostatic condition of the soil. Subsequently, three scenarios of water content addition were applied, namely 19%, 36%, and 53%, which were modeled as increments of pore-water pressure within the soft clay layer. After each infiltration stage, a consolidation period was simulated to allow redistribution of pore pressure and settlement before applying the traffic load equivalent to 20.4 kg.

The stepwise approach enabled observation of how increasing water content progressively influenced soil response. At lower water addition (19%), the clay remained relatively stable with limited deformation, whereas higher water additions (36% and 53%) resulted in greater settlement and stress redistribution. These stages highlight the significant role of moisture variation in determining subgrade performance and the critical threshold at which soil stability may be compromised under traffic loading.



(a) Soil Section Modeling (b) Finite Element Modeling

Fig 2. Stages of Modeling

3.2 Displacemnt

The The displacement analysis was carried out to evaluate the vertical deformation of the soft clay layer under different water content conditions. Numerical modeling showed that the addition of water did not significantly alter the settlement values of the subgrade. This indicates that within the simulated range of water content variations (19%, 36%, and 53%), the soil reached a relatively stable deformation response once subjected to the applied load.

1. Displacement at 19% Water Addition
   At the initial scenario with 19% water addition, the vertical displacement reached 0.204682 mm. The deformation pattern was relatively small and concentrated around the loaded area, indicating that the soil remained stable under this level of moisture.

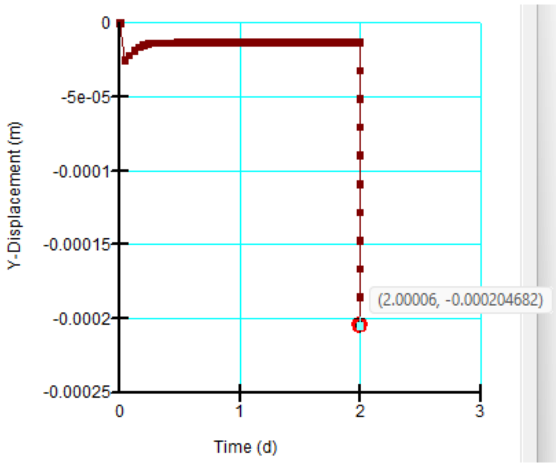


Fig 3. Displacement at 19% Water Addition

2. Displacement at 36% Water Addition
   In the second scenario, when the water content was increased to 36%, the displacement value was recorded at 0.204637 mm. The settlement pattern was similar to the first scenario, with only a negligible difference in magnitude, suggesting that additional water did not significantly influence the soil compressibility.

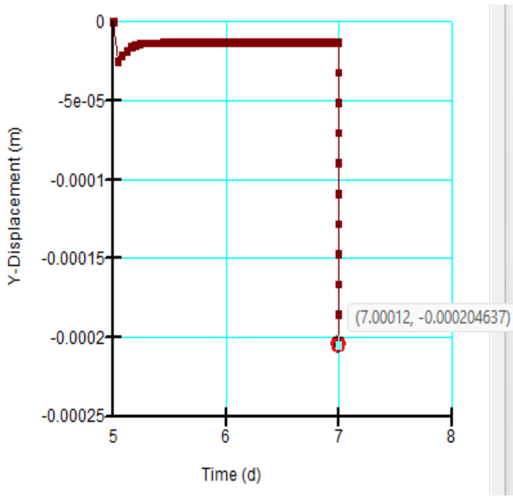


Fig 4. Displacement at 36% Water Addition

3. Displacement at 53% Water Addition
   At the maximum water content of 53%, the displacement remained nearly constant at 0.204637 mm. This confirms that the soil had reached a stable response in terms of deformation, and further moisture increase did not result in additional settlement.

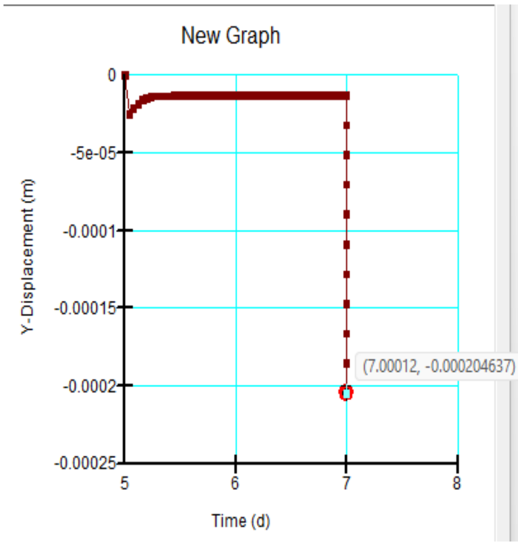


Fig 5. Displacement at 53% Water Addition

A summary of the displacement results for the three infiltration scenarios analyzed using the finite element method is presented in Table 1.

Table 1. Recapitulation of Displacement against Water Addition

No	Water Addition(%)	Displacement (mm)
1	19	0.204682
2	36	0.204637
3	53	0.204637

3.3 Effective Stress

In The effective stress distribution of the soft clay was analyzed under three water content scenarios. The results from the Finite Element Method simulation are as follows:

1. Effective Stress at 19% Water Addition
   At a water content of 19%, the effective stress within the clay layer was measured at 10.57 kN/m². The stress distribution was relatively uniform, and the soil condition indicated sufficient stability with no signs of excessive deformation.

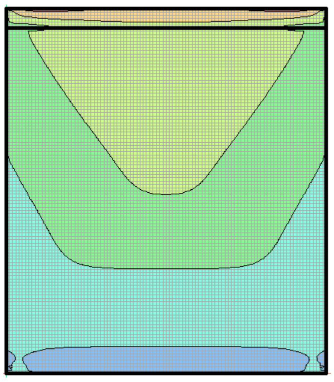


Fig 6. Effective Stress at 19% Water Addition

2. Effective Stress at 36% Water Addition
   When the water content was increased to 36%, the effective stress slightly changed to 11.23 kN/m². Although pore pressure increased, the soil was still able to redistribute stress effectively, maintaining a similar overall stability condition compared to the first scenario.

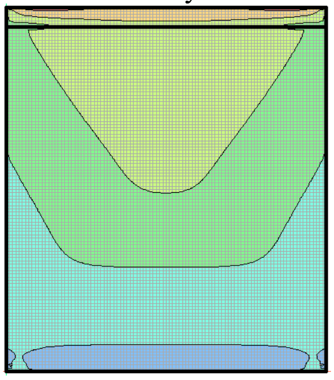


Fig 7. Effective Stress at 36% Water Addition

3. Effective Stress at 53% Water Addition
   At the maximum water content of 53%, the effective stress remained at 11.54 kN/m². The results indicate that despite the higher degree of saturation, the soil's stress response stabilized, and no significant variation in effective stress occurred compared to the previous stage.

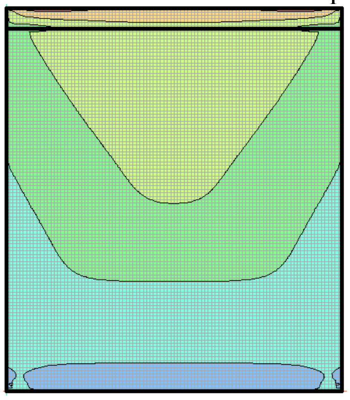


Fig 8. Effective Stress at 53% Water Addition

The recapitulation of effective stress values for the three infiltration scenarios is presented in Table 2, providing a comparison of the soil stress response under varying water content conditions.

Table 2. Recapitulation of Effective Stress Water Addition

No	Water Addition(%)	Effective Stress (kN/m^2)
1	19	10.57
2	36	11.23
3	53	11.54

From these results, it can be seen that the increase in water content from 19% to 53% produced only a negligible change in effective stress. This suggests that under the modeled conditions, the soil exhibited a relatively stable stress–strain response despite variations in water infiltration.

4. Conclusions

The results of the numerical analysis using Finite Element Method show that an increase in water content from 19% to 53% led to a gradual rise in effective stress, ranging from 10.57 kN/m² at 19% to 11.54 kN/m² at 53%. This indicates that higher saturation levels caused a slight increase in soil stress due to pore pressure redistribution. On the other hand, the displacement remained almost constant across all scenarios, with settlement values of 0.204682 mm at 19% and 0.204637 mm at both 36% and 53%. These findings suggest that while variations in water content influence the effective stress within the clay layer, they do not significantly affect the deformation of the soil under the given modeling conditions. Overall, the results imply that the soft clay subgrade maintained adequate resistance to additional settlement despite increased moisture levels, providing useful insights into the performance of flexible pavements on soft soils.

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