

MODELING STUDY AND NUMERICAL ANALYSIS OF FLEXIBLE PAVEMENT IN SOFT SOIL BASED ON FINITE ELEMENT METHOD

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ABSTRACT

Road construction with flexible pavement system on soft clay subgrade faces technical constraints in the form of low bearing capacity, high compressibility, and sensitivity to changes in moisture content, so this study evaluates stress-strain response using finite Element Method (FEM) through two-dimensional modeling (2D) consisting of a layer of clay soil 57 cm thick and a layer of flexible pavement 3 cm thick, with, in three variations of moisture content, namely 19%, 36%, and 53%, where the results of the analysis show that the increase in water content causes an increase in effective stress from 10.57 kN/m² at 19% to 11.54 kN/m² at 53%, while the displacement value is relatively stable at around 0.2046 mm, so it can be concluded that although the variation of water content affects the stress distribution, the impact on total deformation is relatively small and flexible pavement is still able to maintain deformation stability in the problematic soil conditions.

Keywords: Water Content, Finite Element Method, Displacement, Flexible Pavement, Effective Stress.

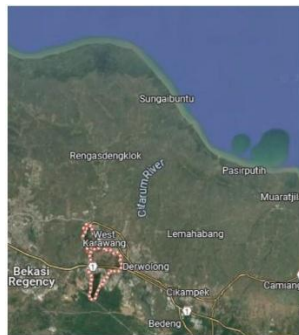
INTRODUCTION

The construction of road infrastructure on soft soils remains a major challenge in civil engineering, especially in areas with low bearing capacity, high compressibility and limited shear strength. These conditions often lead to excessive deformation, subsidence, and premature destruction of pavement structures built on such soils [1]. In Indonesia, soft clay is widespread, especially along the northern coast of Java, the eastern coast of Sumatra, and parts of Borneo, covering more than 20 million hectares [2]. The expansive properties of clay make it very sensitive to changes in water content. In wet conditions, the soil tends to expand and push the overlying structure upwards, while in dry periods, it shrinks and causes cracks or uneven shrinkage of the road surface [3][4]. This problem is exacerbated by the low permeability of clay soils, which often retain water under the road surface layer, accelerating structural damage. In the tropics, heavy rainfall exacerbates this problem and increases the risk of road surface failure on soft soils [5]. Several previous studies have used numerical software to analyze the behavior of soft soils under traffic loads. For example, Plaxis 2D has been widely used to model soil deformation and effective stress under saturated conditions [6]. However, an alternative approach based on the finite element method offers advantages in analyzing the stress-strain response of soils, especially in simulating deformation under gradual loads and varying moisture conditions.

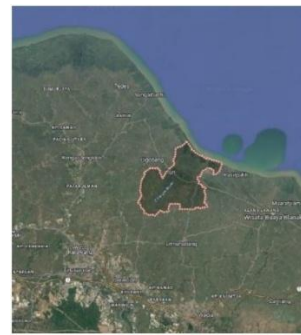
METHODS

Research Locations

This study was conducted in Karawang Regency, West Java, Indonesia, especially along the distribution route between West Telukjambe District and Tempuran District. This area serves as an important transportation corridor that connects the Karawang New Industry City (KNIC) industrial area in Wanajaya with the location of the Cilamaya port development. As a result of the rapid expansion of industry, the corridor is subjected to significant traffic loads, so it is very susceptible to road damage if it is built on a layer of soft clay. The soil in this region is dominated by soft clay, which has low shear strength, high compressibility and poor bearing capacity, so it is not suitable to withstand heavy traffic loads without reinforcement. Soil sampling was conducted at several points along the corridor to obtain disturbed and undisturbed samples for laboratory testing and numerical modeling. These samples are essential for determining the physical and mechanical properties of subgrade soils, including water content, specific gravity, unit weight, and stress-strain parameters required for Numerical Analysis. The location of the soil sample can be seen in Figure 1.



(a). Telukjambe Regency



(b). Tempuran Regency

Figure 1. Soft Soil Research Sites

Field Data Collection Techniques

Soil research in Karawang Regency is conducted through disturbed and undisturbed sampling in accordance with ASTM standards. Undisturbed samples are obtained using thin-wall tube samplers in accordance with ASTM D1587, and these samples are used for laboratory tests related to soil physical and mechanical properties, including water content (ASTM D2216), specific gravity (ASTM D854), and unit weight (ASTM D7263). Disturbed samples, on the other hand, are collected for classification tests and serve as representative material for numerical modeling.

Numerical Analysis Using Finite Element Method

Numerical analysis was performed using the finite element method to model the behavior of soft clay layers under traffic loads. The geometry of the model is built in 2D, consisting of a 57 cm thick layer of soft clay overlaid by a 3 cm thick layer of flexible pavement. Boundary conditions are defined with full rigidity at the base and horizontal rigidity 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 network is smoothed around the load area to more accurately capture local deformations. The simulation is carried out in sequential stages: initial stress conditions, water content variations, consolidation, and traffic loads. Three infiltration scenarios were introduced with additional water content of 19%, 36%, and 53%, which were modeled as an increase in pore water pressure prior to the application of an

equivalent traffic load of 20.4 kg. Outputs, including vertical deformation, effective stress distribution, and pore water pressure changes, were analyzed to evaluate the effect of variations in water content on the stability of flexible road surfaces built on soft soils.

RESULTS AND DISCUSSION

Stages of Numerical Modeling and Simulation of Soft Clay Soils Under Water Infiltration Conditions

Before the modeling process begins with the preparation of a two-dimensional geometry consisting of a layer of soft clay with a thickness of 57 cm and a layer of flexible pavement with a thickness of 3 cm on top. The geometry is discretized into triangular elements, with mesh smoothing applied around the load area to improve accuracy in capturing stress-strain responses. The initial boundary conditions were established by fixed displacement at the base and horizontal rigidity along the vertical boundary, while the constitutive behavior of the soil was defined using the Mohr-Coulomb model with parameters obtained from laboratory tests. The simulation is carried out through a phased construction analysis, starting from the initialization of in-situ stresses to represent the geostatic conditions of the soil. Furthermore, three scenarios of adding water content were applied, namely 19%, 36%, and 53%, which were modeled as adding pore water pressure in soft clay layers. After each stage of infiltration, a period of consolidation was simulated to allow redistribution of pore pressure and a decrease before applying a traffic load equivalent to 20.4 kg. The stepwise approach allows observation of how a gradual increase in water content affects soil response. At lower water additions (19%), the clay remained relatively stable with limited deformation, while higher water additions (36% and 53%) led to greater degradation and stress redistribution. This stage highlights the important role of moisture variations in determining the performance of the base layer and the critical thresholds at which soil stability can be impaired due to traffic loads.

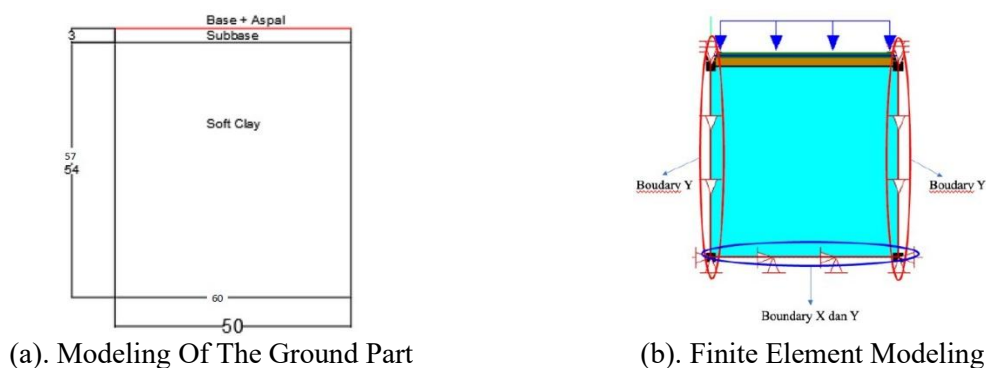


Figure 2. Stages Of Modeling

Displacement

Displacement analysis was performed to evaluate the vertical deformation of soft clay layers under different water content conditions. Numerical models show that the addition of water does not significantly change the subsidence value of the base layer. This shows that within the range of simulated water content variations (19%, 36%, and 53%), the soil achieves a relatively stable deformation response after being subjected to the applied load.

1) shift in the addition of water by 19%

In the initial scenario with the addition of water by 19%, the vertical displacement reached 0.204682 mm. The deformation pattern is relatively small and concentrated around the area subjected to the load, indicating that the soil remains stable at this moisture level.

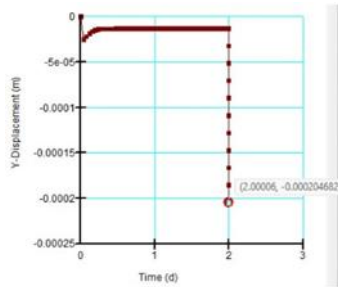


Figure 3. Shift In The Addition Of Water By 19%

- 2) the shift in the addition of water by 36%

In the second scenario, when the water content was increased to 36%, the displacement value was recorded at 0.204637 mm. The pattern of soil subsidence is similar to the first scenario, with a very small difference in magnitude, indicating that the addition of water does not significantly affect soil compressibility.

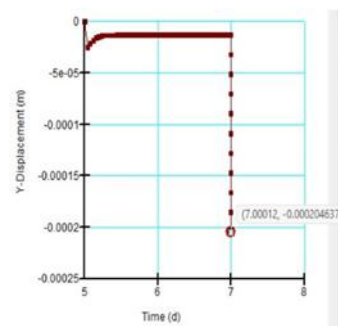


Figure 4. Shift In The Addition Of Water By 36%

- 3) shift in the addition of water by 53%

At a maximum water content of 53%, the shift remains almost constant at 0.204637 mm. This suggests that the soil has achieved a stable response in terms of deformation, and a further increase in moisture does not lead to additional shifts.

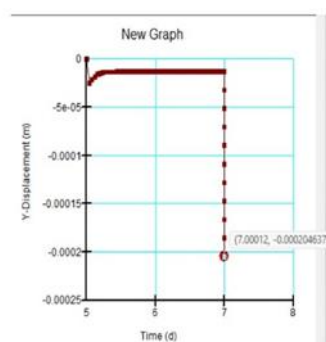


Figure 5. Shift In The Addition Of Water By 53%

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

Chart 1. Summary Of Shifts Due To Water Addition

No.	Addition Of Water (%)	Shift (mm)
1	19	0,204682
2	36	0,204637
3	53	0,204637

Effective Voltage

1) Effective Voltage At Water Addition 19%

At a water content of 19%, the effective stress in the clay layer was measured at 10.57 kN/m². The stress distribution is relatively even, and the soil conditions show sufficient stability without signs of excessive deformation.

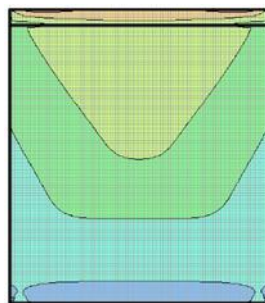


Figure 6. Effective Voltage At Water Addition 19%

2) Effective Voltage At Water Addition 36%

When the water content is increased to 36%, the effective stress changes slightly to 11.23 kN/m². Despite the increased pore pressure, the soil is still able to effectively distribute the stress, so the overall stability conditions remain similar to the first scenario.

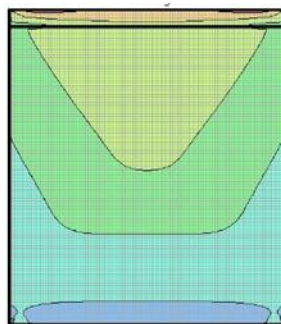


Figure 7. Effective Voltage At Water Addition 36%

3) Effective Voltage At Addition Of Water 53%

At a maximum water content of 53%, the effective stress remains at 11.54 kN/m². The results showed that despite the higher saturation level, the ground stress response was stable, and no significant variation in effective stress occurred compared to the previous stage.

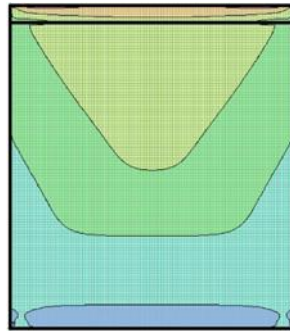


Figure 8. Effective Voltage At Water Addition 53%

A summary of the effective stress values for the three infiltration scenarios is presented in Table 2, which provides a comparison of soil stress responses under varying water content conditions.

Chart 2. Recapitulation Of Water Addition At Effective Stress

No.	Addition Of Water (%)	Effective Voltage (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% produces only a very small change in the effective voltage. This suggests that under the modeled conditions, soils exhibit a relatively stable stress-strain response despite variations in water infiltration.

CONCLUSIONS

The results of numerical analysis using the finite element method showed that an increase in water content from 19% to 53% led to a gradual increase in effective stress, ranging from 10.57 kN/m² at 19% to 11.54 kN/m² at 53%. This suggests that higher saturation levels cause a mild increase in soil stress due to pore pressure redistribution. On the other hand, displacement remained almost constant in all scenarios, with depreciation values of 0.204682 mm at 19% and 0.204637 mm at 36% and 53%. These findings suggest that although variations in water content affect effective stress in clay layers, they do not significantly affect soil deformation under given modeling conditions. Overall, these results show that the soft clay layer retains adequate resistance to additional subsidence despite increased moisture levels, providing useful insight into the performance of flexible pavement over soft soils.

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