A Finite Element Framework for Designing Unreinforced Unpaved Roads

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Abstract. Traditional design practice of unpaved roads mostly considers the subgrade layer to be purely cohesive such as in soft marshy lands. However, a huge bulk of Indian sub-urban and rural unpaved roads rest on *c*-*φ* soil subgrade soil whose strength characteristics are contributed both by cohesion (*c*) and angle of internal friction (*φ*). Conventional methods of utilizing analytical expressions for arriving at the thickness of aggregate layer are affected by the semi-empirical assumptions. Further, these methods do not consider any deformation scenario when such unreinforced unpaved roads are subjected to quasi-static vehicular loading. Furthermore, it is idealistically assumed that the individual components (aggregate and subgrade) would not undergo failure under the transfer of stress generated by surface loads. To overcome these constraints, a finite-element (FE) based design methodology is proposed to model unreinforced unpaved road resting on *c*-*φ* soil subjected to a typical combination of axle loads and tire pressures. Considering the individual failure of the subgrade and aggregate under construction and vehicular load respectively, a step-by-step design guideline is developed to assess the minimum shear strength parameters of the individual components required to prevent failure considering coupled stress-deformation effects.

Keywords: Unreinforced Unpaved Roads, Finite-Element Framework, Stress-Deformation Analysis, Design Procedure, Component Failure, Aggregate Layer Thickness.

1 Introduction

India is a developing country; with a second largest road network in the world. With rapid urbanization the roads are being paved every year. However, a large portion of the country is still unpaved. Unpaved roads are quite common across the vast rural parts of India's landscape. Unpaved roads are easy to construct, require less material compared to paved roads and very economical. Although unpaved roads have many advantages proper design methodology still limited. Conventional construction practice of unpaved roads is limited to either replacing the unsuitable soils or bypassing them with costly foundations of embankments dug to greater depths. Earlier researchers have proposed different design considerations, however they considered the subgrade comprising soft clayey or peaty soil in order to accommodate the worst-scenario undrained analysis, and hence, only undrained cohesion of the subgrade has been used to develop the design charts. Undrained condition prevails for the instant time when the vehicle passes over the saturated subgrade. That ultimately leads to overestimated magnitudes of aggregate thickness which might not be practically required owing to inherent subgrade strength. In real field scenario, soil subgrade has both cohesion and angle of internal friction as the strength parameters. In this study, an attempt has been made to design the thickness of unpaved road for *c*-*φ* soil subgrade. Analytical formulations are developed for first hand idea of designing the unpaved roads. Further using those formulations, a Finite Element (FE) based design methodology is proposed to find out the minimum strength required by aggregate and subgrade so that they may remain stable under all operational conditions.

2 Quasi-static Analysis of Unpaved road

In the present study, analytical formulations are developed to determine the thickness of unpaved roads using the conventional approach by Giroud and Noiray (1981), for a more generalized subgrade (*c*-*φ* soil subgrade) encountered more frequently in field. The aggregate layer performs as a stress distribution mechanism and hence has been assumed mechanically stable. The analysis follows limit equilibrium (LEM) approach to account for the distribution of vehicular load through aggregate to the aggregate-subgrade interface.

Dual wheels truck is considered as vehicular loading since they are more common. The axle load *P* is considered to be evenly distributed among the 4 wheels. In the analytical formulations, the contact area between two tires is considered to be a rectangle as shown in Figure 1a.

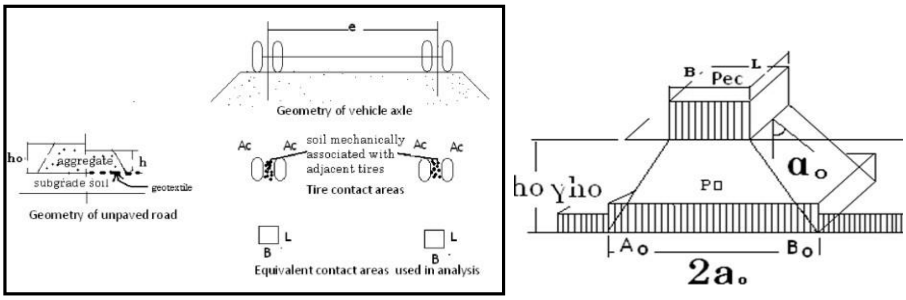

Fig. 1. (a) Geometry of unpaved roads, vehicle axle and contact area (b) Load distribution by aggregate layer on the subgrade soil [Adopted from Giroud and Noiray (1981)]

2.1 Load distribution mechanism through aggregate layer

The stresses coming from the wheels are considered to be distributed pyramidically through the aggregate layer to the surface of the subgrade layer as shown by Figure 1b. Equation 1 gives the final expression of the stress accumulated on the surface of subgrade layer.

$$P_0 = 0.5P\,[(B + 2h_0 \tan \alpha_0)\,(L + 2h_0 \tan \alpha_0)] + \gamma h_0 \qquad (1)$$

where, γ is the unit weight of the soil and aggregate (considered to be the same), P is the axle load, P_0 is the stress generated at the aggregate-subgrade interface, B and L are the dimensions of the equivalent tire imprint, h_0 is the thickness of the aggregate, and α_0 is the load-distribution angle.

2.2 Bearing Capacity of the Subgrade soil

Analytical formulations used the allowable bearing capacity (q_{all}) derived by Terzaghi (1943) for c-φ soil subgrade, which is expressed as:

$$q_{all} = (cN_c + \gamma h_0 N_q + 0.5\gamma B^{/} N_\gamma)/FoS \qquad (2)$$

where, γh_0 is the overburden pressure on the soil due to aggregate layer, FoS is the factor of safety, $B^{/}$ is the width of the distributed soil after load spreading, and N_c, N_q, N_γ are Terzaghi's bearing capacity factors for shallow foundations.

2.3 Determination of thickness of unpaved road

For safe design of unpaved roads, the maximum pressure on the subgrade soil should be less than or equal to the allowable bearing capacity of the subgrade (Equation 3).

$$0.5P/[(B + 2h_0 \tan \alpha_0)\,(L + 2h_0 \tan \alpha_0)] + \gamma h_0 = (cN_c + \gamma D N_q + 0.5\gamma B^{/} N_\gamma)/FoS \qquad (3)$$

The above equation gives the final expression for design thickness (h_0) of unpaved roads for c-φ soil subgrade under a particular axle load combination.

3 Finite element Modeling

Theoretical expressions developed in the previous section follows limit equilibrium approach to model unpaved roads for generalized subgrade (*c*-*φ* soil subgrade) encountered more frequently in field conditions. However, LEM approach has its demerit when it comes to complicated problems involving to many parameters. As LEM approach does not consider deformation scenario, the system is considered to be a rigid structure; however, in reality both subgrade and aggregate undergoes deformation. Although theoretical approach gives a conservative solution to the problem, a reliable alternative approach is required to understand real field scenario. For this, finite element analysis is carried out using PLAXIS 2D v2018 as an approach to determine the stresses and strain generated in the unpaved road system.

3.1 Model Description

Two layered unpaved road system is represented through a plane-strain system, wherein the aggregate layer is placed suitably over the subgrade layer. 15-noded triangular elements are used to model soil layers to produce higher precision results. Suitable boundary conditions are provided around the soil layer with vertical and horizontal fixities at the bottom boundary of subgrade and only horizontal fixities along vertical boundaries. Mohr-Coulomb material model characteristics are used to portray the constitutive behavior of the subgrade soil and aggregate layer and account for the permanent deformations. Aggregate layer has a uniform side slope of 3H:1V to avoid any unwarranted slope failure. On the surface of aggregate layer, uniformly distributed vehicular load is applied under tires over suitable contact width and spread over a chosen axle width. The unpaved road model is discretized into meshes by setting the global element distribution to 'Medium' with relative element size value is set to '1'. Further, in critical areas, such as the aggregate-subgrade interface, loading points and at the embankment corners, local mesh refinement is also provided. Figure 2 shows the typical geometry of unpaved road model for a typical axle load combination. Various model parameters for the subgrade and the aggregate layer used in the present study are shown in Table 1.

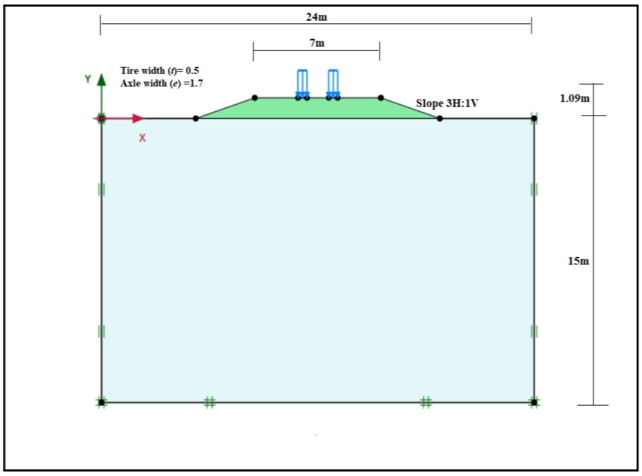

Fig. 2. FE model of a typical unreinforced unpaved road section

Table 1. Material properties used in the present study

	Subgrade	**Aggregate**
Soil model	Mohr-Coulomb	Mohr-Coulomb
Unit weight (γ)	19 kN/m^3	19 kN/m^3
Elastic modulus (E)	20 MPa	6 MPa
Poisson's ratio (ν)	0.4	0.3
Initial void ratio (e_{int})	0.5	0.1

3.2 Critical/Limiting Failure Conditions

While modeling the unpaved road system in Plaxis 2D using the c and φ parameters used in the analytical expressions, the model undergoes a failure either in soft subgrade layer or in the aggregate layer. Separate expressions have been developed to determine the minimum shear strength parameters required individually by the subgrade and aggregate so as their stability is ensured under aggregate loading and under vehicle loading.

Minimum strength equation for subgrade ($c_{s,min}$). The minimum strength of subgrade strength has been developed by equating the aggregate load ($\gamma_s h_0$) to the allowable bearing capacity of the soft subgrade (following Terzaghi's bearing capacity formulation for shallow foundations) for a particular value of factor of safety without any vehicular loading.

$$\gamma h_0 = (c_{s,min}N_c + 0.5\gamma B_a N_\gamma)/FoS \quad (4)$$

where, $c_{s,min}$ is the minimum cohesion required in subgrade to sustain operational aggregate loading, and B_a is the width of aggregate layer (equal to the road width). Solution of the Equation 4 would provide the minimum cohesion required in the subgrade to sustain the aggregate load during the construction of the aggregate layer itself.

Minimum strength equation for aggregate ($c_{a,min}$). For aggregate not to fail under vehicular loading, the stress intensity under the tire should be less than or equal to the allowable bearing capacity of the aggregate alone, as expressed through Equation 5:

$$P/2BL = (c_{a,min}N_c + 0.5\gamma B N_\gamma)/FoS \quad (5)$$

where, $c_{a,min}$ is the minimum cohesion required in aggregate. Solution of Equation 5 provides the minimum cohesion required in the aggregate layer to avoid punching shear failure under the action of wheel loads.

4 Results and Discussion

A step by step PLAXIS FE based modeling and analysis is carried out for unreinforced unpaved roads. Using the equations formulated in the previous section, minimum shear strength parameters $c_{s,min}$ and $c_{a,min}$ required individually by the subgrade and aggregate is found out to ensure stability under operational conditions. For this particular analysis, vehicular axle load (*P*) of 30 kN and tire pressure (P_c) of 600 kPa is applied on the aggregate layer. The strength parameters (cohesion, c_{soil}, and angle of internal friction, φ_{soil}) of subgrade were considered to be are 1 kPa and 5° respectively. A relatively stronger aggregate layer of cohesion (c_{agg}) and angle of internal friction (φ_{agg}) 0.0001 kPa and 35° respectively is chosen for the analysis. Following are the steps used for this particular analysis with their output results.

Step 1. [Determination of aggregate thickness]: At first, aggregate thickness (h_0) is determined using Equation 3 developed in analytical formulations and it is found to be 0.98 m.

Step 2. [Development of PLAXIS FE model]: Using the material properties provided in Table 1, PLAXIS 2D model is developed under aggregate loading with side slopes 3H:1V (Figure 3).

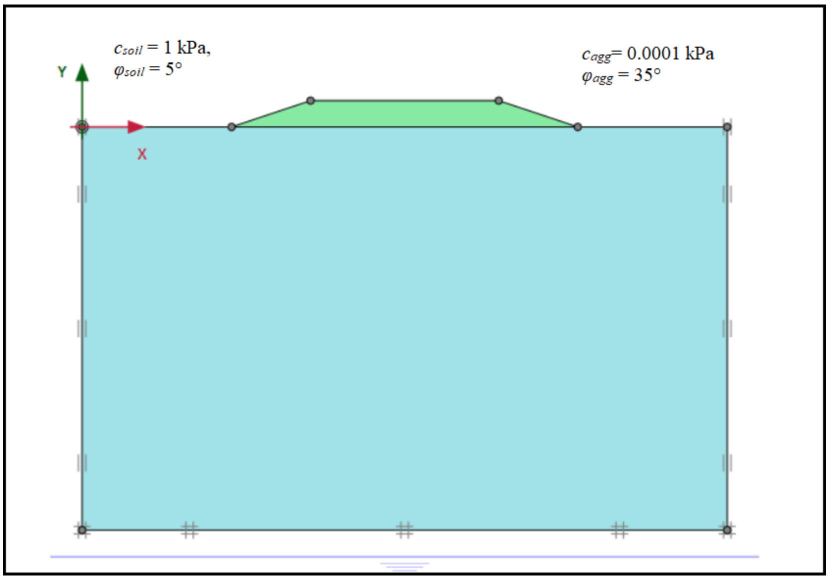

Fig. 3. Finite element model of unreinforced unpaved road under aggregate loading

Step 3 [Analysis of the developed model under aggregate loading]: The model developed in Step 2 is analyzed under aggregate loading. It is found that the subgrade fails under aggregate loading. It can be seen from the total deviatoric strain (Figure 4) diagram that a significant strain accumulation takes place in the aggregate and the subgrade. From the incremental deviatoric strain diagram, it can be noted that the failure line is developed from the top of aggregate layer, and then passes through interface and to the subgrade. Therefore, the strength of the subgrade used from the analytical study is not enough to stabilize the model.

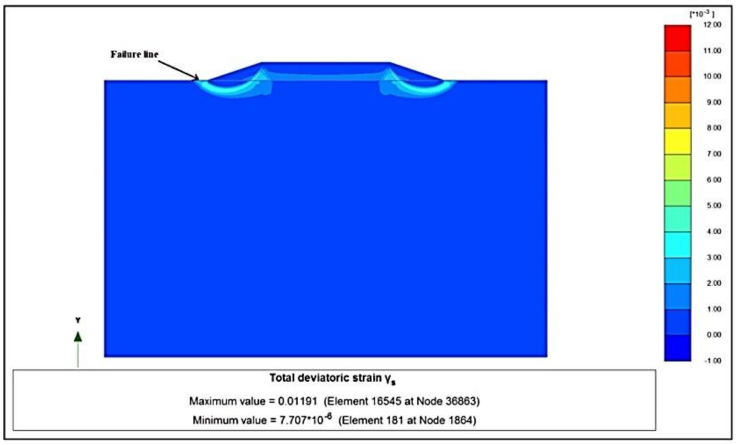

Fig. 4. Total deviatoric strain diagram in subgrade subjected to aggregate loading considering basic parametric set as obtained from analytical modeling

Step 4. [Determination of $c_{s,min}$]: In this step, strength of the subgrade is altered and the minimum cohesion required to achieve the desired strength is established using Equation 4. The new cohesion of subgrade obtained is designated as $c_{s,min}$ and the value obtained is 3.65 kPa, which is more than the previous value of c_{soil} = 1 kPa.

Step 5 [Use of $c_{s,min}$]: The modified subgrade cohesion value $c_{s,min}$,, obtained in the previous step, is further used in the model developed in Step 2. It is found that the aggregate-subgrade system did not show failure under this circumstance. The output results show that the strains are well captured and restricted within the aggregate layer as shown in Figure 5.

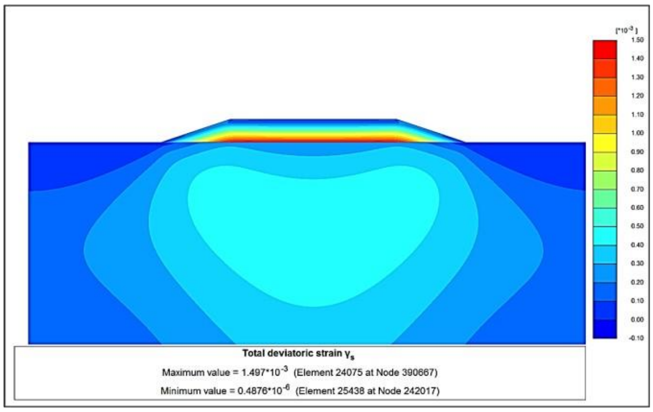

Fig. 5. Total deviatoric strain diagram in subgrade subjected to aggregate loading considering the improved strength parameter of subgrade

Step 6 [Introduction of vehicular load]: In the next step, vehicular load is applied on the modified subgrade-aggregate unpaved road system as shown in Figure 6. An axle load (P) = 30 kN with tire pressure (P_c) = 600 kPa is applied on the aggregate layer and it is found that the system exhibited failure.

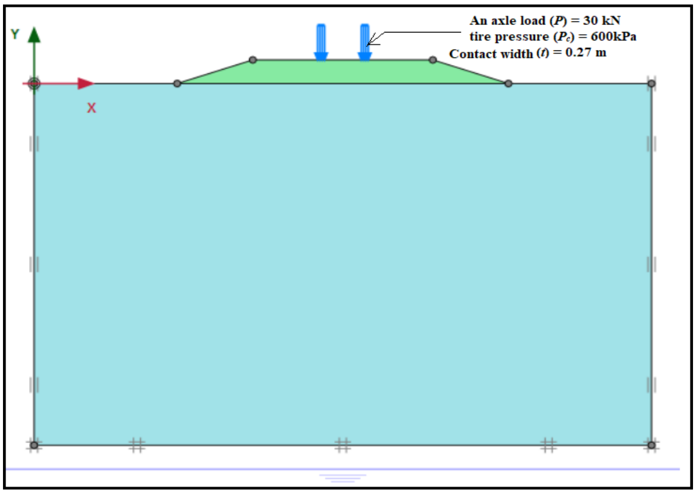

Fig. 6. FE model of unreinforced unpaved road subjected to vehicular load

Figure 7 shows the total deviatoric strain diagram due to the wheel load applications and it is observed that the strains are heavily concentrated near the surface of aggregate at the edges of the wheel loads. The maximum strain is present directly below the wheel, which is an indication of punching shear failure mechanism, and its value is approximately 0.2143 (i.e. 21.43%). Hence, there is a necessity to improve the aggregate strength in order to bear the wheel stresses.

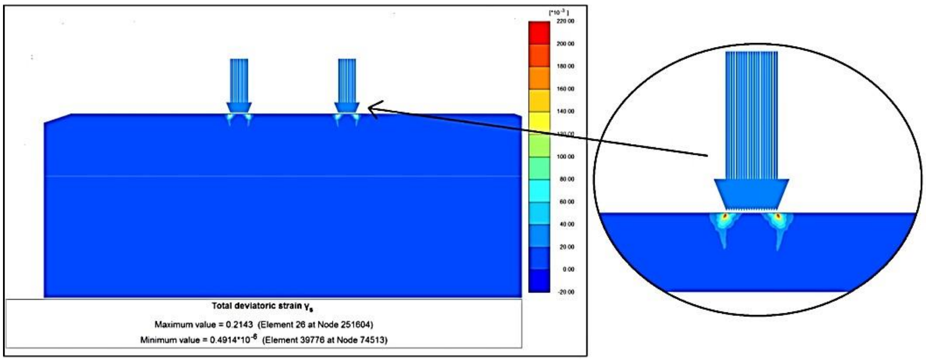

Fig. 7. Total deviatoric strain diagram in the aggregate layer of unpaved road with basic strength parameters of aggregate layer and subjected to vehicular load

Step 7 [Determination of $c_{a,min}$]: As understood from the previous step, failure of the model is fully confined in the aggregate layer. Therefore, the strength of aggregate layer needs to be improved to avoid failure. The modified strength value of cohesion required ($c_{a,min}$) in the aggregate is determined from Equation 5, and it is found to have a value of 12.77 kPa.

Step 8 [Use of $c_{a,min}$]: The model developed in Step 6 is further analysed with modified cohesion value of aggregate layer. The output results show that the system remains stable under the new strength parameter of the aggregate. The total deviatoric strain diagram (Figure 8) clearly shows that the strains are distributed evenly to a larger area, successively from wheel to aggregate and then to the subgrade. The maximum strain developed is almost 30 times less than the maximum strain value obtained in Step 6.

It can be concluded that the cohesive strength values obtained in Step 4 and Step 7 are the minimum strength parameters for safe design of unpaved road for an axle load 30 kN and tire pressure of 600 kPa.

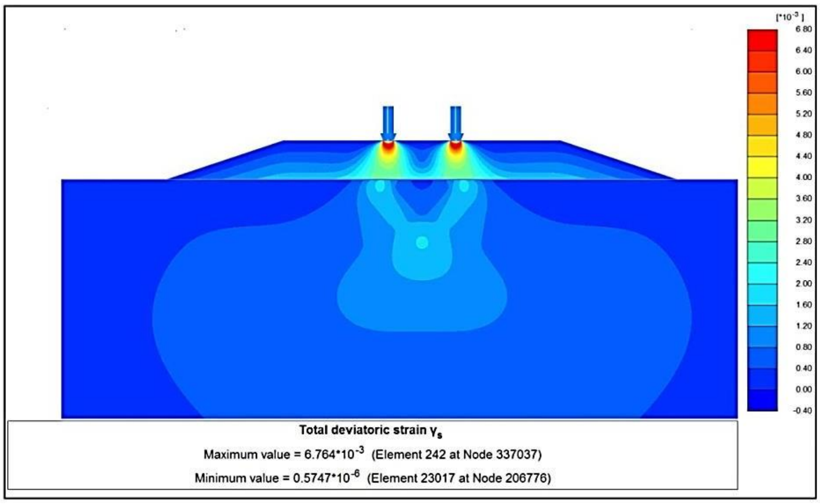

Fig.9. Total deviatoric strain diagram of subgrade subjected to vehicle loading considering the improved strength parameter of aggregate

5 Conclusion

Existing analytical studies consider undrained cohesion as the strength parameter for designing unpaved roads. However, this leads to the overestimation of aggregate layer thickness, thereby eventually increases project cost involved in laying of aggregate layer. New analytical formulations were developed to determine the aggregate thickness for unpaved roads for *c-φ* soil subgrade. However, the analytical solutions considered the system to be rigid, which means subgrade does not fail under aggregate loading or the aggregate does not fail under applied wheel loading. However, unpaved road on weak subgrade should get deformed; therefore, the strength of subgrade and aggregate used in analytical expression might not be sufficient enough to stabilize the system. Therefore, finite element analysis is carried out to assess the response of unreinforced unpaved road resting on weak subgrade soil. A design methodology is proposed to find the minimum strength parameters required by the subgrade and aggregate during construction and vehicular loading. The newly developed FE based design methodology proves to be effective in arresting the deformation based failure generated in the system under the operational conditions of aggregate loading and wheel loading.

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