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Quasi-Static Analysis of Geotextile Reinforced Unpaved Road Resting on $c$-$\phi$ Subgrade

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Abstract

This article provides an estimate of the aggregate thickness required for unpaved roads resting on $c$-$\phi$ soil. Conventional practice of design 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 $c$-$\phi$ soil subgrade soil whose strength characteristics are contributed both by cohesion ($c$) and angle of internal friction ($\phi$). It is imperative that if cohesion is considered as the sole strength criterion, it will provide lower bearing resistance, and hence, will overestimate the aggregate thickness required, which will eventually lead to undesirable increase in the overall project cost. In this regard, this article reports the result of an attempt made to identify the diminution in the required aggregate thickness of the unpaved road when both the strength characteristics of the subgrade soil are taken into account. Utility of a single geotextile layer beneath the aggregate has also been investigated towards further reduction of the required aggregate thickness. Incorporating bearing capacity estimation of the $c$-$\phi$ soil, necessary expressions have been developed for estimating the required aggregate thickness as a function of the axle load, tire inflation pressure, cohesion and angle of internal friction of subgrade soil, angle of internal friction and load distribution angle of the aggregate. Extended ranges of the aforementioned parameters, as suitable in Indian context, have been considered and the effect of the same, in the absence and presence of geotextiles, has been reported. Efficacy of the geotextiles has been elucidated in terms of the degree of improvement represented as reduction of aggregate thickness. Encouraging improvement up to the level of 70% has been observed in many instances.

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1. Introduction

As per the Central Intelligence Agency (CIA) world fact-book published in 2012, India has a road network of over 4,245,429 kilometers, and ranks third in the world. Qualitatively, Indian roads are a mix of modern paved highways and narrow, unpaved roads. As per the 2008 survey by the Ministry of Road Transport and Highways (MoRTH), nearly 48% of the total road network still belongs to the category of unpaved roads. Unpaved roads (including haul roads and access roads) are categorized as those where sand or stone aggregate are placed directly over the local soil subgrade without immediate application of any permanent surfacing such as given for an asphalt or concrete pavement. With the constant passage of traffic over such roads, settlement and subsequent rutting triggers its deterioration over time.

Nomenclature

| Symbol | Definition |
|--------|------------|
| $A_c$  | Tire contact area |
| $B'$   | Enhanced imprint of tire width after load distribution |
| $B, L$ | Dimensions of tire imprints in contact with soil |
| $c$    | Cohesion of subgrade soil |
| $h$    | Thickness of aggregate required with geotextile |
| $h_0$  | Thickness of aggregate required without geotextile |
| $N_c, N_q, N_f$ | Terzaghi’s bearing capacity factors |
| $P$    | Axle load |
| $p_0, p$ | Stresses generated at the aggregate-subgrade interface without and with geotextile |
| $P_e$  | Tire inflation pressure |
| $P_{cc}$ | Equivalent tire contact pressure |
| $\alpha_0, \alpha$ | Load-dispersion angle without and with geotextile |
| $\gamma$ | Unit weight of aggregate and subgrade soil |
| $\sigma$ | Incumbent stress on any section of subgrade |
| $\tau$ | Shear stress developed on any section of subgrade |
| $\varphi$ | Angle of internal friction of subgrade soil |
| $\varphi_{agg}$ | Angle of internal friction of aggregate |

The application of geotextiles for the maintenance of unpaved roads has been initiated in the late 1970s. Based on the experimental investigations by Barenberg (1980), Giroud and Noiray (1981) proposed a theoretical quasi-static model to establish the utility of geotextile in reduction of the thickness of the aggregate layer to be used over the natural subgrade. Governed by the threshold rut depth, parametric studies highlighted the effects of the subgrade strength, axle load, tire pressure, tensile strength of the geotextile and number of vehicle passes. Design charts have for practicing engineers considering different rut depths, tire pressures and axle loads had been provided. Holtz and Sivakugan (1987) extended the design charts for few other rut depths to study its effect on the functionality of the geotextile reinforcement. It was observed that for smaller rut depths, the effect of the
reinforcement is negligible. The effect is more pronounced for the cases where the rut depth is higher due to proper mobilization of membrane tension (Houlsby and Jewell, 1990). Instead of the rut depth, Douglas and Valsangkar (1992) proposed to use the stiffness of the road as the key design criterion. The efficiency of geogrids has also been assessed in terms of better reinforcement action due to the mobilization of the passive packing strength (Elias and Meyer, 1999; Giroud and Han, 2004a, b; Giroud 2009). Laboratory experiments have also been conducted to comprehend the effect of geotextile as a reinforcing material in terms of enhancement of the load-capacity of the subgrade (Som and Sahu, 1999). Hawkins (2008) provided a treatise on a 35 year long case-history showing the effect of durability of eight different geotextile separators.

All the earlier researches have been carried out considering the subgrade to be a 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. However, depending on the degree of saturation and permeability of the subgrade, the state of drainage can vary (undrained, partially drained or fully drained). Different drainage state governs the choice of the subgrade strength parameters (effective or undrained strength parameters) and their magnitudes. Mostly, the subgrade is a \( c-\phi \) soil characterized by both cohesion and angle of internal friction as the strength parameters. Thus, application of the conventional design charts (with or without geotextile) in such conditions inevitably lead to over-estimated magnitudes of aggregate thickness which might not be practically required owing to inherent subgrade strength. Hence, it is necessary to extend or modify the established convention and develop new design charts for generalized subgrade, wherein the conventional scenario can be considered as a degenerated condition. This attempt would help in achieving a proper safe and economic design of unpaved roads.

Such an attempt has been made wherein the soil is considered to be a general \( c-\phi \) soil and estimates of the required aggregate thickness have been determined for several combinations of the contributory parameters. The basic model proposed by Giroud and Noiray (1981) have been modified to take into account the internal friction angle of subgrade soil in estimating its bearing resistance which revealed a substantial reduction in the aggregate thickness. Detailed parametric study helped in identification of the influence and sensitivity of the various contributory parameters. Tire inflation pressure and the angle of internal friction of the aggregate have been found to provide marginal influence on the required aggregate thickness while rut depth has been found to be the key consideration. Explicit design charts have been developed for several possible combination of various parameters based on the Indian soil and Indian traffic characteristics. A limitation/anomaly, in the analysis by Giroud and Noiray (1981), pertaining to the deformed shape of the geotextile under the action of the traffic load has been identified. It has been observed that the deformed shape of geotextile is governed by the thickness of aggregate itself, and in all cases, do not pertain to the shape as assumed by Giroud and Noiray (1981). This, in turn, will result in a different formulation of the governing equations. This issue needs further inspection, and hence, the present article does not provide a detailed treatise of the same.

2. Quasi-static Analysis of Unpaved Roads

Unpaved roads are usually temporary roads built over soft, weak subgrade with base aggregates placed directly above it, and hence, are prone to the problems of rutting and mud-pumping especially under saturated conditions. The aggregate cover on the subgrade is primarily meant for passage of traffic with lessened hindrance. The aggregate behaves as a load-dispersion mechanism and result in the reduction of the stresses, generated due to vehicular load, incumbent on the subgrade. Although traffic passage is a problem of moving loads, the analysis is simplified on the basis of considering the maximum axle load to be static at one location, and hence, the consideration of ‘quasi-static analysis’. Stress transferred by the moving loads, being instantaneous, is actually lower than that of a static mechanism, and hence, the quasi-static analysis represents a worst-case scenario when
the vehicle is static, and the axle load is fully transferred to the subgrade. For the present study, the subgrade has been considered as a $c$-$\phi$ soil, and under any incumbent stress ($\sigma$), the shear stress ($\tau$) of the same is expressed as:

$$\tau = c + \sigma \tan \phi \quad (1)$$

The shear stress generated should not exceed the allowable bearing capacity of the subgrade soil ($q_{all}$) which can be expressed using Terzaghi’s proposition (1943) as:

$$q_{all} = \left( cN_c + \gamma h_0 N_q + 0.5\gamma B' N_r \right) / FoS \quad (2)$$

where, $\gamma$ is the overburden due to the aggregate layer overlying the subgrade, $B'$ is the enhanced tire-width after load distribution (to be explained later), and $FoS$ is the factor of safety used to obtain allowable load. The bearing capacity factors are dependent on the angle of internal friction of the subgrade, and are expressed as:

$$N_q = e^{2(3\pi/4-\phi/2)} \left[ 2 \cos \left( \pi/4 + \phi/2 \right) \right], N_r = 2 \left( N_q + 1 \right) \tan \phi, N_c = \left( N_q - 1 \right) \cot \phi \quad (3)$$

2.1. Axle load on an unpaved road and load distribution

Total load from any vehicle on the road can be replaced by an equivalent single axle load. Dual wheels are considered because they are more common than single wheels for cargo vehicles, and the equivalent single axle load ($P$) is considered to be evenly distributed among the 4 wheels as shown in Figure 1. The axle load can be represented in terms of the contact areas of tires ($A_c$) and the tire inflation pressures ($P_c$). The soil between the tires of a dual wheel is mechanically associated with the tires (Figure 1) and it is assumed that no failure of the aggregate layer and subgrade soil can occur between the tires. Hence, the same can be represented as an equivalent rectangular contact area of size $L \times B$. An equivalent uniformly distributed contact pressure ($P_{ec}$) is assumed which should produce the same mechanical effect in the subgrade as that by the actual contact pressure (non-uniformly distributed) between each tire and aggregate.

![Fig. 1. Geometry of unpaved road, vehicle axle loads and contact areas (Giroud and Noiray, 1981)](image)

Based on the examination of typical dual tire prints, for on-highway and off-highway trucks respectively, Giroud and Noiray (1981) proposed the equivalent contact dimension of the tires as follows:

$$L = B/\sqrt{2} \quad \text{and} \quad L = B/2 \quad (4)$$

$$B = \sqrt{P/P_c} \quad \text{and} \quad B = \sqrt{P/\left( P_c \sqrt{2} \right)} \quad (5)$$

The same has been adopted for the present study.

2.2. Load distributed due to aggregate layer on subgrade soil

The aggregate layer is assumed to provide a pyramidal dispersion of equivalent contact stress applied on its
surface due to the vehicular load (Figure 2). The load-dispersion angle \( \alpha_0 \) is expressed as (Giroud and Noiray, 1981):

\[
\alpha_0 = \alpha = \frac{\pi}{4} - \frac{\phi_{agg}}{2}
\]  

(6)

With and without a geotextile layer at the aggregate-subgrade interface, the stresses generated due to load distribution and aggregate overburden is denoted as \( p \) and \( p_0 \) respectively, and the aggregate thicknesses are demarcated as \( h \) and \( h_0 \) respectively. Based on the force equilibrium, the stresses generated at the aggregate-subgrade interface for both the conditions can be expressed as:

\[
p_0 = P/[(B + 2h_0 \tan \alpha_0)(L + 2h_0 \tan \alpha_0)] + \gamma h_0 \quad \text{...without geotextile}
\]

(7)

\[
p = P/[(B + 2h \tan \alpha)(L + 2h \tan \alpha)] + \gamma h \quad \text{...with geotextile}
\]

(8)

3. Design of Unpaved Road without Geotextile

For all practical purpose, the design of an unpaved road without geotextile should satisfy the following criterion: The maximum pressure on the subgrade soil should be less than or equal to the allowable bearing capacity of the subgrade. As a limiting condition, it should never exceed the ultimate bearing capacity of the subgrade stratum. The equilibrium criterion can be mathematically represented as:

\[
\frac{cN_c + \gamma h_0 N_q + 0.5\gamma(B + 2h_0 \tan \alpha_0)N_y}{FoS} = \frac{P}{(B + 2h_0 \tan \alpha_0)(L + 2h_0 \tan \alpha_0)} + \gamma h_0
\]

(9)

The above equation is expressed in a polynomial form as

\[
C_1h_0^3 + C_2h_0^2 + C_3h_0 + C_4 = 0
\]

(10)

where, the coefficients of the polynomial expression are defined as:

\[
C_1 = 4\gamma \tan^2 \alpha_0 \left[ N_y \tan \alpha_0 + N_q - FOS \right]
\]

\[
C_2 = 2 \tan \alpha_0 \left[ \{N_y \tan \alpha_0 + N_q - FOS \} \gamma (L + B) + \left( \gamma BN_y + 2cN_c \right) \tan \alpha_0 \right]
\]

\[
C_3 = \gamma LB \left[ N_y \tan \alpha_0 + N_q - FOS \right] + (L + B) \tan \alpha_0 \left( \gamma BN_y + 2cN_c \right)
\]

\[
C_4 = \frac{P.FOS}{2} + cN_c LB + 0.5\gamma LB^2 N_y
\]

(11)

Fig. 2. Load distribution by aggregate layer on the subgrade soil (a) Without geotextile (b) With geotextile
Solution of the above expressions will yield the estimate of the required thickness of aggregate layer for an unpaved road resting on \( c-\varphi \) subgrade in the absence of a geotextile layer.

4. Design of Unpaved Road with Geotextile

The subgrade soil is considered to be incompressible and as a result, the settlement under the wheels causes heave between and beyond the wheels, and thus, causing the geotextile to attain a stretched wavy shape (Figure 3). This phenomenon induces ‘membrane effect’ as a result of which, between the wheels (BB in Figure 3) and beyond the wheels (AC in Figure 3), although to a lesser extent, the pressure applied by the geotextile on the subgrade soil is higher than the pressure applied by the aggregate layer on the geotextile; whereas, under the wheels (AB in Figure 3), the pressure applied by the geotextile on the subgrade soil is smaller than the pressure applied by the wheels plus the aggregate layer on the geotextile (Giroud and Noiray, 1981).

The pressure applied by the wheels and aggregate layer on the portion AB of the geotextile (\( p \)) is given by Equation 8. Due to the reduction of pressure by the use of geotextile (\( p_g \)), the pressure transferred to the subgrade soil by the portion AB of the geotextile (\( p^* \)) is expressed as

\[
p^* = p - p_g
\]

(12)

Since the confinement of the subgrade soil provided by the geotextile keeps the deflection to small magnitudes for all applied pressures less than the ultimate bearing capacity, the pressure \( p^* \) can be as large as the ultimate bearing capacity of the subgrade soil, which is expressed as:

\[
p^* = \frac{P}{2(B+2h\tan\alpha)(L+2h\tan\alpha)} + \gamma h - p_g = cN_c + \gamma h N_q + 0.5\gamma(B+2h\tan\alpha)N_y
\]

(13)

The reduction of pressure due to the use of geotextile is expressed as:

\[
p_g = K\varepsilon \sqrt{1 + \left(\frac{a}{2s}\right)^2}, \quad a = \frac{(B+2h\tan\alpha)}{2}
\]

(14)

where, \( K \) is the tension-elongation modulus of geotextile, \( \varepsilon \) is the elongation of geotextile, and \( s \) is a function of the rut depth (\( r \)) used in the design. The details of the derivation of the above expression can be obtained from Giroud and Noiray (1981). Solution of equation 13 results in the estimation of the aggregate thickness (\( h \)) required when a single layer of geotextile is used at the aggregate-subgrade interface.
5. Results and Discussions

Based on above theoretical background, modular MATLAB codes have been developed to compute the required aggregate thickness for unpaved roads in the absence and presence of geotextile layer. The ranges of various parameters chosen for the present study as per the Indian traffic condition are as follows:

- Axle Load \((P)\): 30 kN – 360 kN (MORTH, GOI, 2005; IRC-37-2001)
- Tire inflation pressure \((P_c)\): 150 kPa – 750 kPa (AFJM, 1994; Khanna and Justo, 2001)
- Angle of internal friction of aggregate \((\phi_{agg})\): 25° – 35°
- Angle of internal friction of soil \((\phi)\): 0 - 50° [This range has been considered to cover the broad domain of soil characteristic that can be present from purely cohesive soil to rocky subgrade]
- Soil cohesion \((c)\): 0 – 500 kPa [This broad range covers from purely cohesionless soil to the presence of the hard clay in the subgrade]
- Unit weight of soil and aggregate \((\gamma)\): 19 kN/m³ [The unit weight of soil and aggregate has been kept same owing to the fact that the variation in unit weight for any type of soil is not significant]
- Track widths of Indian Cargo vehicles: 1.7 – 2.4m
- Tension-elongation modulus of geotextiles: 1-5000 kN/m (Giroud and Noiray, 1981)
- Factor of safety \((FOS)\): 1 – 3 [FOS =1 indicates the consideration of ultimate bearing capacity of subgrade for evaluation of the thickness of aggregate layer, while the other values of FOS considers the use of allowable bearing strength of the subgrade]

Figures 4a-f depicts the effect of various parameters on the estimated aggregate thickness of unpaved roads. Figure 4a reveals that subgrade cohesion has a significant effect on the required aggregate thickness. Soft/Poor soils with very low cohesion and angle of internal friction requires immensely thick aggregate layer, whose magnitude is substantially reduced with the increase in soil cohesion. It is observed that for a purely cohesive soil, an optimum cohesion of 30 kPa for the subgrade soil is sufficient to reduce the required aggregate thickness to practical magnitudes (<1m). Hence, it is recommended to adopt some simple subgrade modification techniques where unpaved roads are to be laid over areas having subgrade cohesion lower than 30 kPa. Application of geotextiles might prove beneficial in this regard. It is also observed that subgrade consisting of stiff clays (very high cohesion) does not necessitate the aggregate layer, owing to their inherent bearing strength.

Figure 4b depicts that an increase in axle load results in the increment of aggregate layer thickness, which is certainly obvious. Figure 4c reveals that required aggregate thickness is not significantly affected by the tire inflation pressure. A low tire inflation pressure will result in higher equivalent contact area, thus complementing each other to support the same axle load, and hence the observation.

The angle of internal friction of the aggregate governs the pyramidal load dispersion angle with an assumption of complete punching of the aggregate layer into the subgrade under high load. Hence, as per the classical definition (Equation 6), an increase in the angle of internal friction of the aggregate results in the decrement of the load-dispersion angle, thus resulting in higher magnitude of stresses transferred to the subgrade. Hence, as observed from Figure 4d, this phenomenon results in the requirement of higher aggregate thickness, although the influence on the outcome is only moderate.

Similar to the observation with increase in cohesion, Figure 4e illustrates that an increase in the angle of internal friction of the subgrade soil results in substantial reduction of the required aggregate thickness, owing to the increase in the bearing strength of the subgrade. These results, qualitatively and quantitatively, indicate that the earlier studies [Giroud and Noiray (1981), Koerner (2005)] based on purely cohesive subgrade, if used for a generalized c-\(\phi\) subgrade will lead to significantly undesirable over-estimated aggregate thickness, as it can be observed for low angle of internal friction of subgrade.

On-highway and off-highway vehicles are specifically characterized by the difference in their tire widths, type of tread, suspension and ground clearance characteristics. Their differences can be simulated in terms of
modification in the tire inflation pressure and contact area (Giroud and Noiray, 1981). Figure 4f depicts the effect of the location of the vehicle on the required aggregate thickness. The effect is being largely insignificant owing to the fact that change in the location results in only minor change in the equivalent contact area in the tires.

Figures 5a-b depicts the benefit of application of geotextiles in reducing desired aggregate thickness in terms of the tensile strength of the geotextile. A zero tensile strength signifies the absence of geotextile. Tensile strength is observed to have a significant influence on the reduction of aggregate thickness. Two typical combinations of the axle load and tire pressure is reported herein. As in Figure 5b, the efficacy of geotextile can be described in terms of degree of improvement, defined as the percentage reduction of the aggregate thickness

**Fig. 4.** Typical representations of the aggregate thickness required based on the variation of contributory parameters
with reference to the thickness required for an unreinforced unpaved road i.e. \( I_f = \left( K_i - K_0 \right) / K_0 \times 100 \). It is noted that, depending on the tensile capacity of the geotextile, significant amount of reduction in the aggregate thickness layer can be achieved. Improvement of 100% theoretically signifies that aggregate cover is not necessary. However, it is worth mentioning that the degree of improvement referred herein is solely based on the tensile strength, and hence, further studies concerning other properties of geotextile should be considered before any conclusive recommendation is made, in absence of which a nominal cover of aggregate should be provided.

![Fig. 5. Effect of tensile strength of geotextile on the aggregate thickness and degree of improvement](image)

![Fig. 6. Effect of rut depth on the aggregate thickness and degree of improvement](image)

Figure 6 reconfirms the fact that the efficiency of geotextile applied at the aggregate-subgrade interface is not actually portrayed for lower rut depths (Holtz and Sivakugan, 2005). Deformation of the geotextile increases with larger rut depth which results in the enhanced mobilization of the membrane tension in the geotextile, and hence, results in increased efficiency of the geotextile in reducing the aggregate thickness.

6. Conclusions and Future Scope

The results reported herein hints that the conventional estimates of aggregate thickness considering only the undrained cohesive property of the subgrade soil may lead to undesirable over-estimated magnitudes. Aggregates resting on the subgrade subjected to quasi-static vehicle axle loads present a condition similar to the load-distribution under a loaded strip footing, and hence the subgrade bearing resistance can be idealized using
Terzaghi’s bearing capacity theory. Results from the present study illustrated that consideration of both the strength parameters of the subgrade aids in the realistic estimation of the required aggregate thickness, leading to a more economical design. Amongst the contributory factors, the tire inflation pressure and the location of the vehicles have been found to pose a negligible effect on the aggregate thickness estimate, and hence can be discarded from further investigations. Angle of internal friction of the aggregate has moderate influence, while the axle load and subgrade strength parameters have substantial effect on the estimated aggregate thickness.

Tensile strength of the geotextile significantly affects the degree of improvement represented in terms of the reduction in the aggregate thickness, in instances, the degree of improvement theoretically can attain a magnitude of 100%. However, beneficial effect of geotextile is observed with prominence for higher rut depths which can elevate the ‘tensioned membrane’ effect of the geotextile. Extensive investigations in this respect will aid in the development of a series of design charts which can suffice as a ready-reference tool for the design engineers in two possible aspects. If the tensile strength of the available geotextile is known, then the amount of aggregate required for the construction can be determined, or if the target thickness of the layer is predetermined, proper choice of a compatible geotextile can be arrived at.

The present study reports the investigations performed with a single passage of traffic with maximum axle capacity. Further studies are to be carried out for multiple passages of vehicles which would definitely affect the aggregate thickness and might reveal the increased necessity of the geotextile inclusion. The present study has been limited to theoretical analysis. In order to check the validity of the present study, experimental works and finite element validation (using PLAXIS 2D) are required to be conducted in due course of the present research. The FE model is supposed to provide much better understanding of the distribution of stresses within the soil subgrade beneath the aggregates supported by the geotextiles. Moreover, it will also provide detailed idea about the deformation of the geotextile depending upon its location and the amount of stresses transferred to it.

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