Short Term Training Program

Innovative Approaches to Road Safety and Material Engineering (IARSME 2026)

NERIST, Arunachal Pradesh

A Novel FE-Based Framework for Designing Unpaved Roads

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Introduction

- India: Second largest road network in the world
  - ❖ **Over 42 lakh kms (CIA, 2012)**
  - ❖ **~35% unpaved roads (MoRTH, 2019)**
- Unpaved roads (includes haul roads and access roads)
  - ❖ **Sand or stone aggregate placed directly over the local soil subgrade**
  - ❖ **No permanent surfacing**
  - ❖ **Major problems due to constant passage of traffic over time**
    - Settlement
    - Rutting and surface heave
      - Both occurs due to subgrade deformation

  - ❖ **Pertinent question**
    - How much aggregate cover is required to protect the subgrade from excessive wheel stresses?

Pioneering Model: Unpaved Unreinforced Roads

- **Giroud and Noiray (1981)**
  - **Main assumption related to subgrade strength**
    - The subgrade soil is purely cohesive and saturated
      - Strength is defined in terms of the undrained cohesion of soil (c_u)
  - **Deviation from the assumption**
    - Diverse subgrade profile in India
      - Purely cohesive soil (Marine region) → *c* soils
        - Above assumption is only valid for this type of soil, and that too, if saturated
      - Purely cohesionless soils (Desert regions) → *φ* soils
      - Mixed soils (mostly predominant) → c-φ soils
    - All the above categories of soils can actually be in various degrees of saturation
      - Undrained cohesion of soil cannot be considered as subgrade strength for most of the cases

Present Model: Unpaved Unreinforced Roads

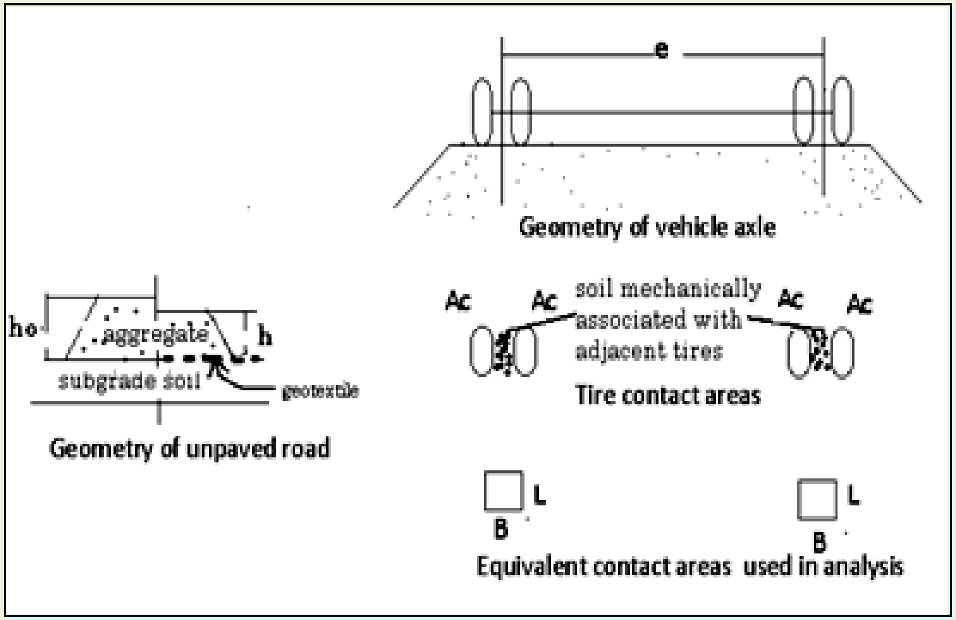
- Generalization and improvisation of the pioneering model
  - **Consider the generalized *c*-*φ* subgrade**
    - Subgrade soil strength parameters
      - Cohesion / Cohesive strength of subgrade (c)
      - Angle of internal friction of subgrade (φ)
    - The pioneering model becomes a degenerated representation of the present study
  - **What is the necessity?**
    - Designs carried out on the basis of the pioneering model for any soil
      - Over-estimated aggregate cover
        - May be substantially more than what will be actually required
      - Tend to highly uneconomical design

Unreinforced Unpaved Roads: Quasi-Static Analysis

- Total load of the vehicle
  - ❖ **Moving load is considered as a static load as if the vehicle is immobile**
    - Maximum/Full load transfer to the subgrade via aggregate
  - ❖ **Application of Equivalent Single Axle Load (ESAL - *P*)**
    - Evenly distributed among two pairs of wheels in rear axle

- *ESAL* expressed in terms of
  - ❖ **Contact areas of tires (A_c)**
  - ❖ **Tire inflation pressures (P_c)**

$$P = 4A_cP_c$$



Axle Load on an Unpaved Road: Load Distribution

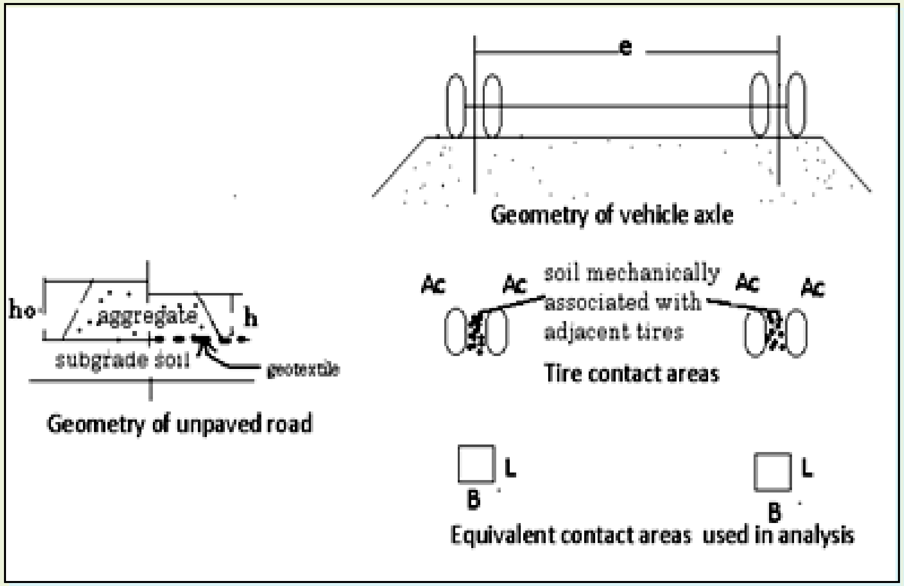
- Equivalent Contact area (L x B)
  - ❖ **2 wheels + Soil mechanically associated with the adjacent tires**

- Dual tire prints **(Giroud and Noiray, 1981)**
  - ❖ **Equivalent Contact Dimensions**
    - Off-Highway trucks

$$L = B/\sqrt{2} \qquad B = \sqrt{P/P_c}$$

    - On-Highway trucks

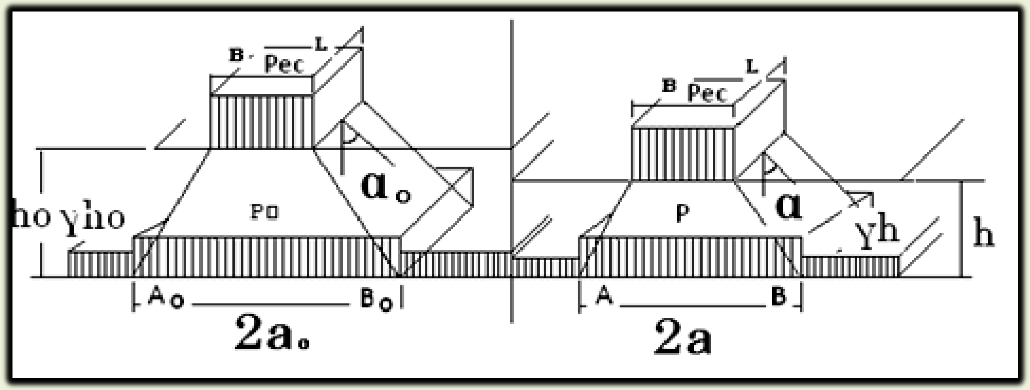
$$L = B/2 \qquad B = \sqrt{P/\left(P_c\sqrt{2}\right)}$$



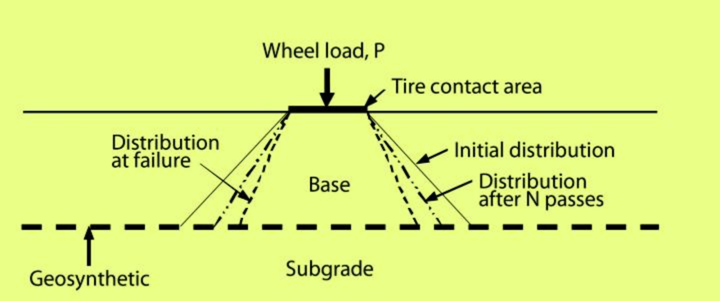
Load Dispersion by Aggregate Layer

- Load-dispersion
  - **Pyramidal**
  - **Load-dispersion angle (α_0)**

$$\alpha_0 = \alpha = \pi/4 - \phi_{agg}/2$$



- Stresses generated on the aggregate-subgrade interface
  - **With geotextile → *p*, Without geotextile → p_0**
- Aggregate thickness
  - **With geotextile → *h*, Without geotextile → h_0**



$$p_0 = P/\left[\left(B + 2h_0 \tan\alpha_0\right)\left(L + 2h_0 \tan\alpha_0\right)\right] + \gamma h_0$$

$$p = P/\left[\left(B + 2h \tan\alpha\right)\left(L + 2h \tan\alpha\right)\right] + \gamma h$$

Aggregate Layer Thickness: Estimation

- Analysis as proposed by ***Giroud and Noiray (1981)***
  - **Shear strength of the subgrade**
    - Based on undrained cohesion (including a FoS)

$$\tau = \pi c_u + \gamma h_0$$

- Stress compatible criterion $p_0 \leq \tau$

- Expression to estimate unreinforced aggregate thickness (h_0)

$$\pi c_u - P \Big/ \left[\left(B + 2h_0 \tan\alpha_0 \right)\left(L + 2h_0 \tan\alpha_0 \right) \right] = 0$$

Pioneering v/s Modified Methodology

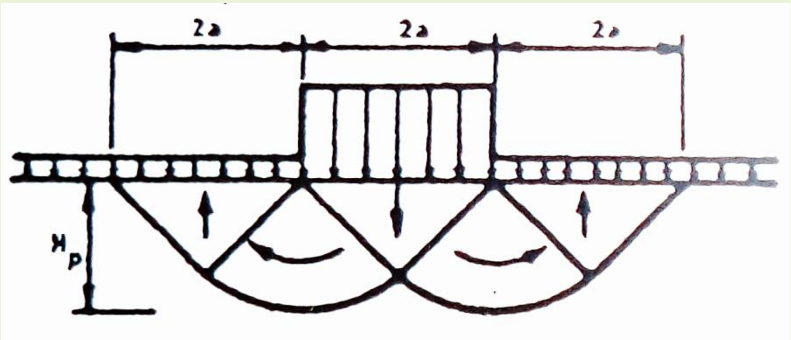
Idea from Past Research

- Proposed design charts
  - ✓ Uses only undrained cohesion
- *c*-φ soil: Strength Parameters
  - ✓ Cohesion
  - ✓ Angle of internal friction
- Conventional Design Charts
  - ✓ Over estimation of aggregate layer thickness
  - ✓ Only a degenerated condition

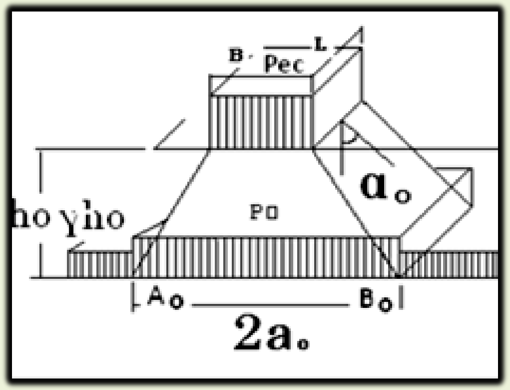
Present Study

- Improvisation over the Giroud & Noiray's Model (1981)
  - ✓ Accounts internal friction angle of soil subgrade
  - ✓ Reveals substantial reduction in aggregate thickness (Compared after inclusion of φ)
  - ✓ Accounts moving load as static
    - Maximum axle load
    - "Quasi-Static Analysis"
  - ✓ Detailed parametric study
    - Influence & Sensitivity of various contributory parameters.
  - ✓ Design Charts (with & without Geotextiles) for several combination of various parameters

Aggregate Layer Thickness: Estimation



- Present methodology (Modified)
  - **Following Terzaghi' s bearing capacity equation for shallow foundations**
    - Stress developed at the aggregate-subgrade interface generates the failure zones beneath the load as obtained in the shallow foundations



- Allowable bearing capacity (q_{all}) **(Terzaghi, 1943)**

$$q_{all} = \frac{cN_c + \gamma h_0 N_q + 0.5\gamma\left(B + 2h_0 \tan\alpha_0\right)N_\gamma}{FoS}$$

- **Bearing capacity factors**

$$N_q = e^{2\left(\frac{3\pi}{4}-\frac{\phi}{2}\right)} \Big/ 2\cos\left(\frac{\pi}{4}+\frac{\phi}{2}\right)$$

$$N_\gamma = 2(N_q + 1)\tan\phi$$

$$N_c = (N_q - 1)\cot\phi$$

Design of Unreinforced Unpaved Road

- Basic design criterion
  - **Maximum pressure on the subgrade soil ≤ Allowable bearing capacity of the subgrade**

$$\frac{cN_c + \gamma h_0 N_q + 0.5\gamma\left(B + 2h_0 \tan\alpha_0\right)N_\gamma}{FoS} = \frac{P}{\left(B + 2h_0 \tan\alpha_0\right)\left(L + 2h_0 \tan\alpha_0\right)} + \gamma h_0$$

  - **Polynomial form** $C_1 h_0^{\ 3} + C_2 h_0^{\ 2} + C_3 h_0 + C_4 = 0$
    - Coefficients of the polynomial expression

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

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

$$C_3 = \gamma LB\left[N_\gamma \tan\alpha_0 + N_q - FoS\right] + (L + B)\tan\alpha_0(\gamma B N_\gamma + 2cN_c)$$

$$C_4 = -\frac{P.FoS}{2} + cN_c LB + 0.5\gamma LB^2 N_y$$

  - **Solution → Required thickness of aggregate layer on *c*-*φ* subgrade in the absence of a geotextile layer**

Computation and Parametric Study

- MATLAB codes
  - Compute required aggregate thickness (with and without geotextile layer)

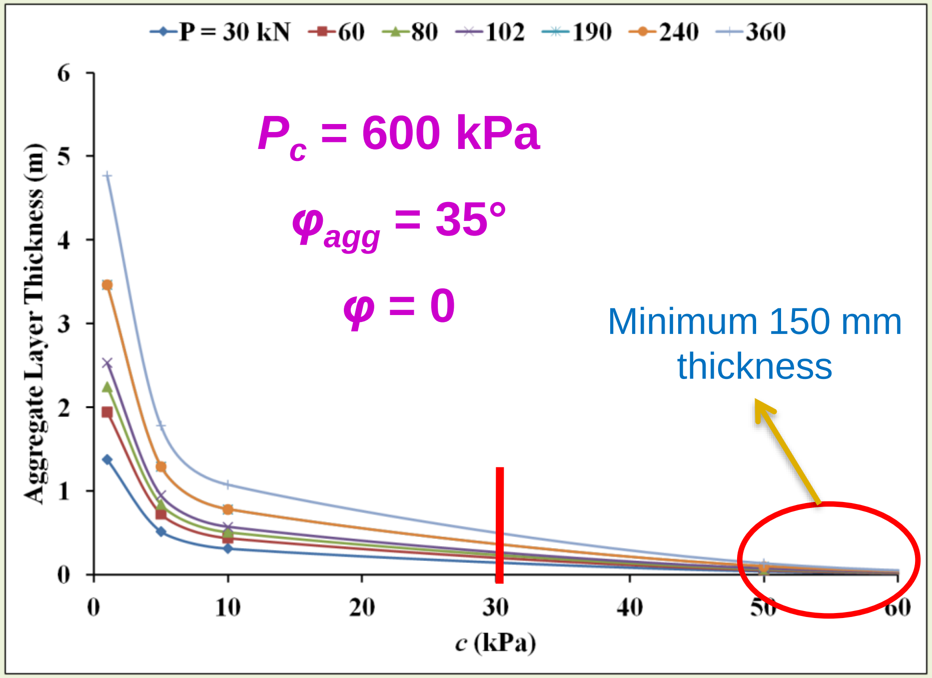
- Ranges of various parameters chosen (Indian traffic conditions)
  - **Axle Load (*P*): 30 kN – 360 kN (MoRTH, GoI, 2005; IRC-37-2001)**
  - **Tire inflation pressure (P_c): 150 kPa – 750 kPa (AFJM, 1994; Khanna and Justo, 2001)**
  - **Angle of internal friction of aggregate (φ_{agg}): 25° – 35°**
  - **Angle of internal friction of soil (φ): 0 - 50° [Covers the broad domain of soil characteristic- purely cohesive soil to rocky subgrade]**

Parametric Analysis

- Ranges of various parameters chosen(Indian traffic conditions)
  - **Soil cohesion (*c*): 0 – 500 kPa [Covers purely cohesionless soil to hard clay in the subgrade]**
  - **Unit weight of soil and aggregate (*γ*): 19 kN/m^3 [Kept same- No significant variation in *γ*]**
  - **Track widths of Indian Cargo vehicles (*e*): 1.7 – 2.4 m**
  - **Factor of safety (FoS): 1 – 3**
    - FOS = 1 considers ultimate bearing capacity of subgrade
    - Other FoS considers allowable bearing strength of the subgrade

Design Charts: Effect of Cohesion

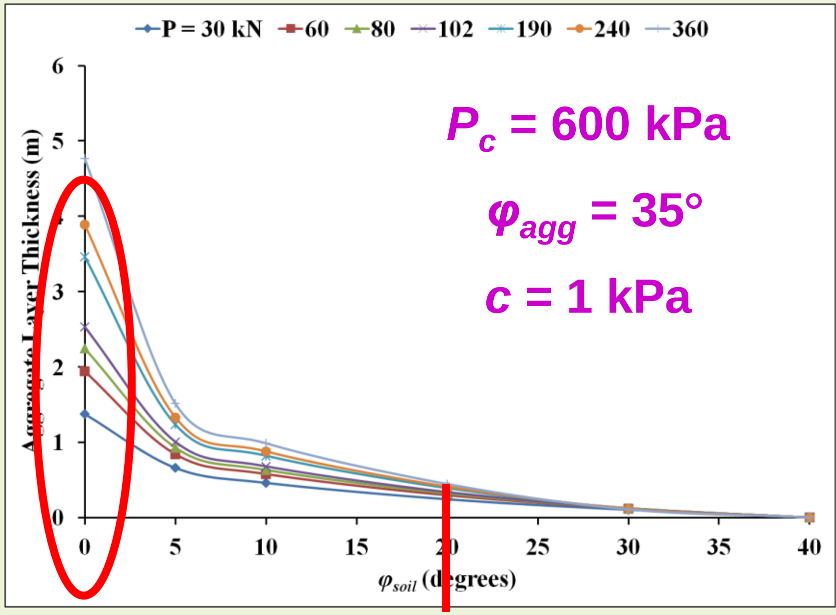
- Poor/soft soil
  - **Very low *c* and *φ* values**
    - Immensely thick aggregate layer
      - Optimum cohesion of 30 kPa to substantially reduce the aggregate layer thickness
    - Adopt some subgrade modification techniques for soils with natural cohesion less than 30 kPa
      - Application of geotextiles can be a solution



  - **Stiffer clays**
    - Theoretically, no necessity of aggregate layer

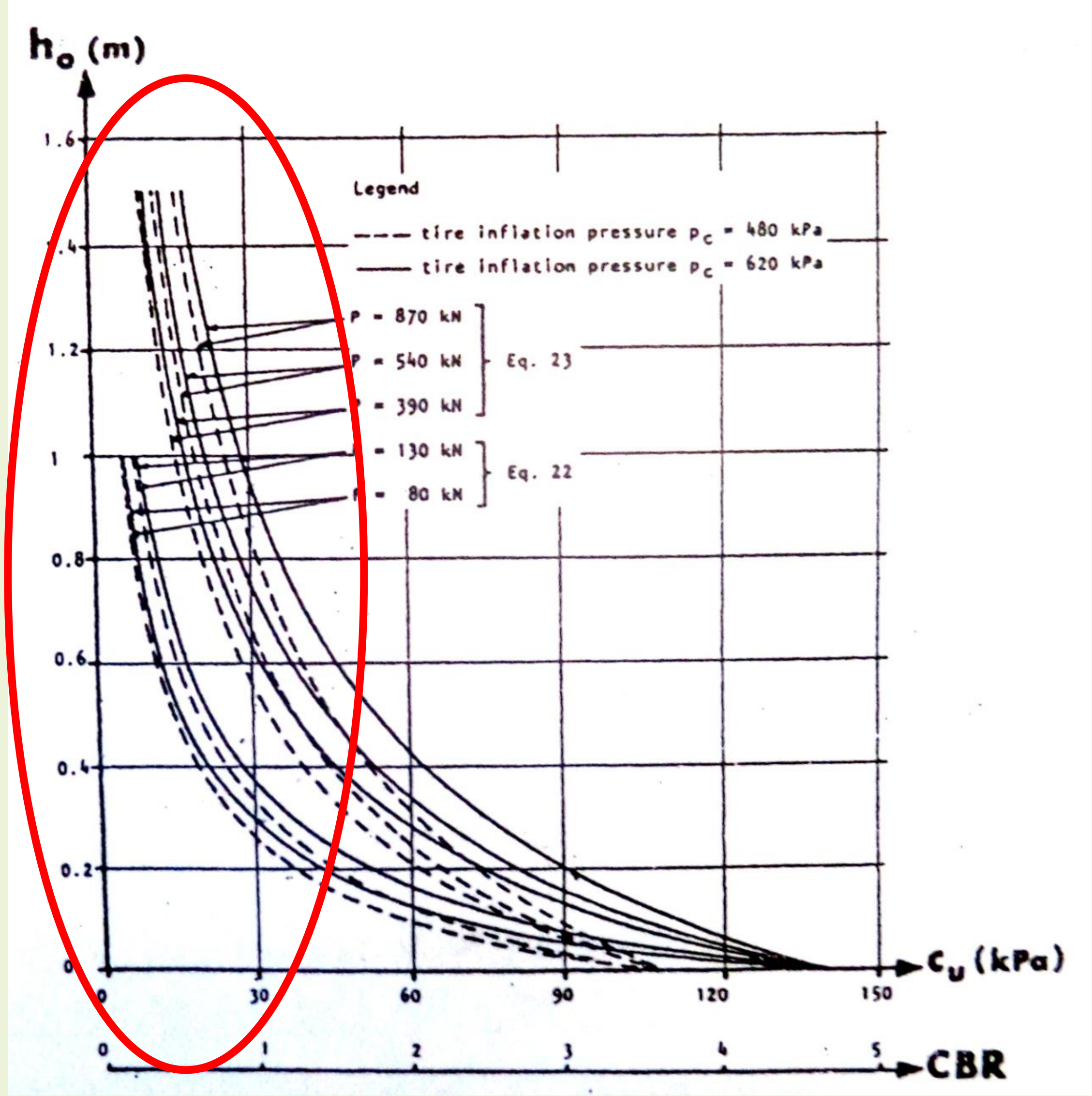
Design Charts: Effect of Angle of Internal Friction

- Subgrade containing coarser soil particles
  - ❖ **Enhanced angle of internal friction**
    - Increase in bearing strength of the subgrade soil
      - Substantial reduction in the required aggregate thickness
- Analysis by **Giroud and Noiray (1981)**
  - ❖ **Based on purely cohesive soils**
    - Results in overestimated results for natural subgrade soils having cohesionless particles as well
- No requirement of aggregate layer



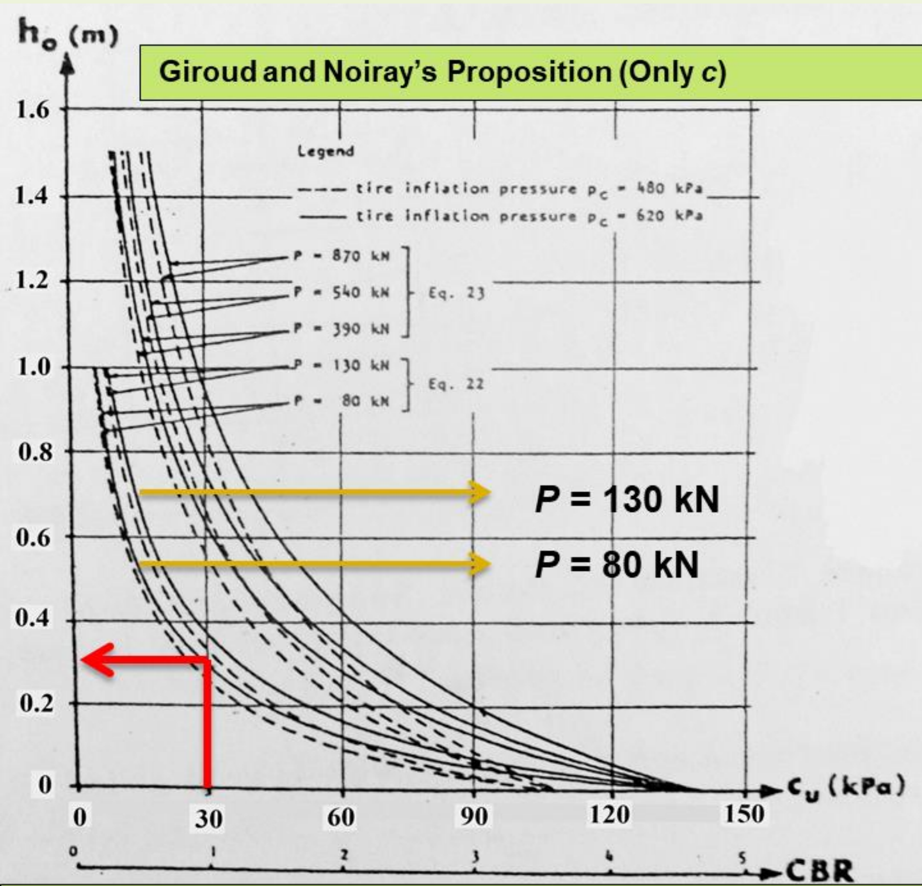
Angle of internal friction (φ) deg	Soil Cohesion (c) kPa
0	100
5	~ 50
10	50
20	10-50
30	10
35	5
40	0

Design Charts: Giroud and Noiray (1981)



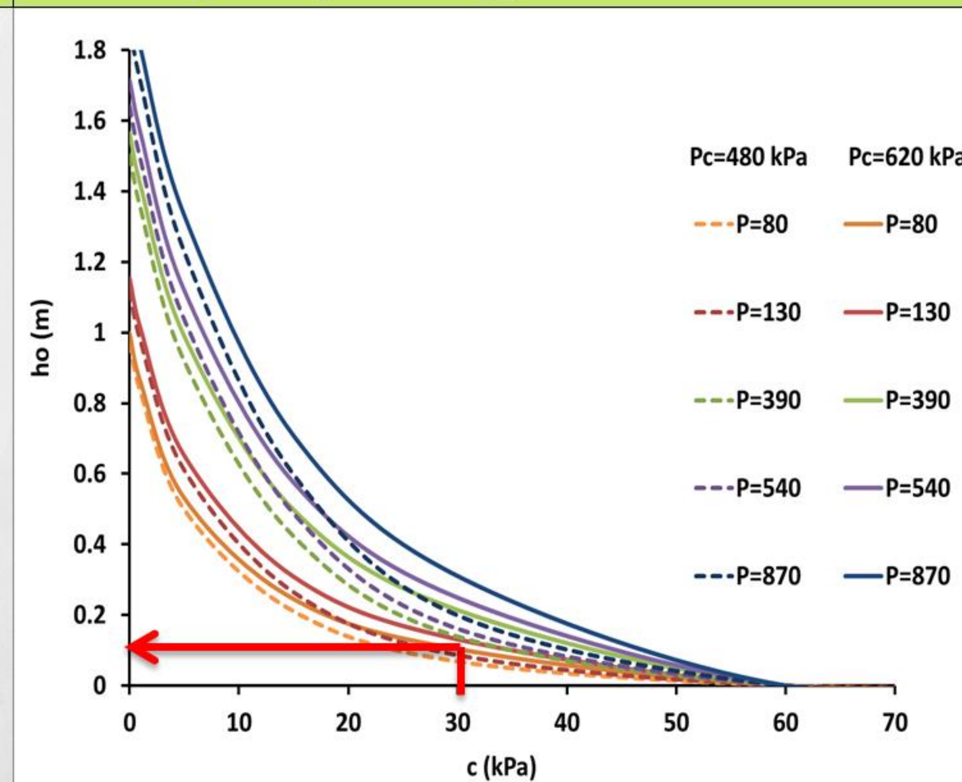
Benefit of Inclusion of *φ*-component

Giroud and Noiray's Proposition (Only *c*)



φagg= 30°, φsoil= 5°

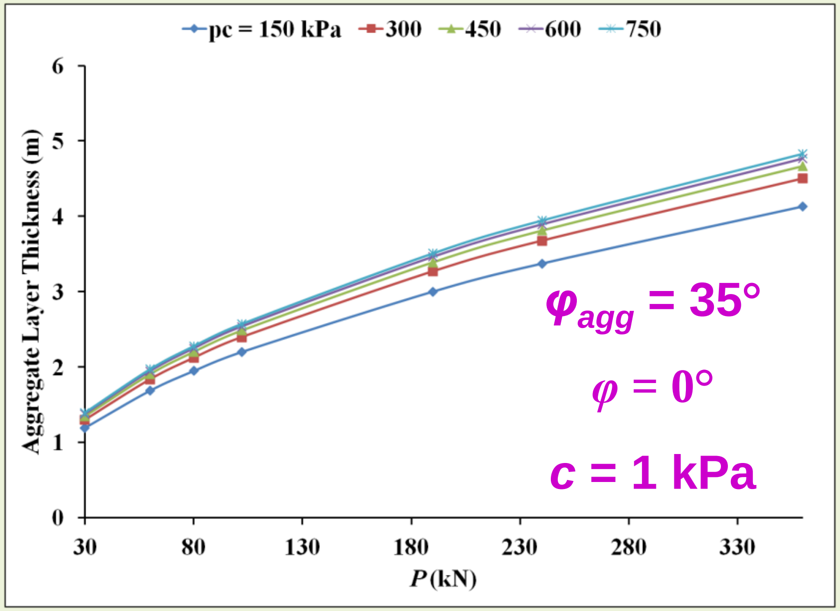
Present Proposition (Both *c* and *φ*)

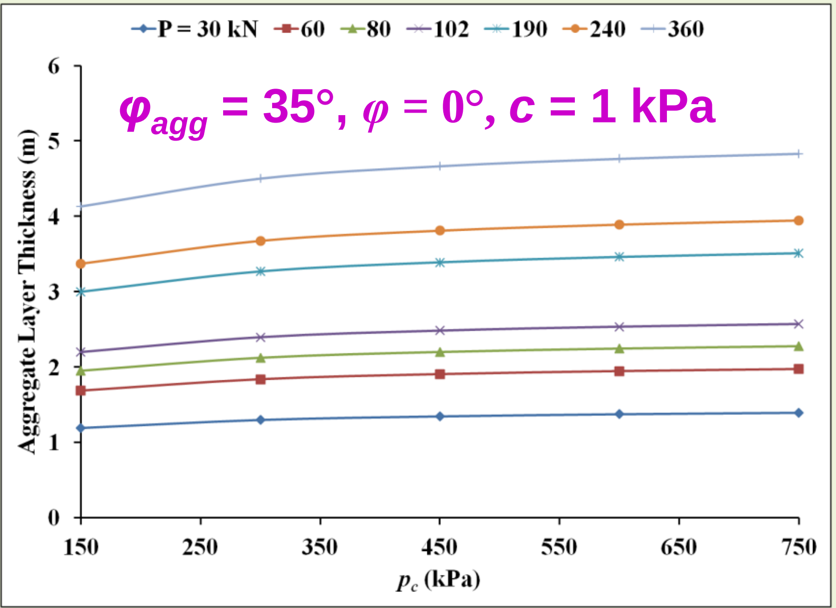


φagg= 30°, φsoil= 5°

Design Charts: Effect of Axle Load and Tire Pressure

- Increment in axle load
  - ❖ **Required aggregate thickness is higher**
    - Obvious observation

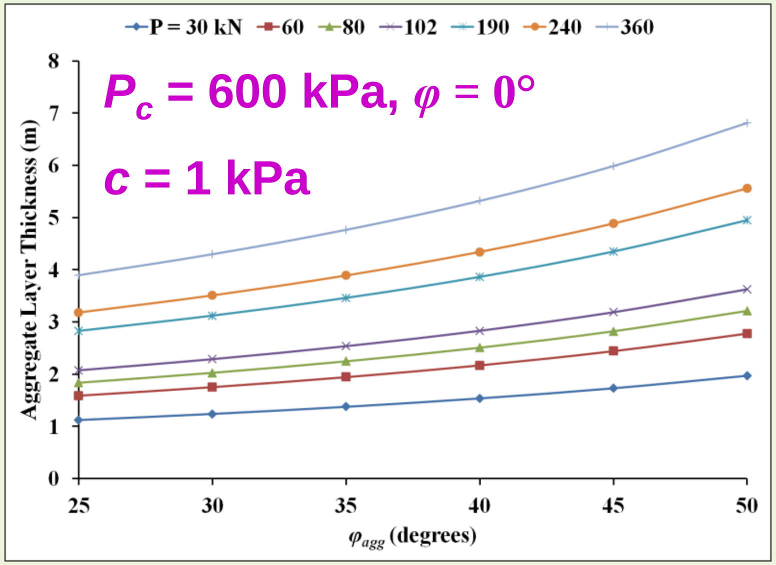




- Increment in tire inflation pressure
  - ❖ **Does not significantly affect the required aggregate thickness**
    - Lower tire inflation pressure → Higher equivalent contact area
      - Mutually complementing to support the axle load

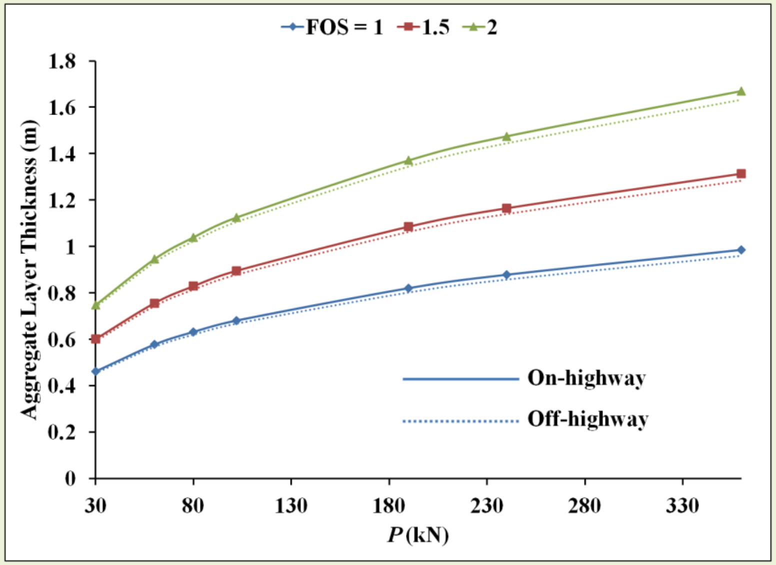
Design Charts: Effect of Aggregates and Vehicle Location

- Angle of internal friction of the aggregate (φ_{agg})
  - **Governs the load dispersion angle**
    - Assumption
      - Higher stress transferred to subgrade
      - Complete punching of the aggregate layer by into the subgrade layer under high load
  - **Increase in φ_{agg} → Decrease in α_0**
    - Larger aggregate thickness required



- Category of vehicles
  - **No substantial effect on the required aggregate thickness**

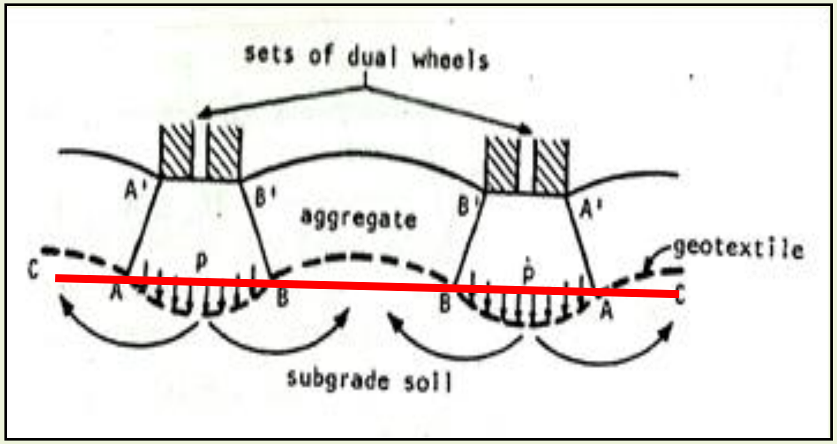
P = 190 kN, P_c = 600 kPa, φ_{agg} = 35°
φ_{soil} = 10°, c = 1 kPa



Design of Unpaved Road with Geotextile

- Geotextile placed at the aggregate-subgrade interface
  - **Deforms due to the stress transferred at aggregate-subgrade interface**
    - Concave shaped settlement under the tires
    - Convex shaped heave between the tires
      - Assumption
        - Friction is fully mobilized at the geotextile interfaces and no-slip condition prevails
    - Geotextile gets stretched to generate ***Tensioned-membrane effect***
  - **Reduction of pressure by geotextile : p_g**
    - Pressure transferred to subgrade soil, p^* (portion AB)

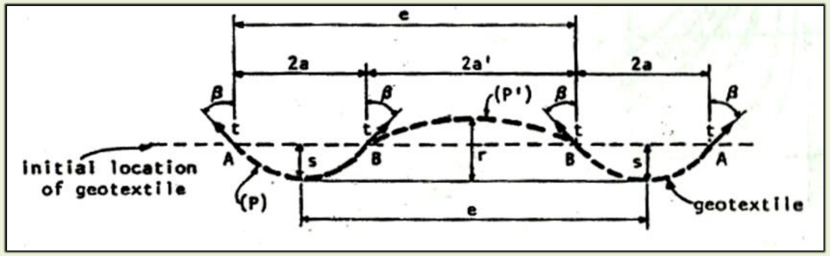
$$p^* = p - p_g$$



Aggregate Layer Thickness: Estimation

- **Giroud and Noiray (1981)**

$$\frac{P}{2(B+2h\tan\alpha)(L+2h\tan\alpha)} - p_g = (\pi+2)c_u$$



- Present methodology (Modified)
  - **Pressure *p** ≤ Ultimate bearing capacity of the subgrade soil**

$$\frac{P}{2(B+2h\tan\alpha)(L+2h\tan\alpha)} + \gamma h - p_g = cN_c + \gamma h N_q + 0.5\gamma(B+2h\tan\alpha)N_\gamma$$

$$p_g = K\varepsilon \Big/ a\sqrt{1+\left(\frac{a}{2s}\right)^2} \qquad a = (B+2h\tan\alpha)/2$$

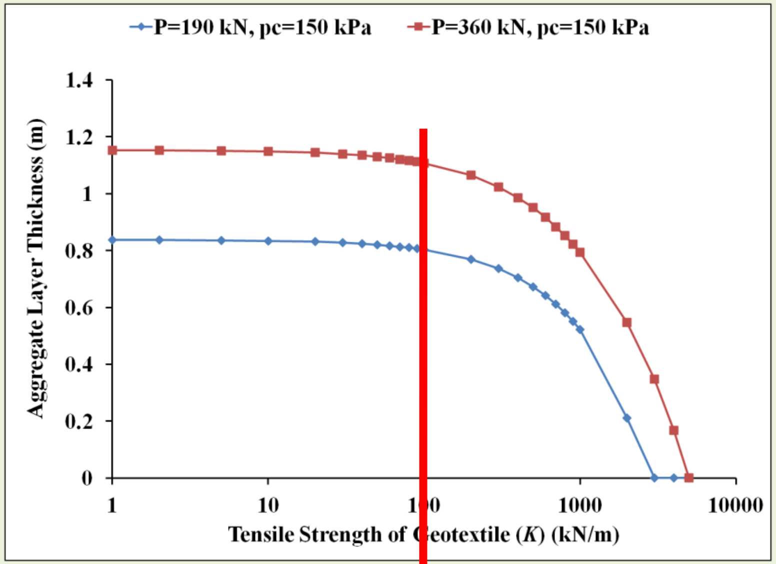
$$\varepsilon = \frac{b+b'}{a+a'} - 1$$

- K → Tension-elongation modulus (1-5000 kN/m, as per Giroud and Noiray, 1981)
- ε → Elongation of Geotextile
- s → Settlement beneath the wheels → Function of rut depth (r)

  - **Solution → Required thickness of aggregate layer on *c-φ* subgrade with single layer of geotextile**

Benefit from Geotextile: Tensile Strength

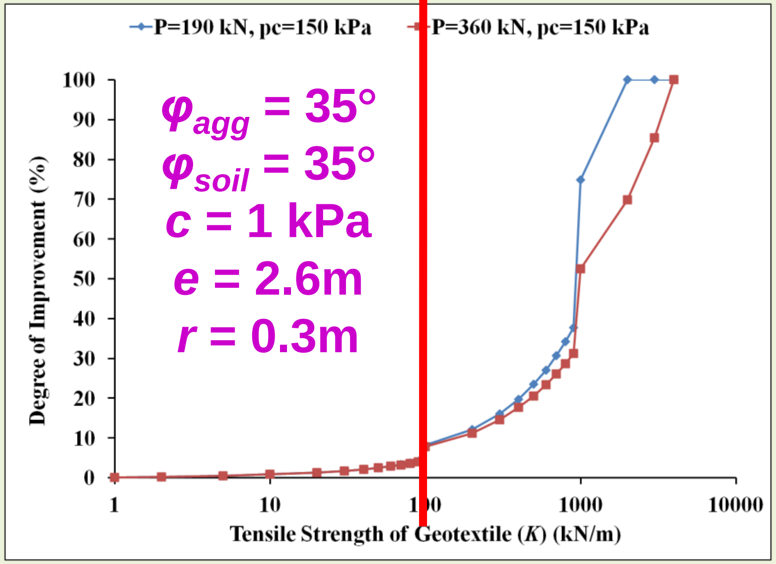
- Depicts benefit of geotextiles
  - ❖ **Enhanced tensile strength of geotextile)**
    - Reduction in required aggregate thickness
  - ❖ **Zero tensile strength**
    - Absence of geotextile



- Efficacy of geotextiles

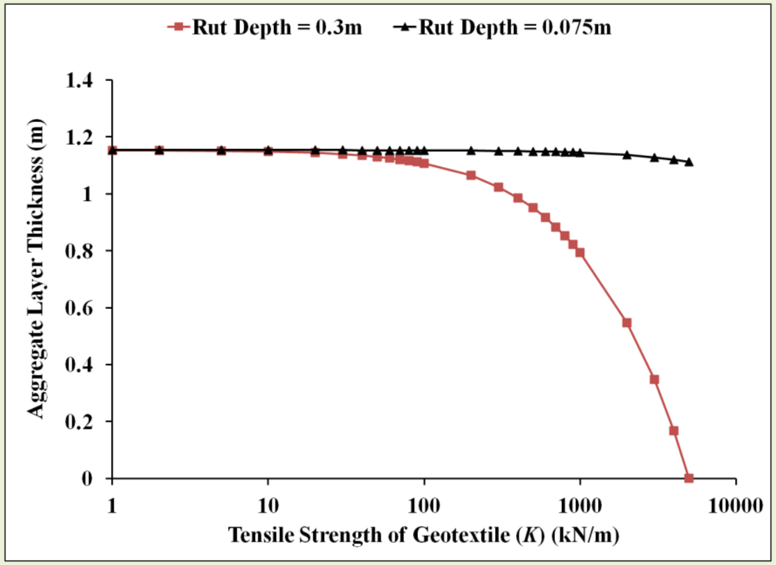
$$I_f = (k_i - k_0)/k_0 \times 100$$

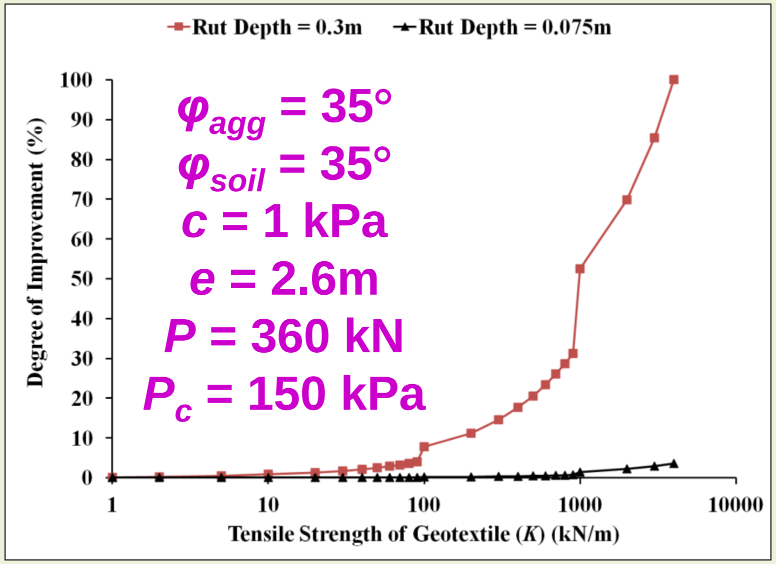
  - ❖ **Degree of improvement**
    - 100% improvement theoretically signifies that aggregate cover is not necessary



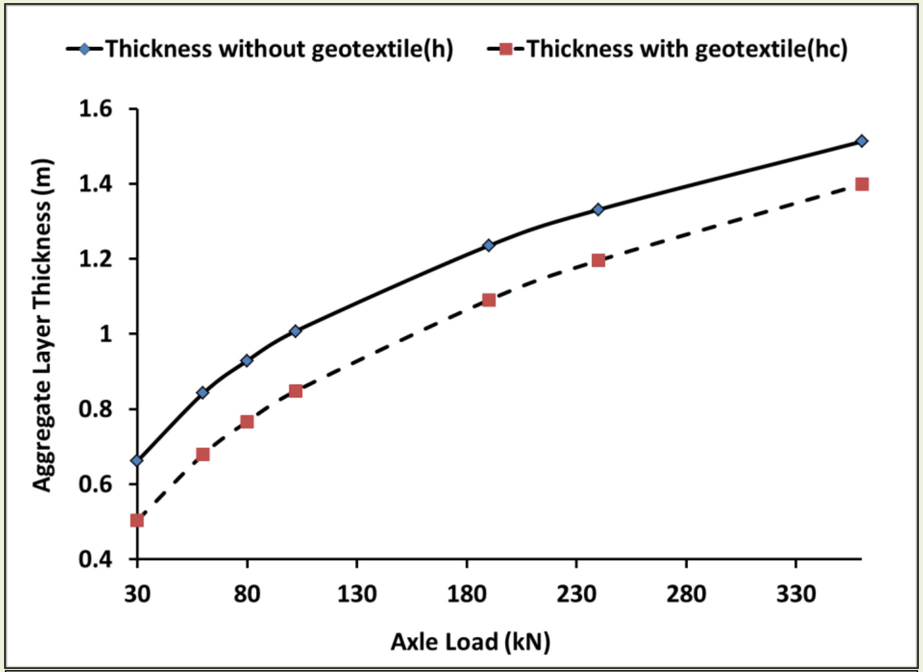
Effect of Rut Depth

- Lower rut depths
  - ❖ **Negligible or Nil efficacy of geotextiles**
    - Reconfirms the finding of Holtz and Sivakugan (2005)
- Larger rut depth
  - ❖ **Large deformation**
    - Enhanced mobilization of membrane tension
      - Increased efficiency of the geotextile
        - Substantial reduction in *h*
- *Rutting*
  - ❖ **Not desirable**
  - ❖ ***A design rut is required to extract the beneficial effect of geotextile***





Benefit of Utilizing Geotextile

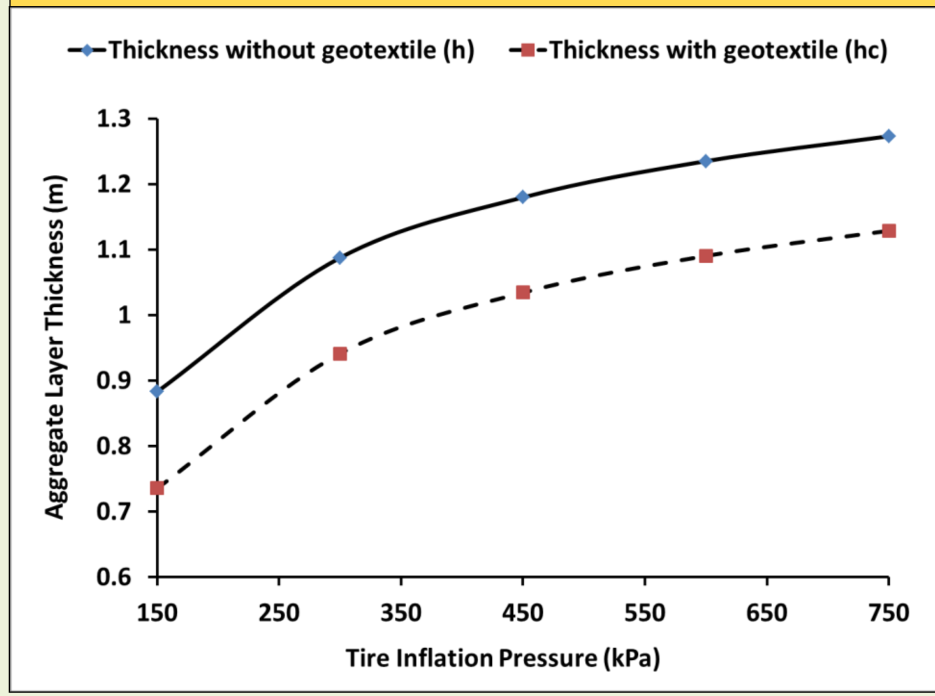


- With Geotextile: Critical Case (*K*= 400 kN/m)

- The reduction in thickness increases with increase in tensile strength- Economy

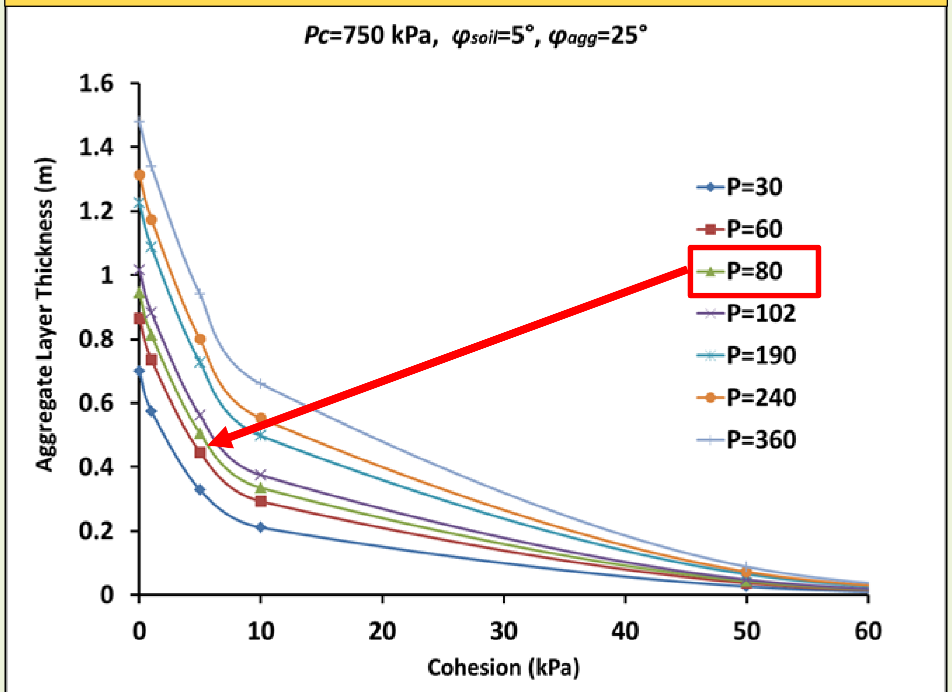
- Comparison shows a reduction of ~200 mm Aggregate layer thickness

- With Geotextile: Critical Case (*K*= 1000 kN/m)

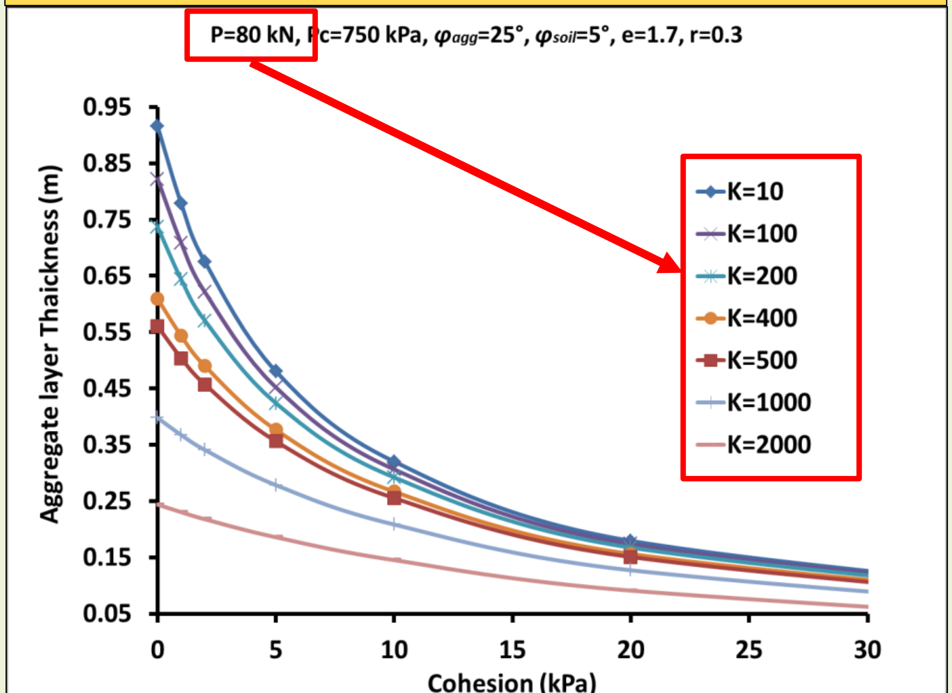


Typical Generalized Design Charts

Without Geotextile



With Geotextile



Influence of Traffic

N=10

N=100

N=1000

Influence of Traffic

- Webster and Alford's Expression

$$h_m = \frac{0.19 \log N_s}{(CBR)^{0.63}}$$

  - ✓ CBR= California Bearing Ratio
  - ✓ Rut depth = 0.075 m
  - ✓ Standard Axle load = 80 kN

- Extend the applicability
  - ✓ Rut depth

$$\log N_s \Leftrightarrow \left[\log N_s - 2.34(r - 0.075)\right]$$

  - ✓ Other Axle Loads

$$P_s \Leftrightarrow P_i \qquad \frac{N_s}{N_i} = \left(\frac{P_i}{P_s}\right)^{3.95}$$

✓ Bearing capacity of subgrade

Black's Expression (1961) (Field test data)

$$q_u = 10\ CBR$$

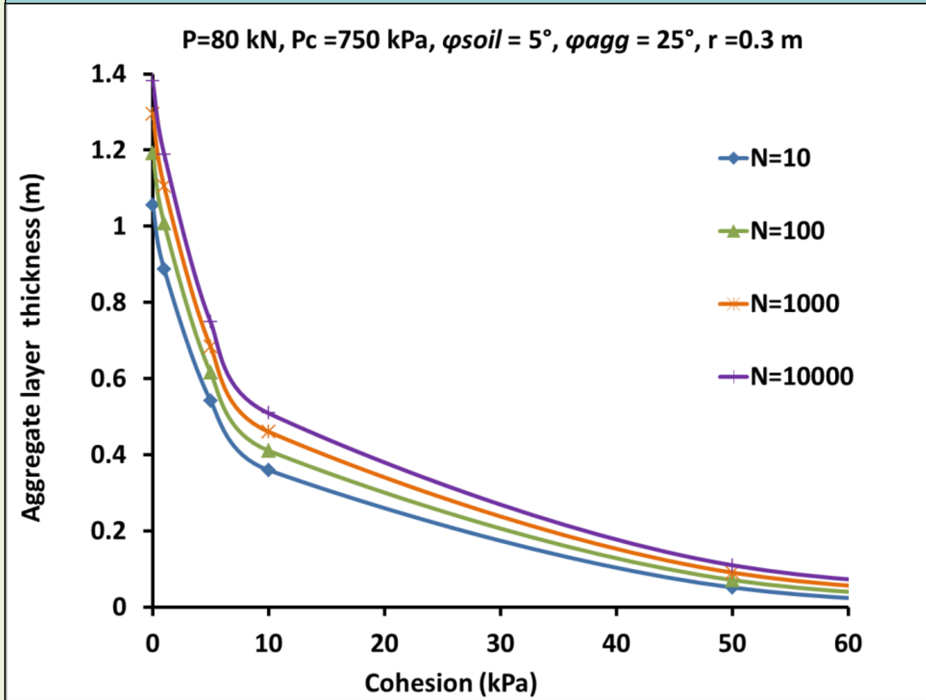
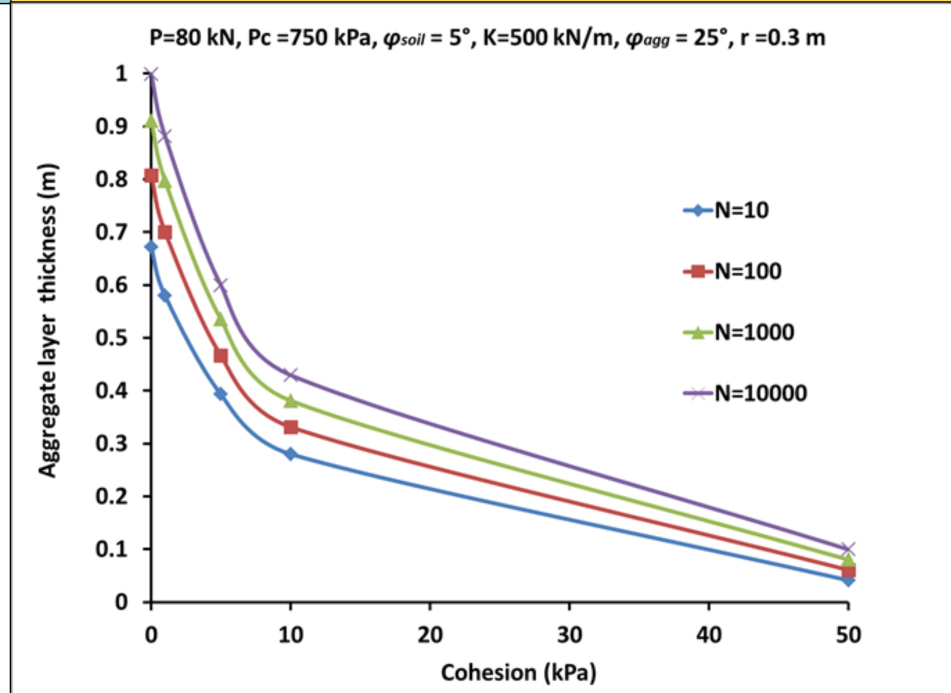
- Equation: Multiple passage

$$h_m = \frac{0.81 \log N_i + 3.19 \log P_i - 1.89r - 5.95}{(q_u)^{0.63}}$$

✓ Solution Technique : MATLAB

- ✓ Yields additional cumulative aggregate thickness (h_m)

Design Charts with Geotextile: Multiple Passage

Multiple Passage: Without Geotextile	Multiple Passage: With Geotextile
	
P = 80 kN	K = 500 kN/m, e = 1.7

Finite Element Design of Unpaved Roads

Advantages of Analytical formulations

- Easy determination of unpaved road aggregate layer thickness (***h***)
- Analytical formulations are applicable
  - **For stiffer system**
    - Higher *c* and *φ* value

Shortfall of Analytical Formulations

- A stress-based approach.
  - **Individual components of the unpaved road structure are considered to be rigid or non-deformable**
- In reality
  - Unavailability of good quality construction materials
    - Failure within subgrade layer due to the weight of stacked unbounded and poorly-graded coarse aggregate layer
    - Failure within aggregate layer due to the stresses developed by quasi-static vehicular loading.
    - Deformation under different operational conditions becomes a guiding factor
- Assumed Limit Equilibrium Approach.
  - Does not consider internal stress and strain.
- Not applicable for weak subgrade

Requirement of Finite Element (FE) modeling

- **Consider deformable system**
  - Consider internal stress and strain developed.
- Real field scenario.
  - Failure of subgrade and aggregate
- Response of weak subgrade under loading

Need of the hour : FE Analysis to tackle real field scenario

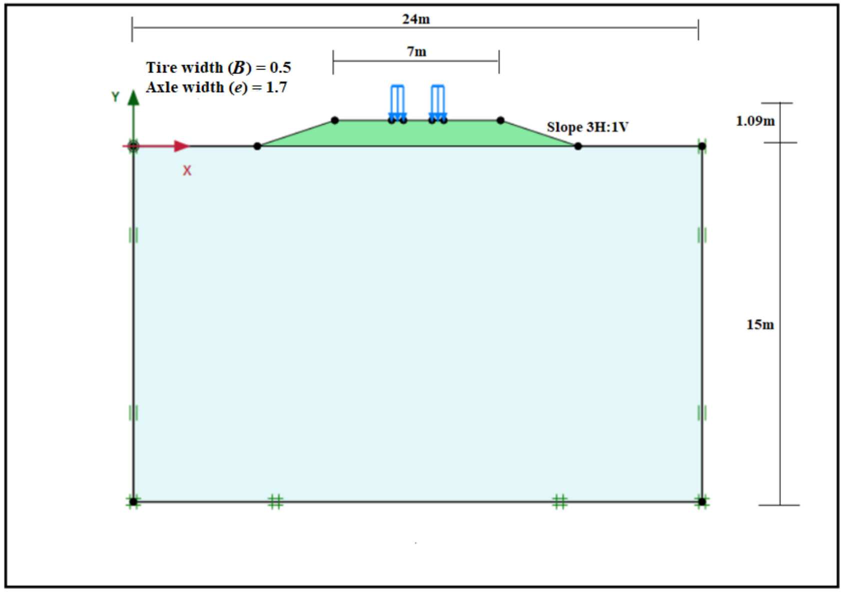
FINITE ELEMENT STUDY

- **Finite Element (FE) based design methodology is developed based on coupled stress-deformation approach under quasi-static loading condition.**
  - ❖ Unreinforced and reinforced unpaved road structure.
    - FE software PLAXIS 2D is used.
- **Rutting developed under Quasi-Dynamic loading condition is studied.**

Model Description

Unreinforced Unpaved Road model

- Two layered system
  - ❖ Subgrade and aggregate layer
  - ❖ Thickness of the aggregate layer
- Boundary conditions for subgrade
  - ❖ Vertical and horizontal fixities at the bottom boundary
  - ❖ Horizontal fixities along vertical boundary
- Slope of the aggregate embankment
  - ❖ 3H:1V
- Wheel load
  - ❖ Uniformly distributed
  - ❖ Contact width
    - Analytical formulations
  - ❖ Three different vehicular axle loads
    - 80 kN, 190 kN and 360 kN
- Plane strain material model
  - ❖ Uniform cross section
- 15-noded triangle element
  - ❖ Better output results.

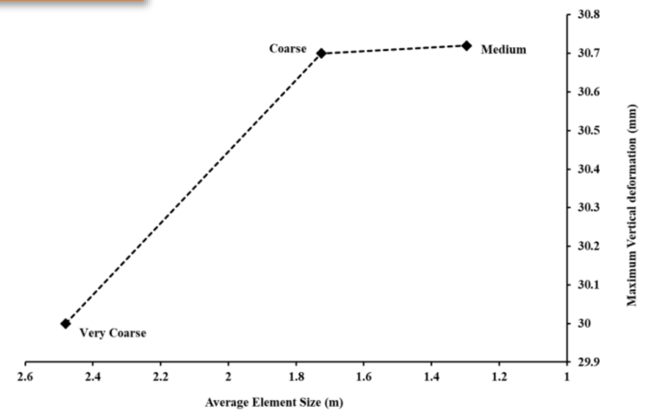


	Subgrade	**Aggregate**
Soil model	Mohr-Coulomb	Mohr-Coulomb
Unit weight (γ)	19 kN/m^3	25 kN/m^3
Elastic modulus (E)	20 MPa	60 MPa
Poisson's ratio (ν)	0.4	0.3
Initial void ratio (e_{int})	0.5	0.1

Model Description

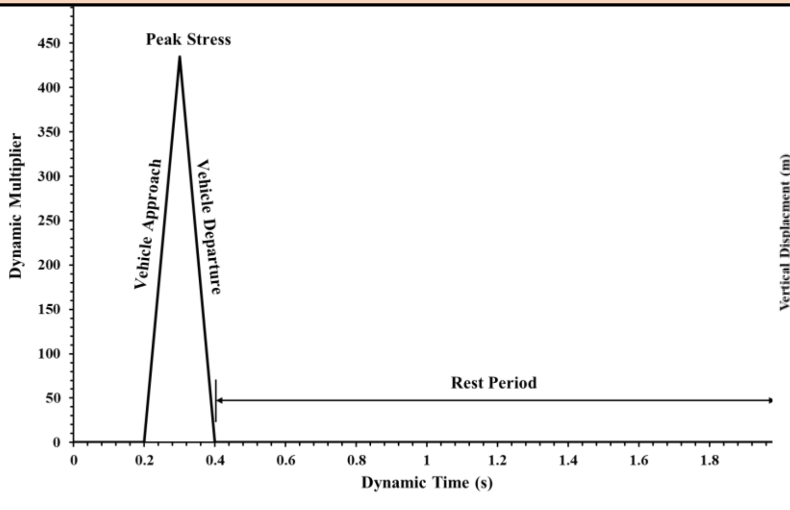
Mesh convergence study

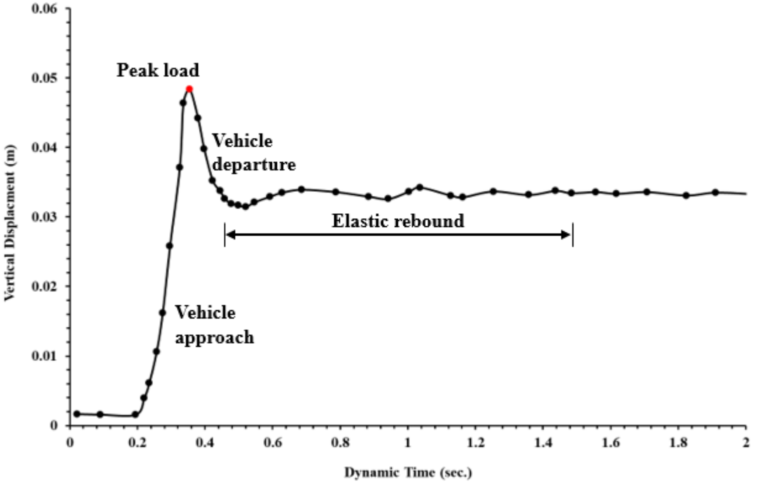
- Variation in mesh size.
    - Soil stratigraphy as well as all objects, loads and boundary conditions.
- Medium mesh size
- In areas of large stress concentrations
    - Local mesh refinement has been also provided
    - Average element size of 0.07727 m



Input parameters of Quasi-dynamic vehicular load

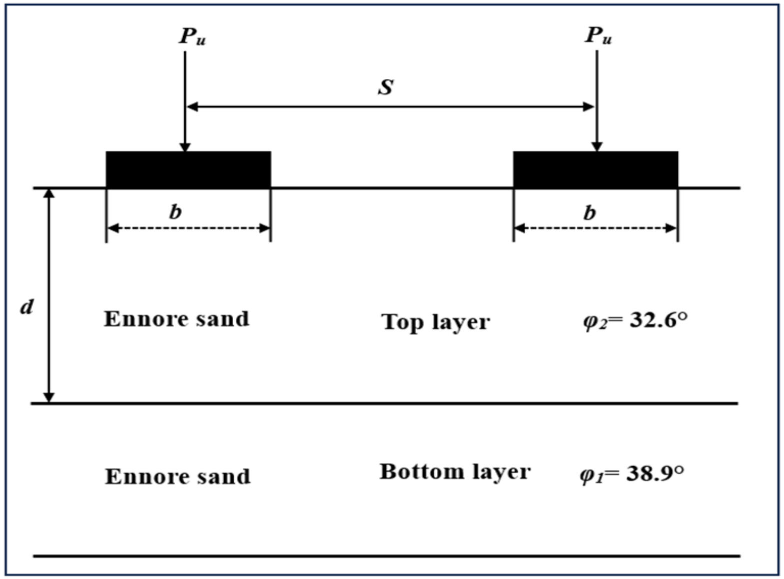
- Actual field load repetition effect comes into picture.
- Number of load passes (*N*), time gap between the arrival and departure of the vehicle through a road section (*t*′) and time interval between two consecutive passes (Δ*t*).
- Triangular or Haversine in nature (Ingle and Bhosale 2017, Sarma and Dey 2024).
    - Dynamic load multipliers repeated at regular time interval (Δ*t*) of 2 s.
    - Overall time duration of the passage of vehicle over a particular section (*t*′) is 0.2 s.



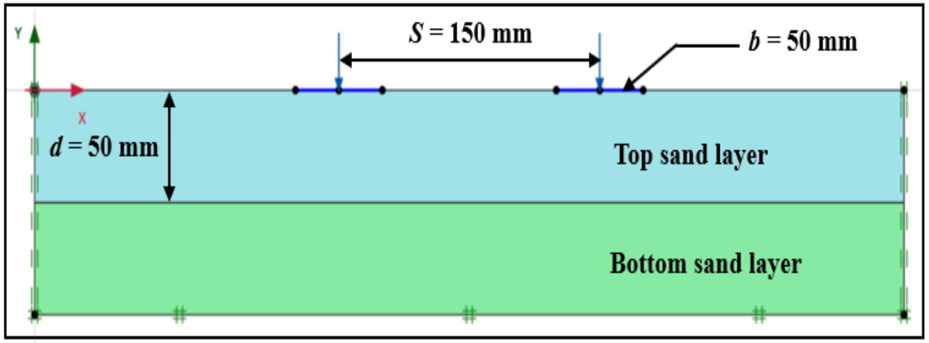


Validation study for unpaved road model

- Assess the accuracy of FE model
  - Physical problems related to interface of footings on layered soil
    - Similar characteristics with FE Model.
  - Work conducted by Ghosh and Kumar, 2011
    - Interference effect of two nearby strip footing on two layered Ennore sand
    - Footing width of 50 mm, centre-to-centre spacing of the footing 150 mm and thickness of the top layer 50 mm



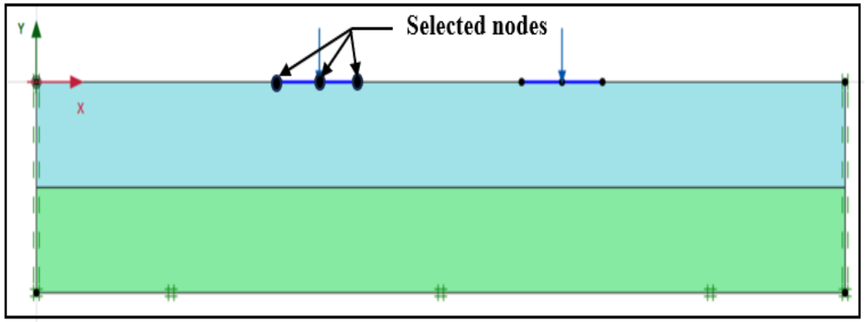
- Finite Element Model
  - Soil layers are
    - Mohr–Coulomb material model
    - Suitable boundary conditions
  - Footing
    - Plates are used from PLAXIS 2D material data set library.
    - Elastic isotropic
    - Material characteristics of mild steel
  - From the plots
    - 60 kg Point loads are applied.

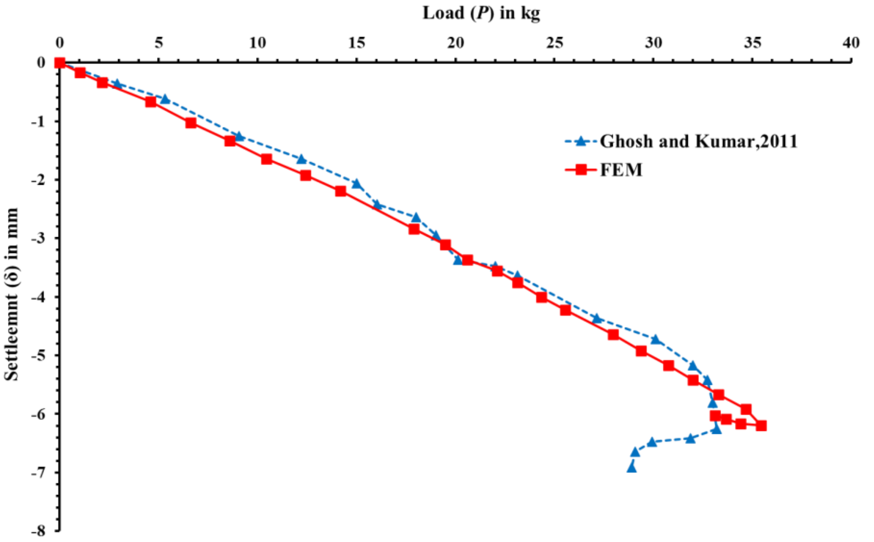


Validation study for unpaved road model in 2D

Validation study

- Selection of Nodes for output results
  - Position of the dial gauges used in the experimental set up.
  - The data obtained for settlement and load are averaged and put in a single plot.
- Output results
  - In form of load-settlement response
    - Exhibited a reasonable agreement for a maximum settlement of 6 mm
      - The ultimate load obtained from the experimental and numerical exercise is 33 kg and 35 kg, respectively.





Operational Failure Conditions under Quasi-Static Loading Scenario in 2-D

- In real field scenario, stability of unpaved road
  - Strength of individual layers during construction stage
    - Subgrade should be stable during aggregate placement.
    - Aggregate must be stable during vehicular load.
    - Analytical expressions are developed to determine the minimum strength of individual layers.

- Minimum shear strength parameter ($c_{sub,min}$) for subgrade
  - Under aggregate loading
  - **Aggregate load (γh) ≤ allowable bearing capacity of the soft subgrade**

$$\gamma h = \frac{c_{sub,\min} N_c + 0.5\gamma B' N_\gamma}{FoS}$$

- Minimum shear strength parameter ($c_{agg,min}$) for aggregate
  - Under vehicular load
  - **Stress intensity concentration under tire ≤ allowable bearing capacity of the aggregate alone**

$$\frac{P}{2BL} = \frac{c_{agg,\min} N_c + 0.5\gamma B N_\gamma}{FoS}$$

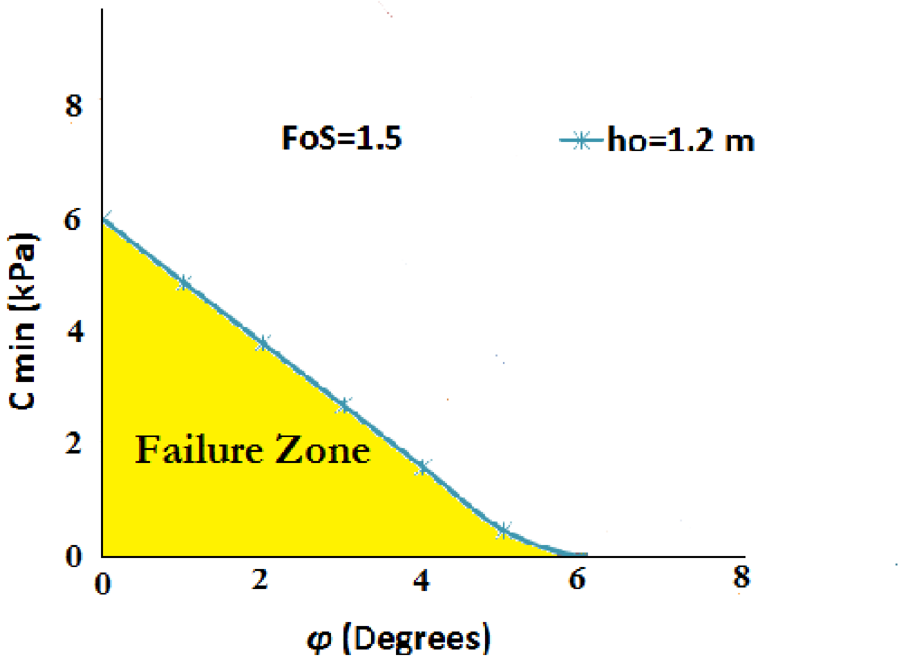
- For higher axle load
  - Stress-deformation mechanism of the different layers
    - Interdependent
      - Subgrade is the deformable medium
    - To achieve **unified stability against secondary stresses**
      - Requirement of modified minimum cohesion ($c_{sa,min}$) value

- Need of the hour : **Proper Design methodology to incorporate all the strength parameters.**

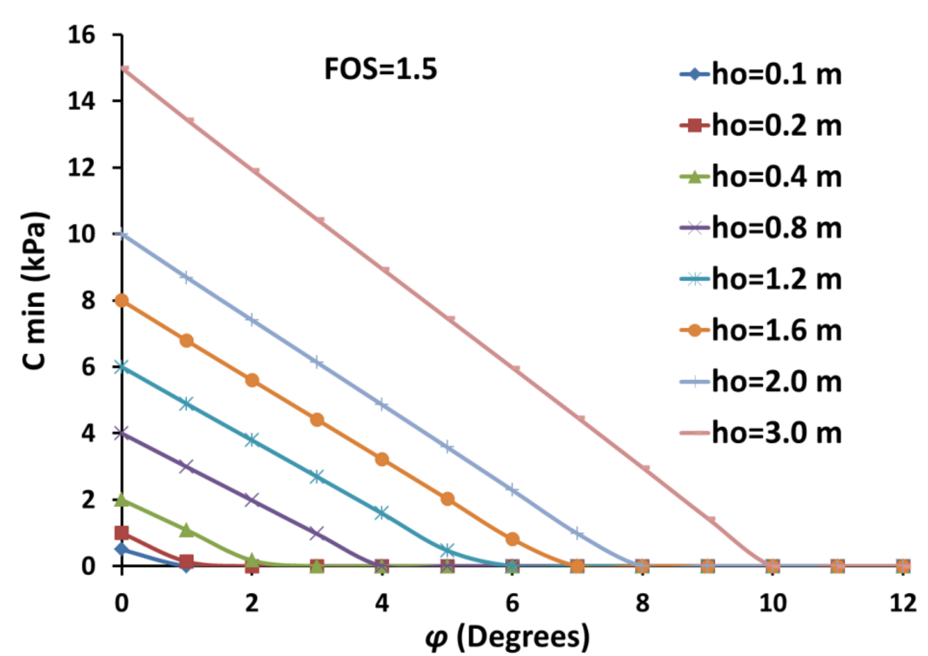
Operational Stability against Subgrade Failure due to Aggregate Loading

$$\gamma h = \frac{c_{sub,\min} N_c + 0.5\gamma B' N_\gamma}{FoS}$$

Failure Zone

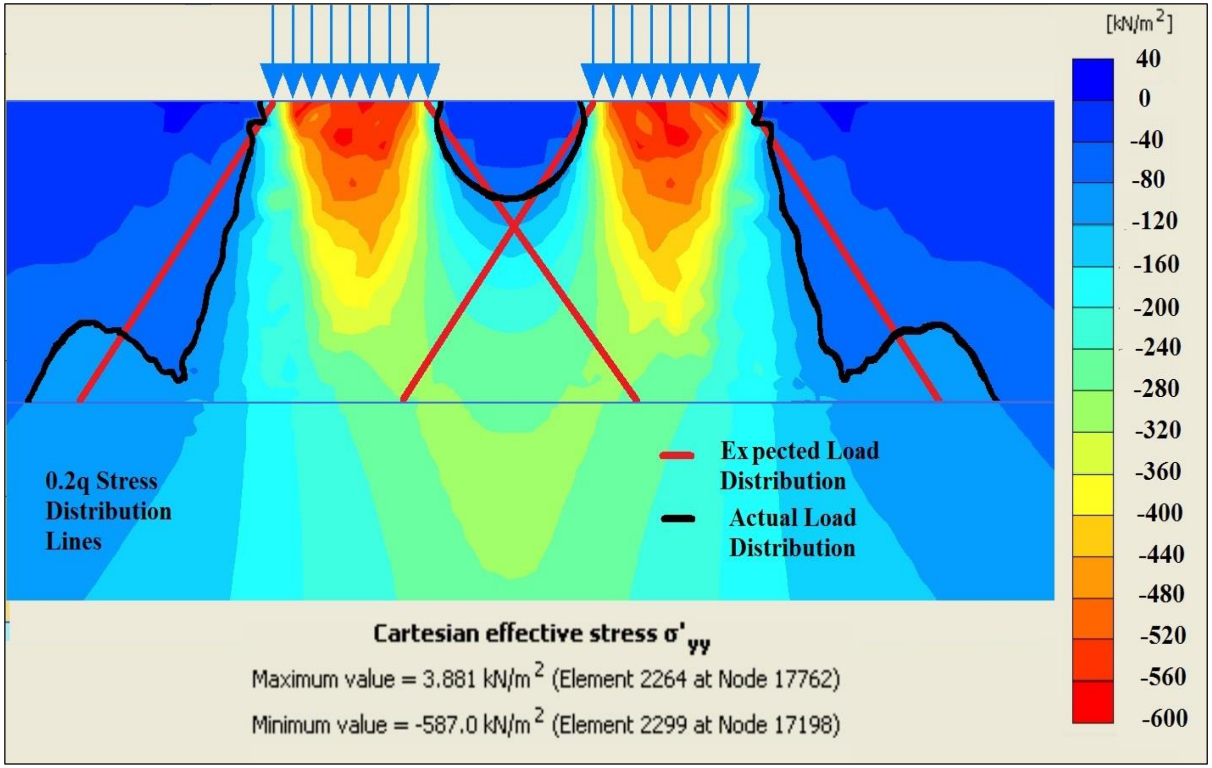


Cmin chart

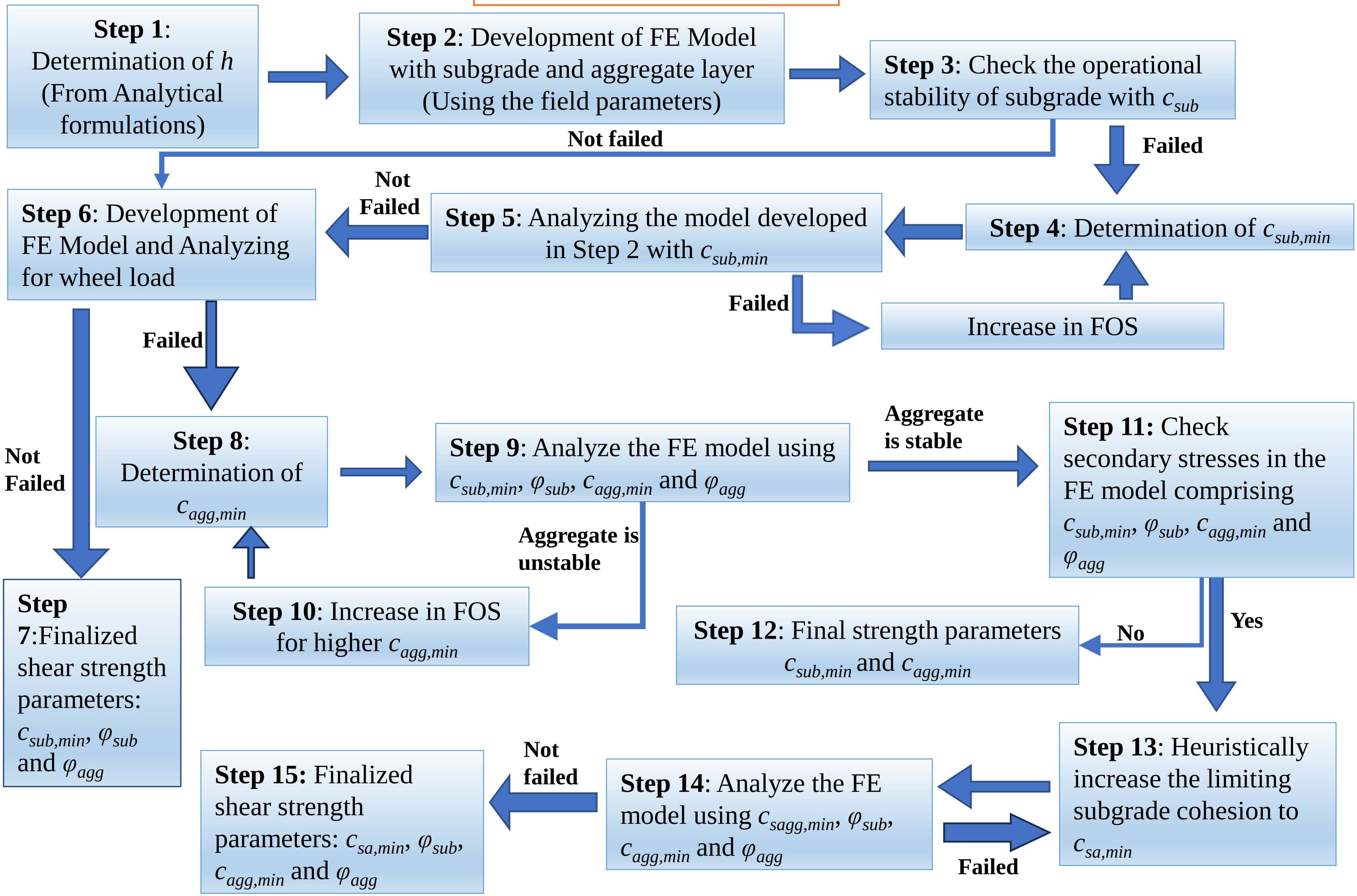


Operational Stability against Aggregate Failure due to Vehicular Loading

$$\frac{P}{2tL} = \frac{c_{a,\min} N_c + 0.5\gamma_a t N_\gamma}{FOS}$$



Design Methodology



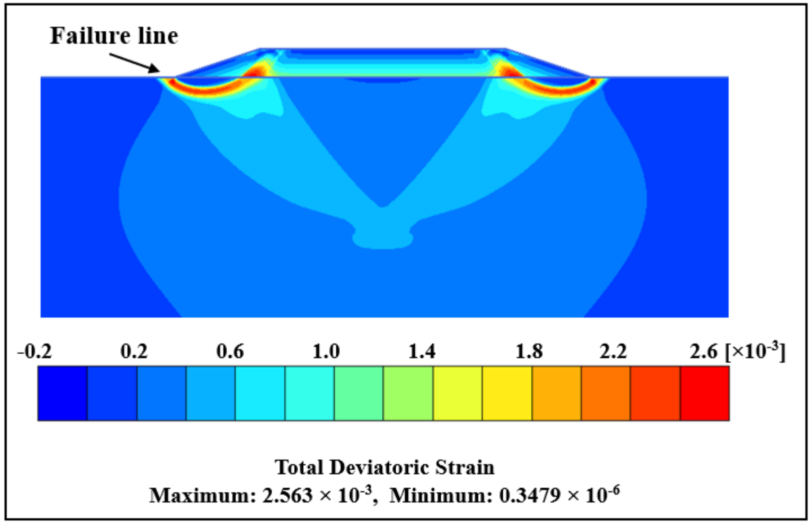
FE simulation results of unreinforced unpaved road in Plaxis 2D

- Following FE analysis is conducted using the design methodology
  - Determine minimum shear strength parameters ($c_{sub,min}$,$c_{agg,min}$ and $c_{sagg,min}$)
  - On weak subgrade (c_{sub} = 1 kPa, φ_{sub} = 5°)
  - Under axle load (P=80 kN)

- Step 1: Aggregate thickness (h) found to be 0.79 m

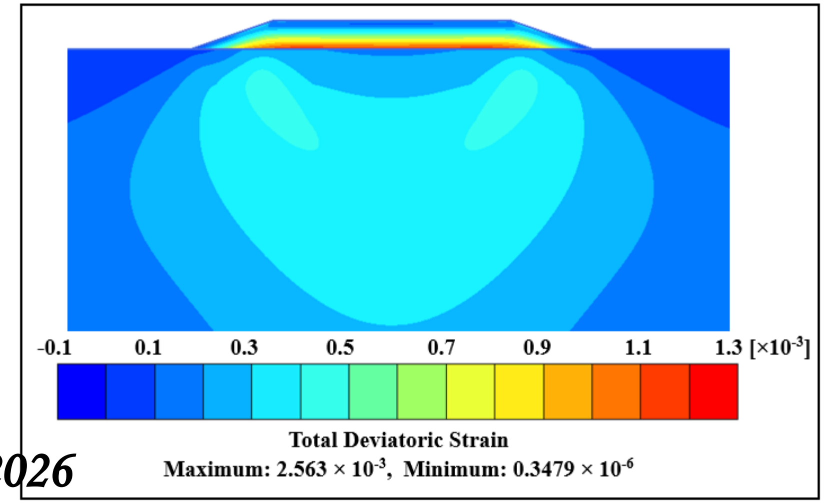
- Step 2: Development of FE Model with subgrade and aggregate layer

- Step 3: Analysis of the developed model under aggregate loading
  - Model failed
  - The maximum strain accumulated in subgrade is 2.563×10^{-3}



- Step 4: Determination of $c_{sub,min}$
  - Minimum subgrade strength $c_{sub,min}$ = 1.82 kPa.

- Step 5: Analyzing the model developed in Step 2 with $c_{sub,min}$
  - Model didn't fail
  - The maximum value of strain obtained is 1.213×10^{-3}.



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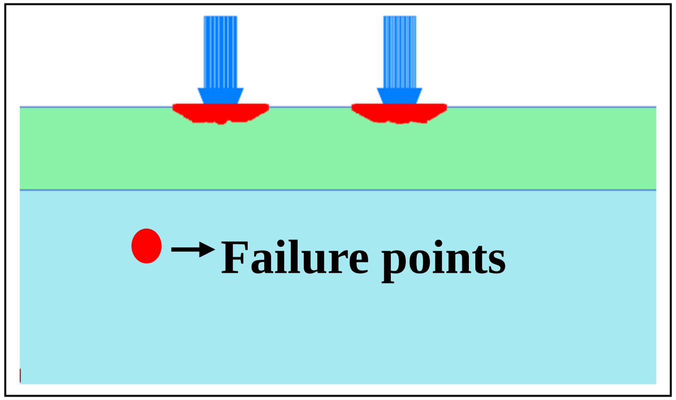
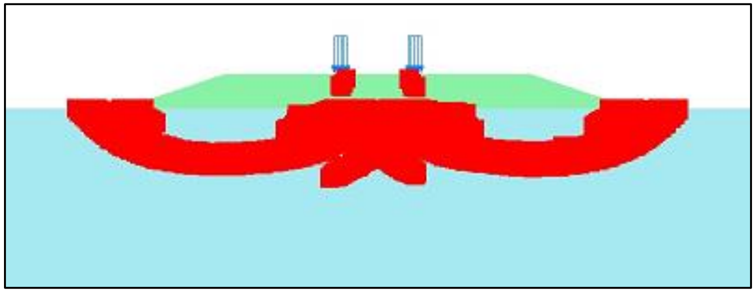
FE simulation results of unreinforced unpaved road in Plaxis 2D

Step 6 [Introduction of vehicular load]
- ❖ Failure lines did not extend all the way down to the aggregate layer
- ❖ Punching shear failure mechanism



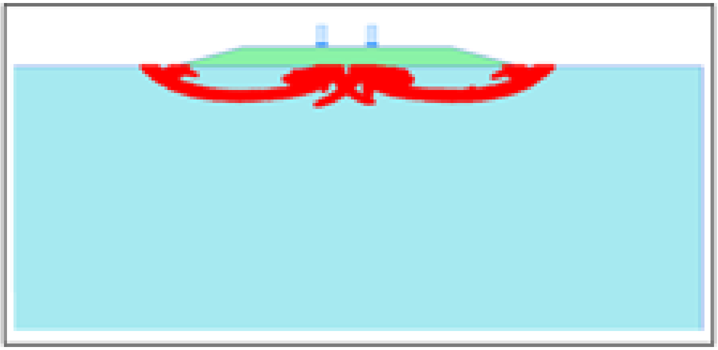
Step 8: Determination of $c_{agg,min}$
- ❖ The minimum value of cohesion required ($c_{agg,min}$) in the aggregate is 15.56 kPa

Step 9: Analyzing the model
- ❖ Model failed again
- ❖ Stress redistribution from the aggregate to subgrade.



Step 10: Modification of $c_{agg,min}$ value
- ❖ Factor of safety is increased upto 1.5.
- ❖ Modified $c_{agg,min}$ value is 24.01 kPa.

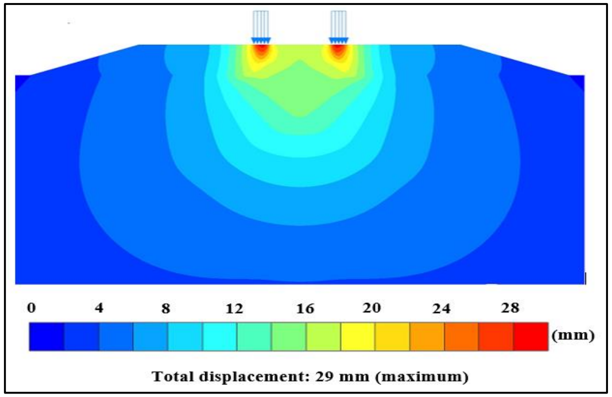
Step 11: Check secondary stresses in the FE model.

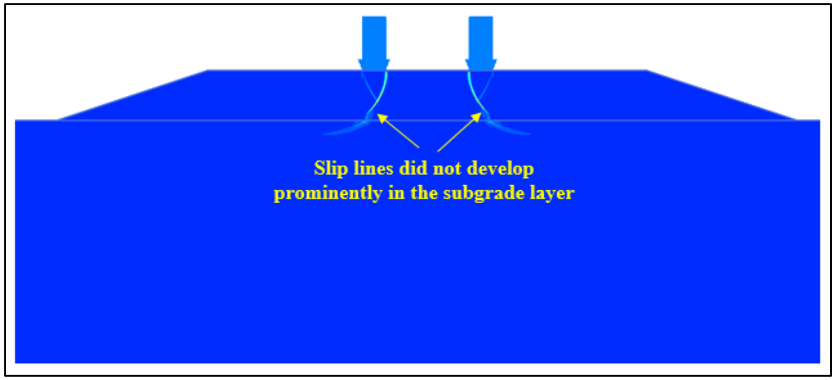


FE simulation results of unreinforced unpaved road in Plaxis 2D

- Step 13: Heuristically increase the limiting subgrade cohesion to $c_{sa,\ min}$
  - $c_{sub,min}$ value is increased from 1.82 kPa to 4 kPa.

- Step 14:Analyze the FE model using $c_{sa,min}$, φ_{sub}, $c_{agg,min}$ and φ_{agg}
  - For $c_{sa,min}$ 4 kPa
    - Uniform stress transfer mechanism
    - Failure lines are confined within the central portion of the aggregate-subgrade system
    - Significant reduction in displacement from 169 mm to 29 mm



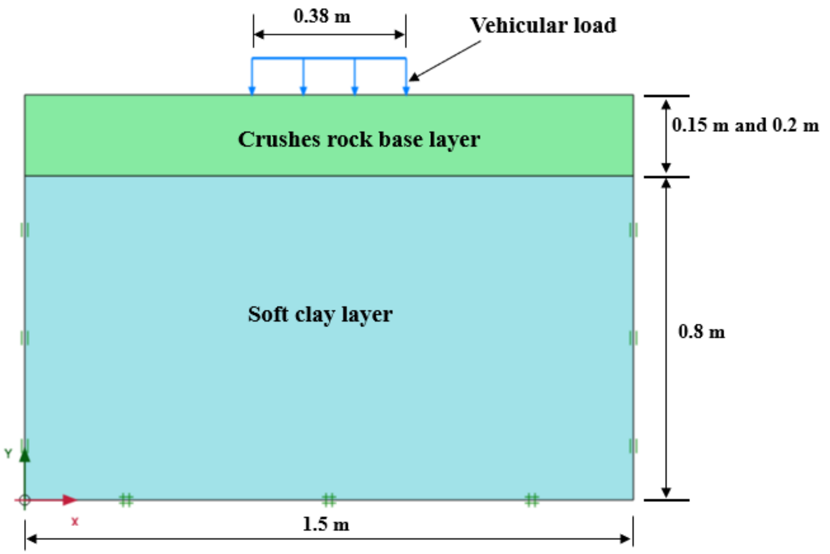


Final step: Final strength parameters
- $c_{sa,min}$ = 4 kPa
- $c_{agg,min}$ =15.56 kPa

Validation of FE Design Methodology of Unpaved road

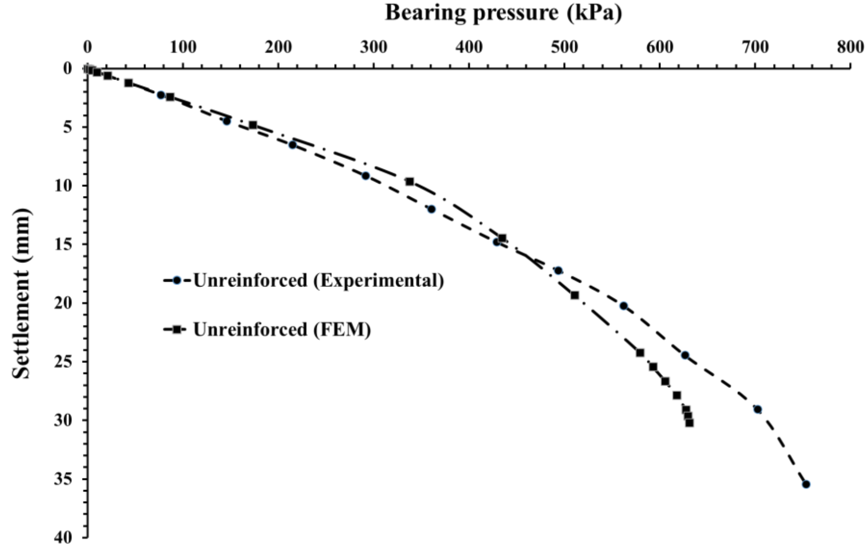
- Experimental work reported by Poorahong *et al.* (2024)
  - Fully instrumented unpaved road model constructed on soft clay subgrade has been used.
  - Bearing pressure versus settlement response
    - Unreinforced as well as geogrid reinforced unpaved road model.

- The unpaved road model
  - A crushed rock base layer of thickness ranging from 0.05 m to 0.2 m
  - Subgrade layer is a soft clay having a fixed thickness of 0.8m.
  - Standard axle load of 80 kN with tire pressure set at 550 kPa.
  - Six plate bearing model tests are conducted.
  - For validation
    - Model no. 2
      - Unreinforced section with crushed rock base layer of thickness 0.20 m on top of soft clay layer.
    - Model no. 6
      - Reinforced sections with different base layer thickness 0.2 m.

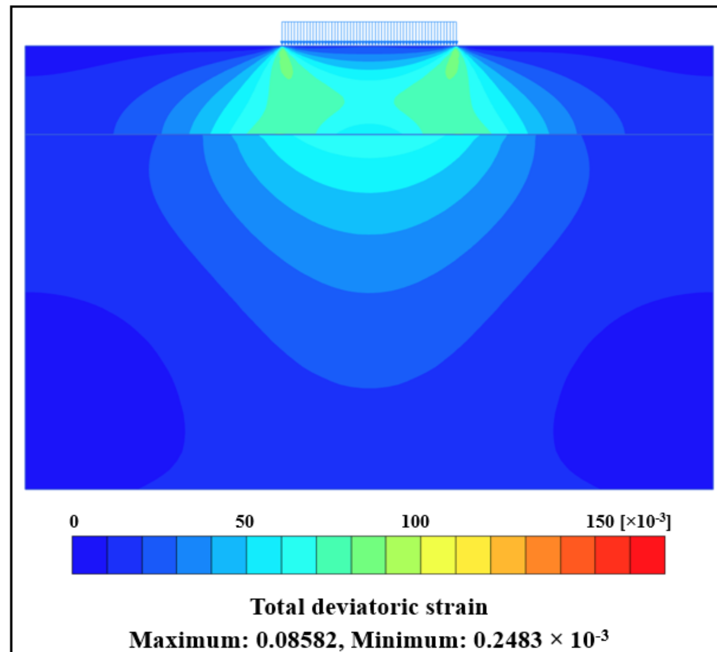


Validation of FE Design Methodology of Unpaved road

- Using the steps of proposed design methodology.
  - A FE model of unreinforced unpaved road is modelled
  - Both the FE and experimental results follows the same trend.
  - **The ultimate bearing capacity (q_{ult}) from the experimental model at 30 mm settlement**
    - **720 kPa.**
  - **Ultimate bearing capacity from FE analysis**
    - **640 kPa.**



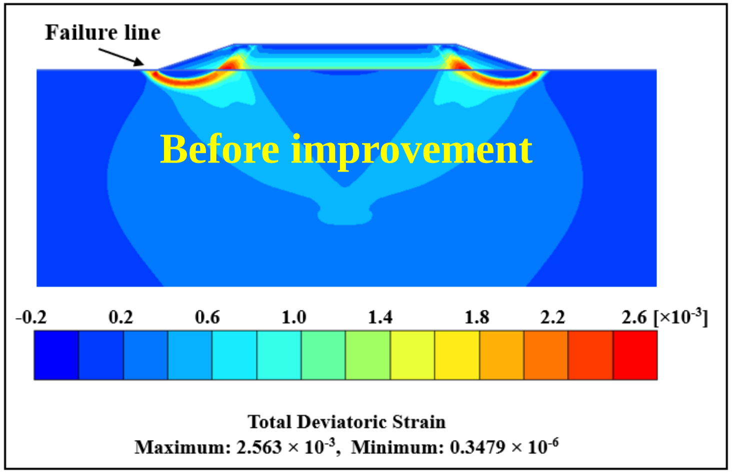
- For model Test no. 6
  - A geogrid layer has been introduced at the interface of base layer and subgrade layer.
  - **The ultimate bearing capacity (q_{ult}) from the experimental model at 30 mm settlement**
    - **1040 kPa.**
  - Ultimate bearing capacity from FE analysis
    - Strength of the subgrade layer (c_u) is heuristically increased
    - **A a c_u value of 1000 kN, the strains are captured at the base-subgrade interface**

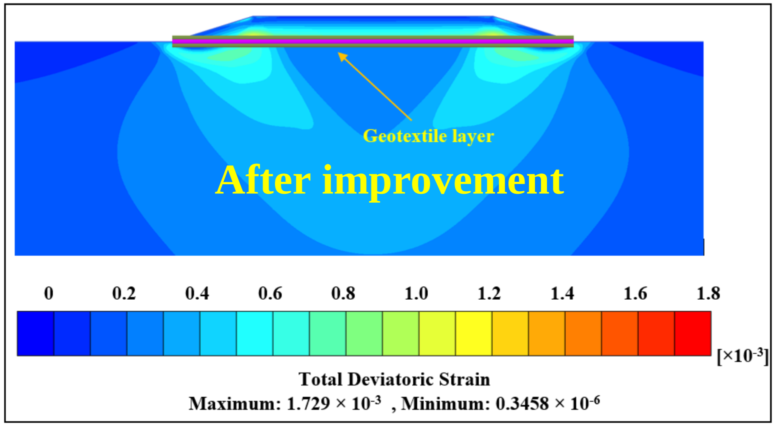


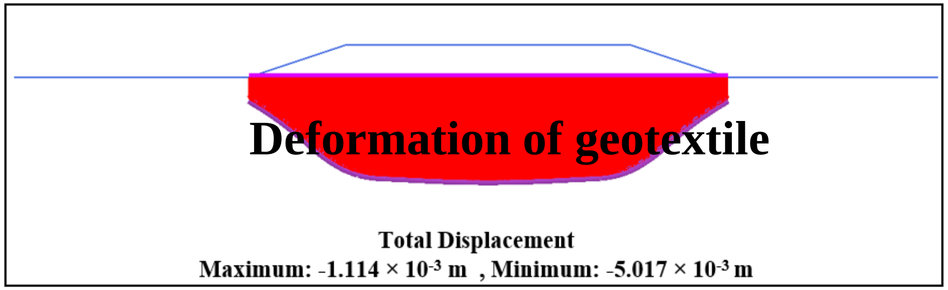
FE simulation results of reinforced unpaved road in Plaxis 2-D

Finite element design methodologies were developed

- Geotextile Reinforced unpaved roads
  - Minimum stiffness required by the geotextile layer
  - When the subgrade was failing under aggregate loading,
  - When the unpaved road system was failing under vehicular loading.
- For standard axle load
  - **In Step 3, subgrade failed due to aggregate load**
  - **The stiffness of the geotextile is considered to be 400 kN/m**
    - Model did not fail
  - Deformation of geotextile
    - Trapezoidal in nature
  - **With increase in stiffness**
    - **Geotextile can sustain more stresses**

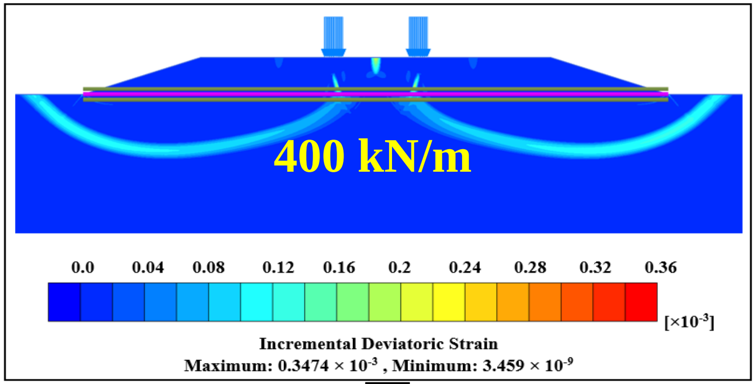


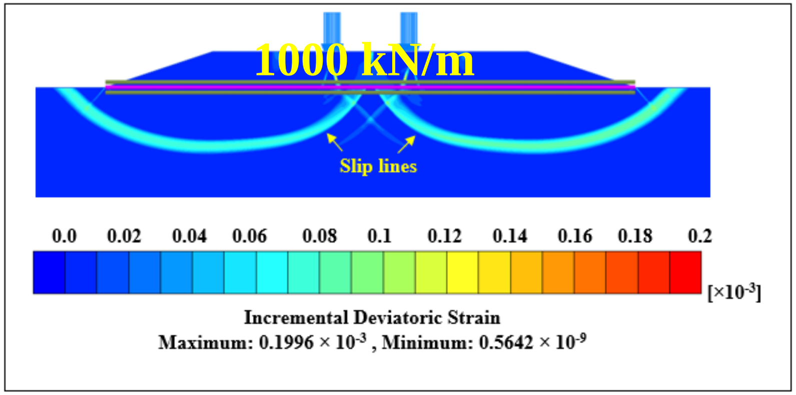


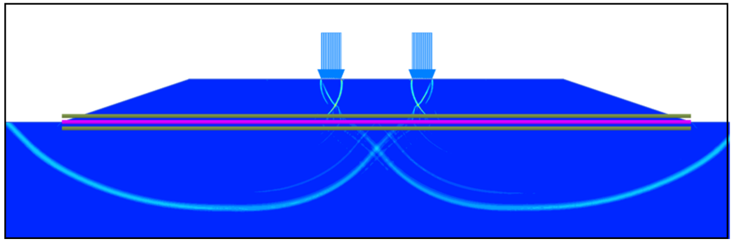


FE simulation results of reinforced unpaved road in Plaxis 2-D

- For standard axle load
  - **In Step 7, under vehicular load**
    - **Secondary stresses are generated in the subgrade layer**
      - **Additional strengthening of the subgrade is required**
  - **Geosynthetic layer is introduced to counter act the secondary stresses**
  - Stiffnesses of the geotextile considered
    - 400 kN/m and. 1000 kN/m
    - Maximum strain value reduced by half
    - Model is observed to exhibit failure
    - **Some additional ground treatment is also required**
      - $c_{sa,min}$**, value increased from 1.82 kPa to 2.5 kPa**





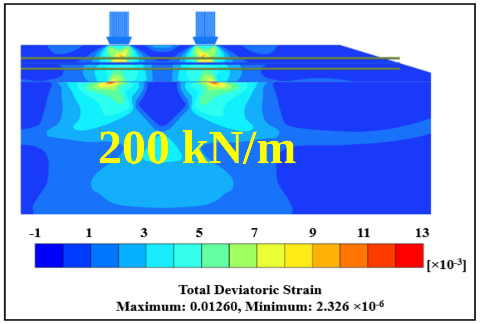


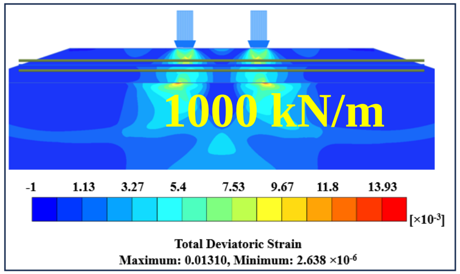
- For higher axle loading on soft subgrade, only geotextile is not enough.
- Some ground improvement of the subgrade is also required.

FE simulation results of reinforced unpaved road in Plaxis 2-D

FE-based simulation for a single geotextile layer inside the aggregate layer

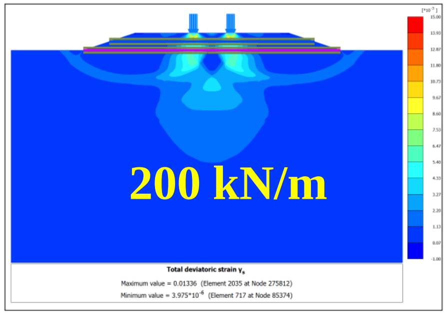
- Higher axle load still some stress transfer occurs from aggregate to subgrade.
- A study is conducted
  - Intercept the stresses coming from the vehicular load in the aggregate layer itself.
  - **Placing a geosynthetic at the mid-depth of aggregate layer.**
  - **Not much change in maximum strain developed in the model.**
  - Accumulation of strain at the interface of the reinforced unpaved layer.

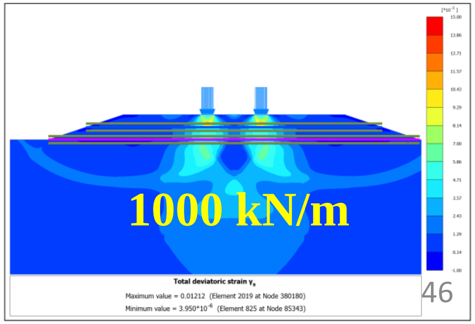




FE-based simulation for double geotextile layer in unpaved road

- For this study
  - Stiffness of the interface geosynthetic layer is kept at 1000 kN/m and that for the layer in the mid-depth of aggregate layer stiffness is varied from 200 kN/m to 1000 kN/m.
- **Strains are mostly accumulated beneath wheel loads.**
  - **Model undergoes failure.**
- For higher axle load
  - Stiffness of single geosynthetic layer is not enough to maintain stability of a reinforced unpaved road; some ground improvement is required simultaneously.





FE simulation results of reinforced unpaved road in Plaxis 2-D

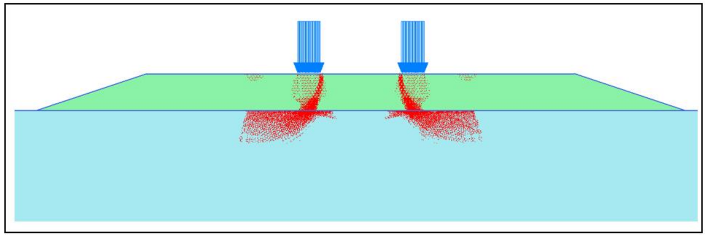
FE-based simulation for reinforced unpaved road with reduced thickness

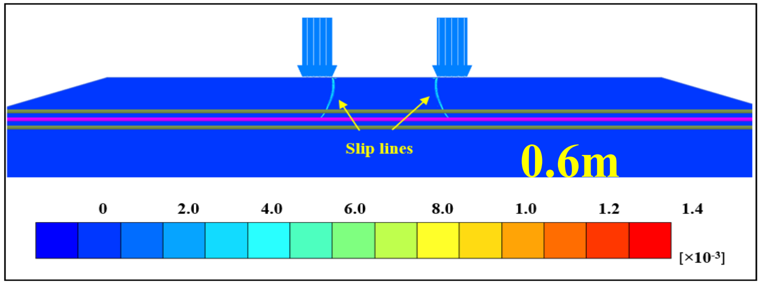
- For a **weaker subgrade or to support a higher axle load**
  - **Thicker aggregate layer would be required**
- **Application of geosynthetic**
  - Sustainable option in utilizing a **reduced thickness of the aggregate layer**
    - Stability of the unpaved road system.

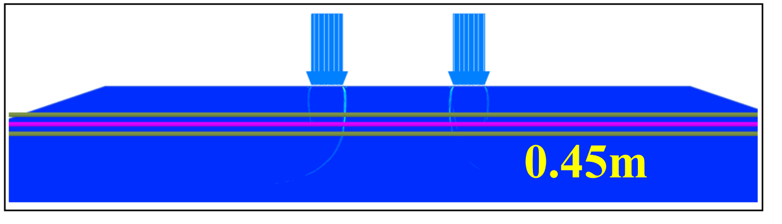
- For **Standard axle load**
  - **Initial thickness of the aggregate layer obtained 0.79 m**
  - The thickness of the aggregate layer is reduced.

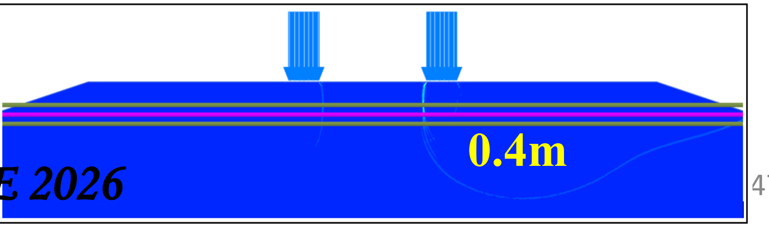
For reinforced case
- **The axial stiffness of the geotextile layer is chosen as 1000 kN/m.**
- **Thickness of the aggregate layer can be reduced up to 0.45 m**
- Beyond 0.45 m
  - Further ground improvement will be required.

For Unreinforced unpaved road
- **Thickness is reduced to 0.6 m.**
- **Model failed**
  - **Strain migration from aggregate to subgrade**







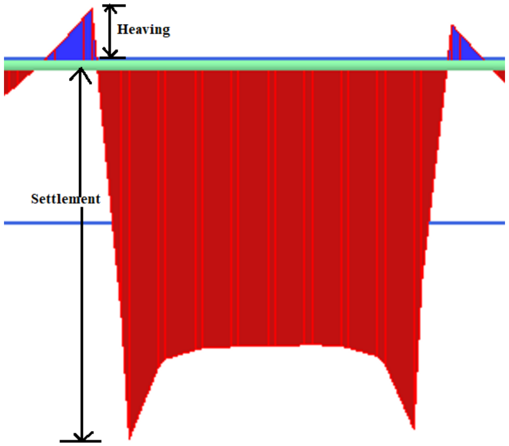


FE simulation results of Unreinforced unpaved road in Plaxis 2-D under Quasi-Dynamic loading

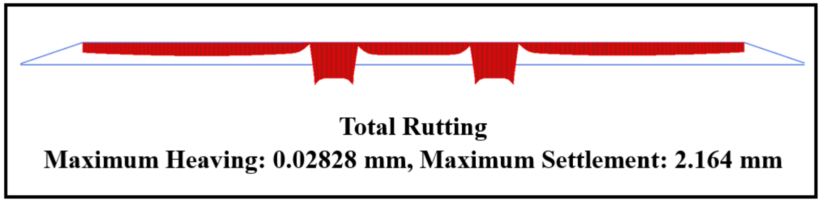
- Three axle loads 80 kN, 190 kN and 360 kN respectively.
  - (c_{sub}) = 20 kPa and (φ_{agg}) = 35° respectively.

For standard axle load

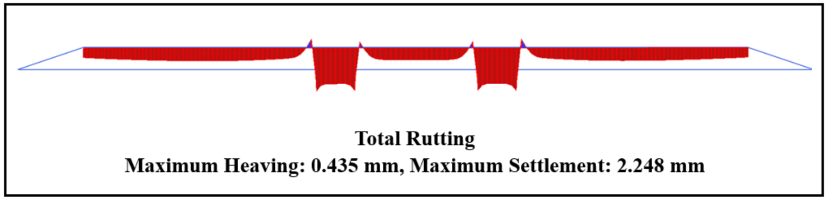
- Unreinforced unpaved road aggregate layered thickness 0.23
- For 1 vehicle pass
  - Heaving value is 0.02786 mm and settlement is 2.165 mm, therefore total rut is around 2.2 mm.
  - Maximum rut occurs near the edges of the vehicle.
- For 2 and 10 Vehicle passages
  - Total rut value are 2.683 mm and 2.716 mm
  - Compare to pass one rutting increase by 21% and 23%.



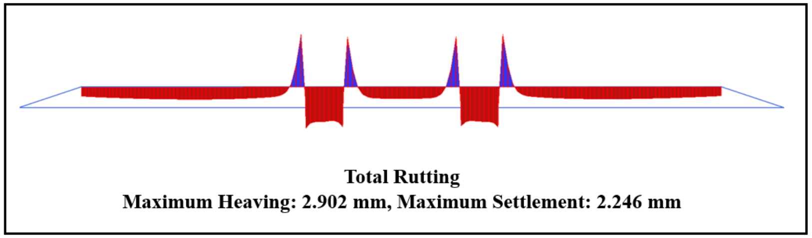
Rutting representation in FE analysis



1 vehicle pass



2 vehicle pass

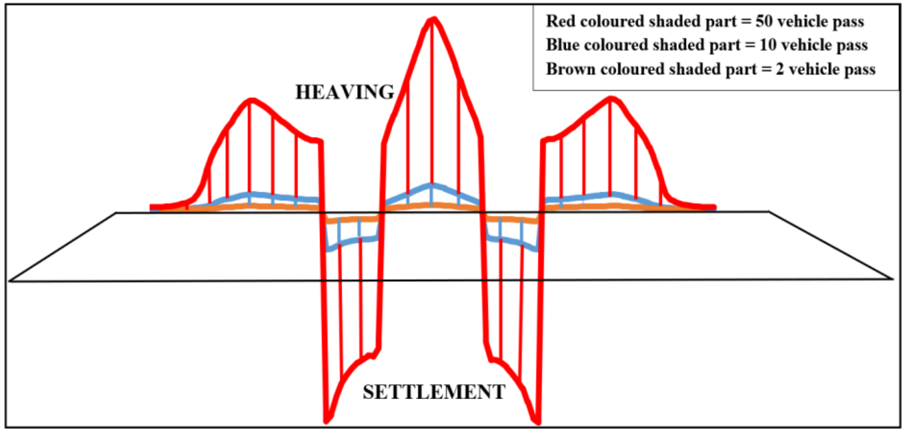


10 vehicle pass

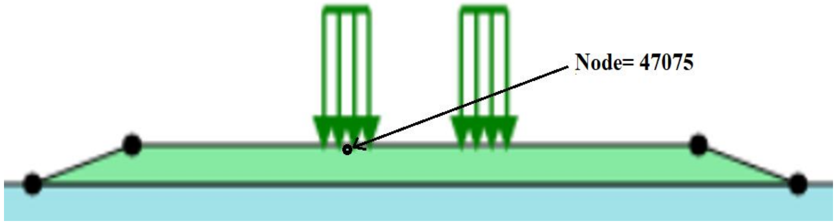
FE simulation results of Unreinforced unpaved road in Plaxis 2-D under Quasi-Dynamic loading

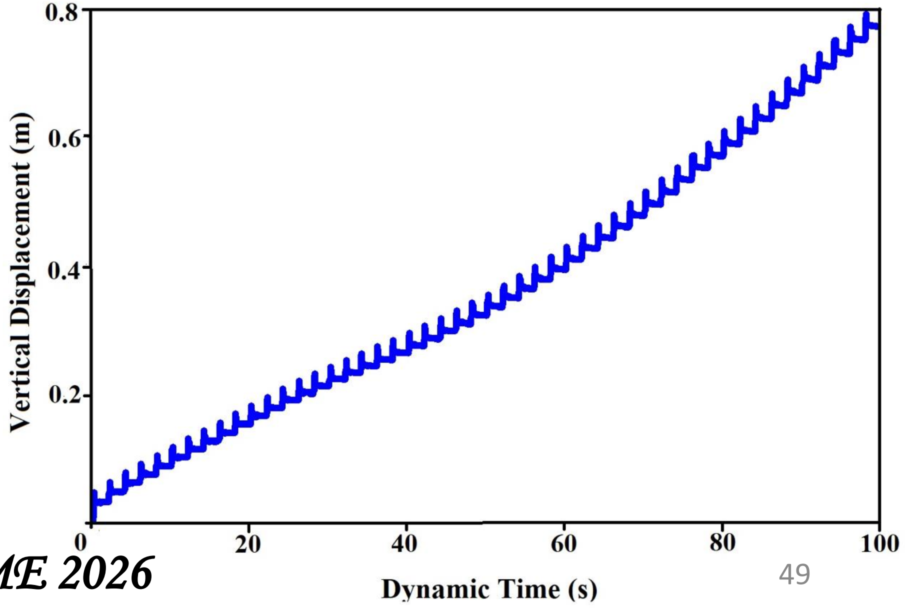
For 190 kN axle load

- Aggregate layered thickness 0.41 m.
- The model is analysed for three different numbers of vehicle passes: 2, 10 and 50 vehicles pass
  - Maximum heaving is at the central zone
  - Maximum settlement is near the edges of the vehicle tire.
  - The rut developed for the mentioned vehicle passes are 0.0823 m, 0.3233 m and 2.02 m respectively



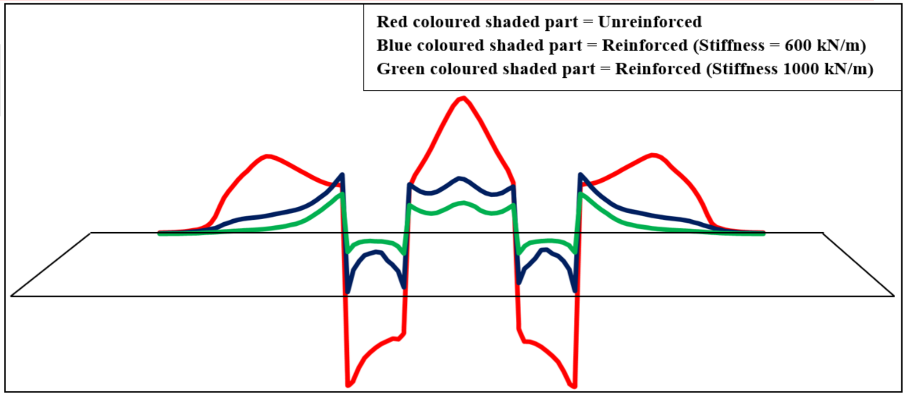
- Displacement vs dynamic time curve
  - With increase in passage the amount of permanent deformation increases.
  - The elastic rebound is observed
  - In each vehicle passages permanent settlement increase by 1.5 times.

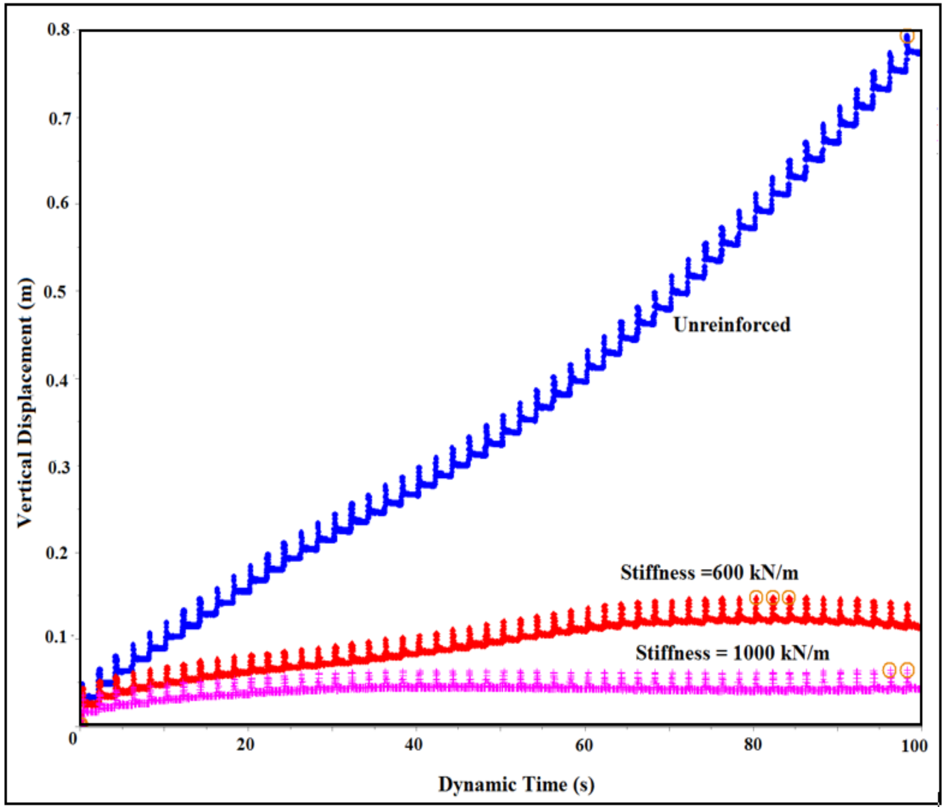




FE simulation results of Reinforced unpaved road in Plaxis 2-D under Quasi-Dynamic loading

Under axle load of 190 kN for 50 vehicle passes



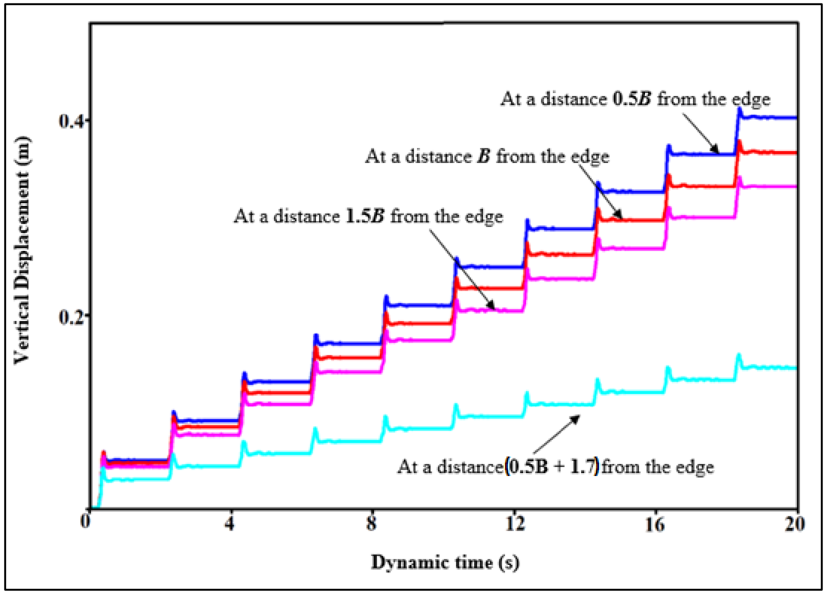


- For unreinforced case
  - The curve shows a gradual increase in permanent deformation with vehicular passages
- For reinforced unpaved road (600 kN/m)
  - Initial gradual increase in permanent deformation with vehicular passages
  - After few cycles, the rutting becomes almost constant.
  - Final deformation approximately 100 mm. For a geotextile having axial stiffness of 1000 kN/m.
- For reinforced unpaved road (1000 kN/m)
  - The final permanent deformation approximately 48 mm, which is lesser than the serviceability criteria of 75 mm.

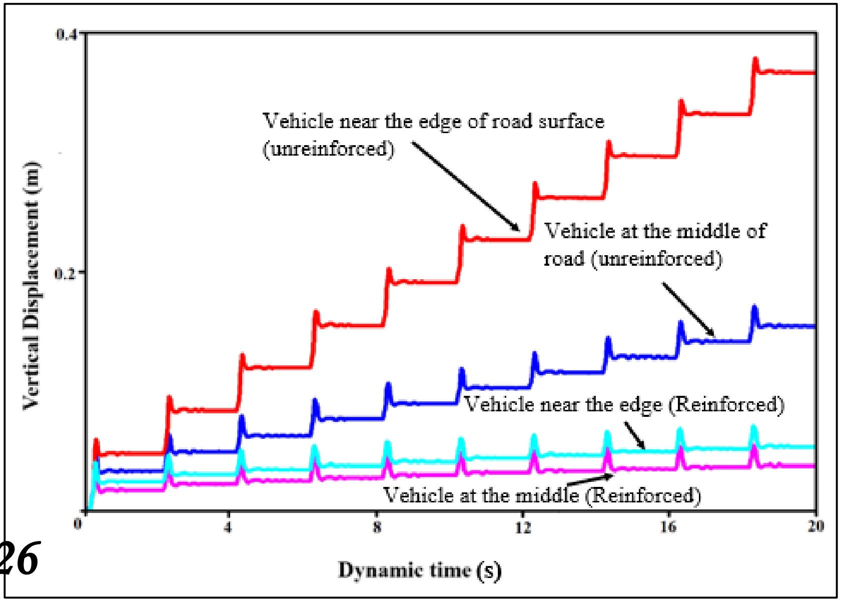
FE simulation results of vehicles at the edge of the road

Quasi-Dynamic Loading Scenario

- For 190 kN.
  - The total rut is around 0.55m, which beyond the serviceability limit criteria.
  - It can be observed near the edge of the road tremendous increase in the settlement.
  - Tire near to the road edge
    - larger vertical deformation can be observed as compared to tire away from the edge.
    - At 0.5*B*, *B* and 1.5*B* from the edge) are 0.4 m, 0.37 m and 0.33 m, respectively.
    - For the inner wheel Permanent vertical deformation is 0.14 m



- A comparative study of vertical displacement vs dynamic time
  - located at the center of the road and near the edge of the road
  - For unreinforced unpaved road system
    - Edge is nearly twice the magnitude of the middle of the road
  - For reinforced unpaved road system
    - Around 50 mm.



Limitations and Future Scopes

- Present study **does not incorporate the hydrological factors (water table fluctuation, seepage, and rainfall)**.
  - For low lying areas, incorporation of such features is important to build further understanding on the failure due to hydrological reasons.
- The entire study **has been conducted following the most basic and popular constitutive model used to represent the soil, i.e. the Mohr-Coulomb model**
  - Utilization of more advanced constitutive models such as the Modified Cam Clay or other elastoviscoplastic models
- **Design methodology** proposed in the present study **well established by the FE simulation results**.
  - **Field experimental on a proper road** will give more clear view on the field factors governing the design.

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  - **A platform to discuss interesting issues related to the Innovative Approaches to Road Safety and Material Engineering (IARSME 2026)**
- **A special appreciation to the contributors**
  - **The workforce to bring out the intricate findings**




- **All those researchers who laid the foundation of present day discussions**

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