Case Study 04: A new approach for modelling vertical stress distribution at the soil/tyre interface to predict the compaction of cultivated soils by using the PLAXIS code

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Objective

- FEM modelling using Plaxis 2D to simulate the vertical stress distribution and to model the compaction.

Background

- Soil compaction with the help of the wheeling of agricultural machines modifies the structure of cultivated soils and affects crop production and the environment.
- The models proposed to predict soil compaction incorporate two components which first include upper boundary conditions (contact area, vertical stress distribution at soil/tyre interface) and second stress propagation and deformation in soil.
- Soil compaction models can be divided into two categories, namely analytical and numerical finite element models.
- FEM models are more accurate than analytical models for generating the mechanical behavior of soil but require more input parameters.
- The problem of difficulty in measurement of vertical stress distribution at the soil/tyre interface because of tyre lugs and soil surface roughness is overcome by measurements on the road, 10 cm below the soil surface and by embedding a pressure gauge directly in the tyre.
- Here, a new approach to numerically model vertical stress distribution perpendicular to the driving direction at the soil/tyre interface, employing the FEM models of PLAXIS.
- The approach consists of a beam (characterised by its geometric dimensions and flexural rigidity) introduced at the soil surface and loaded with uniform stress to simulate the action of a wheel at the soil surface.
- Different shapes of stress distribution are then obtained numerically at the soil surface by varying the flexural rigidity of the beam and the mechanical parameters of the soil.
- PLAXIS simulations show that the soil type (soil texture) modifies the shape of the stress distribution at the edges of the contact interface: a parabolic form is obtained for sand, whereas a U-shaped is obtained for clay.
- The flexural rigidity of the beam changes the shape of the distribution which varies from a homogenous (uniform) to a non-homogeneous distribution (parabolic or U-shaped distribution). These results agree with the measurements of stress distributions for different soils in the literature.

Sensitivity of PLAXIS to soil type, beam flexural rigidity and applied stress

- The flexural rigidity can be used to generate a homogenous or heterogeneous distribution of vertical stress.
- In this case, the circular plate introduced as a beam at the soil interface is used and fully drained, with axisymmetric conditions with the Mohr-Coulomb model implemented.
- The 2D cross-section of 11m x 3m was modelled and no effect for side and depth was considered for calculation. The plate of diameter 0.6m modelled having vertical uniform stress of 150 kPa. Two different cases were considered to have different flexural stiffness which corresponds to flexible ($\Re$ = 0.01kNm^2) and rigid plate ($\Re$= 8500 kNm^2).
- The effect of different soil parameters was also studied by comparing sandy and clayey soil and loamy soil at different water contents (0.23 and 0.26 gg^{-1}).

- For studying the effect of applied vertical stress the vertical stress increased to 180 kPa generated by increasing load above the plate. For the stress effect study, only rigid plates were considered.

Data collection and simulation

- The oedometer, Triaxial and direct shear test performed for generating inputs required for performing analysis in PLAXIS.
- The properties of soil which are used during the tests are mentioned below,

Soil parameter	Clay soil (PLAXIS Bulletin, 1999)	Sandy soil (Gysi et al., 2001)
Dry soil weight γ_{dry} (kNm^{-3})	17.80	17
Young's modulus E (kPa)	784.7	13000
Poisson's ratio ν	0.33	0.3
Cohesion c (kPa)	5.4	2
Angle of internal friction ϕ	31.4	32
Dilatancy angle ψ	0	0

Table 1 : Soil properties of clay soil and sandy soil to be used in PLAXIS software

Soil parameter	W = 0.23 gg^{-1}	W = 0.25 gg^{-1}	w = 0.26 gg^{-1}
Dry soil weight γ_{dry} (kNm^{-3})	12.8	12.8	12.8
Young's modulus E (kPa)	316.5	308.9	305.8
Poisson's ratio ν	0.33	0.33	0.33
Cohesion c (kPa)	15.2	8.3	4.8
Angle of internal friction ϕ	29.1	29.3	29.4
Dilatancy angle ψ	0	0	0
Modified compression index λ*	0.081	0.091	-
Modified swelling index κ*	0.042	0.042	-
Pre-overburden pressure POP (kPa)	40.0 or 49.1[c]	40 or 49.1[c]	-

Table 2 : Soil properties of loamy soil at different water content (0.23, 0.25 and 0.26 gg^{-1})

Plate sinkage test

- The plate of 25cm diameter and 2cm thick pushed by hydraulic jack and average contact pressure between soil and plate was maintained constant during compression at 100 kPa for a loading time of 30s.
- The bulk density profile was generated from 2.5cm to 32.5cm depth under plate center by using gamma ray transmission equipment before applying pressure, and by removing sample cylinders under the plate center after compaction.
- The soil water content profile determined gravimetrically (mean =0.23 gg^{-1}) and rut depth profile also measured.
- The Mohr-Coulomb model used to model soil behavior requires five inputs were generated by oedometer test and simple shear box test.

- Initially, the vertical stress distribution was compared for real plate with $\Re$ = 33.3kNm^2 and very soft plate with $\Re$ = 0.01 kNm^2.
- Uniform stress applied for both cases. Also, bulk density profile was modelled under two vertical stress distributions and fully drained, axisymmetric conditions were assumed.
- For performing calculation, a non-uniform grid with 1119 elements on 2D cross-section of 6.05m X 1m with rigid soil interface at 1m modelled. The 100 kPa stress on a plate of 0.25 m diameter was applied.

Wheeling test

- This test carried out using 6-tonne IH 956 tractors. It has two wheels, the front wheel having width of 50 cm and overall tyre diameter of 123.9cm while a rear one has width of 65cm and overall diameter of 170.4 cm.
- The test was carried out with inflation pressure of 60 kPa. The driving speed of tractor was 8 km h^{-1}.
- The bulk density under center of tyre was measured with gamma ray transmission equipment before and after compaction. Two treatments with two different water contents were carried out in field. (Treatment 1: w = 0.23 gg^{-1} and Treatment 2: w = 0.25 gg^{-1})
- For modelling, soft soil model was used. This model helps to consider effect of passage of first wheel on soil strength with pre-consolidation of soil by using Pre-Overburden Pressure (POP).
- The soil was assumed homogeneous and its compaction modelled perpendicular to driving direction. The shearing effect of wheel can be neglected in this perpendicular direction.
- The distribution of vertical stresses was compared for two cases, one with very rigid cylinder ($\Re$ = 8500 kNm^2) and a very soft cylinder ($\Re$ = 0.01 kNm^2), vertical stress of 49.1 kPa
- Fully drained and plain strain conditions were assumed. The passage of two tractor wheels was modelled step by step by applying two successive vertical stresses on two different cylinders. Both vertical stresses calculated by dividing tyre load by contact area between tyre and soil.
- In this model, Pre-Overburden pressure POP is used.

PLAXIS model

1. Sensitivity analysis

- The model of 11m x 3m is modelled in axisymmetric conditions.
- Drained analysis performed using Mohr-Coulomb soil model.
- The plate of 0.6m width is modelled and uniformly loaded with 150 kPa and its sensitivity is checked with respect to different soils, stiffness of plate.

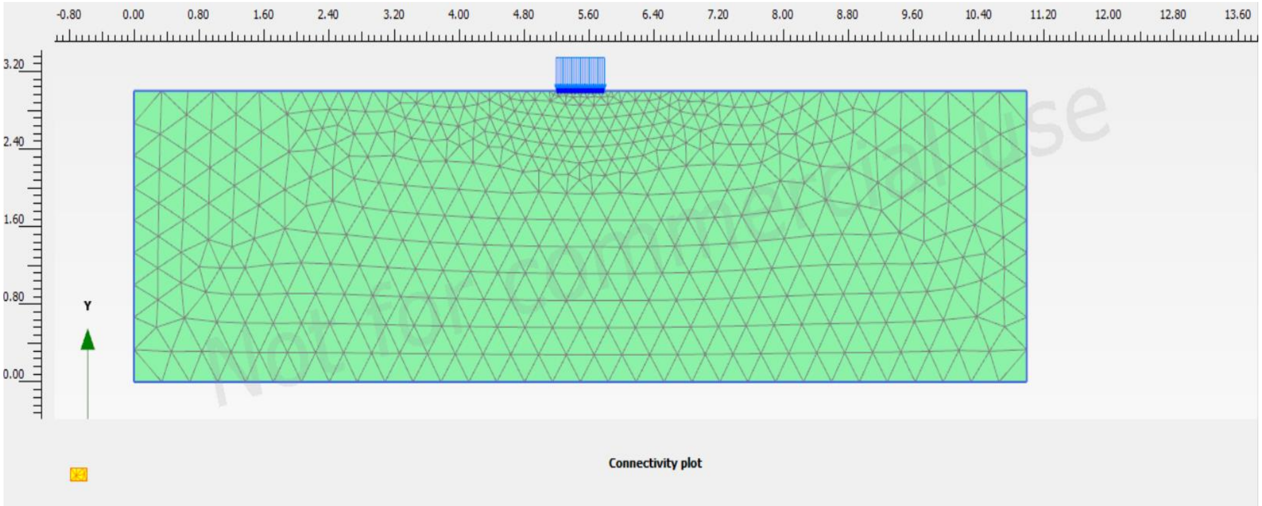


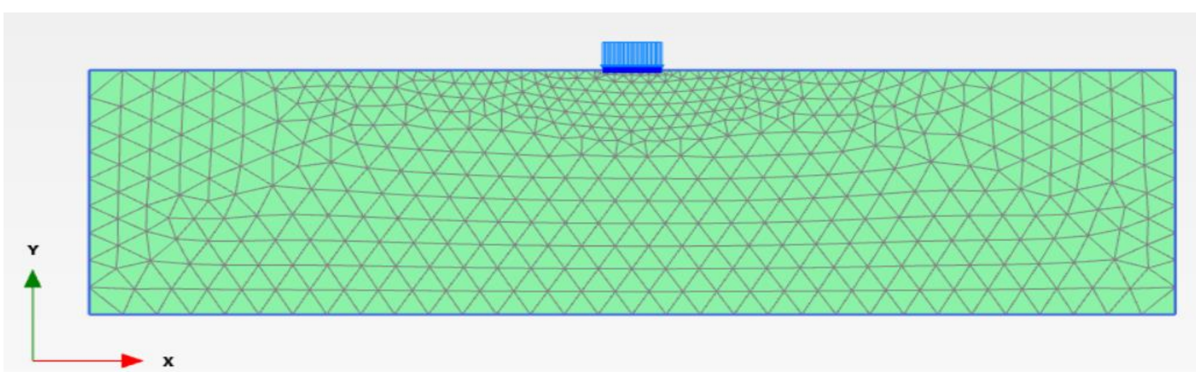
Figure 1 : PLAXIS axisymmetric model with very fine meshing for sensitivity analysis.

2. Sinkage test

- The model of 6.05m x 1m is modelled in fully drained and axisymmetric condition. The Mohr-Coulomb soil model was used.
- Modelled plate is of 0.25m diameter with different stiffness properties. The loamy soil with water content (0.23 gg^{-1}) was used for analysis.

3. Wheeling test

- The model of 10.6m x 1m is modelled in fully drained and plane strain condition. The soft soil model was used.
- Modelled plate is of 0.5m width and with different stiffness properties for very rigid cylinder and very soft cylinder. The soil was loamy with different water content of 0.23gg^{-1} and 0.25gg^{-1} used in analysis.
- After performing fine meshing, 373 elements and 3191 nodes were generated.



- Figure 2 : PLAXIS Plain strain model with fine meshing for wheeling test

Results

1. Sensitivity analysis

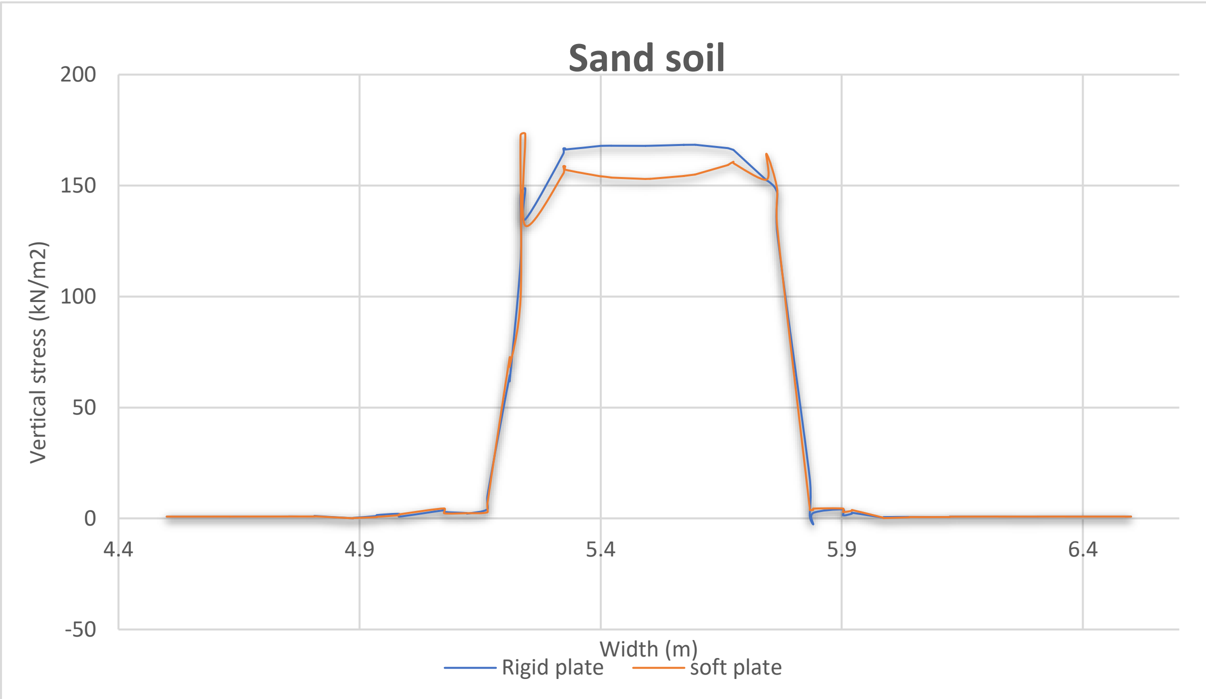


Figure 3 : Calculated vertical stress distribution on soil surface with a flexible (($\Re$ = 0.01 kNm^2) and rigid ($\Re$ = 8500 kNm^2) circular plate on sandy soil (Gysi et al.,2001)

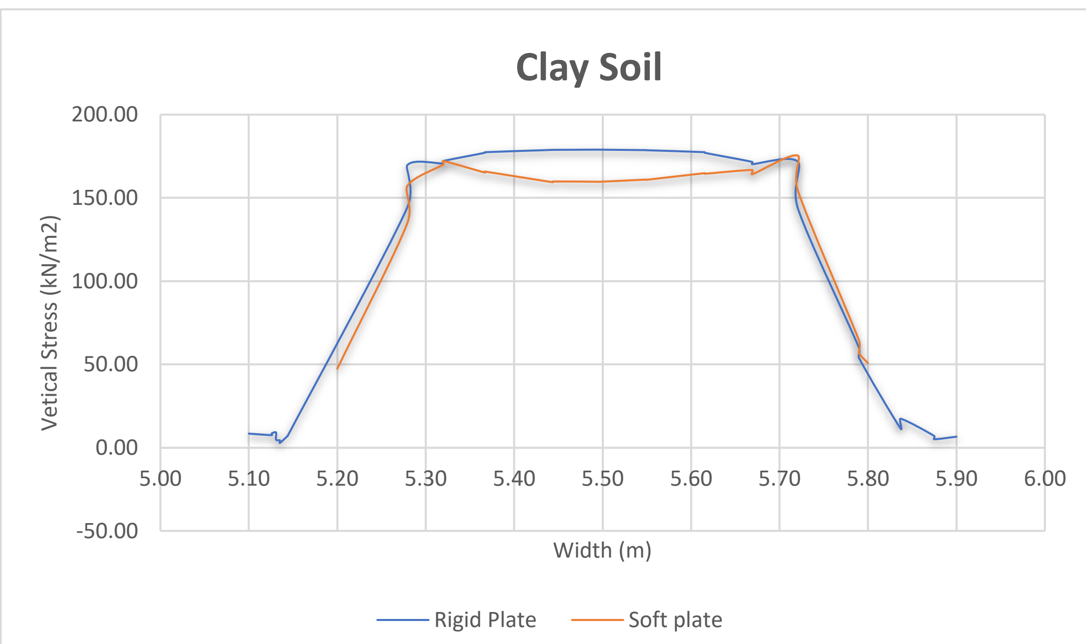


Figure 4: Calculated vertical stress distributions on soil surface with a flexible (($\Re$ = 0.01 kNm^2) and rigid ($\Re$ = 8500 kNm^2) circular plate on clay soil (PLAXIS Bulletin, 1999)

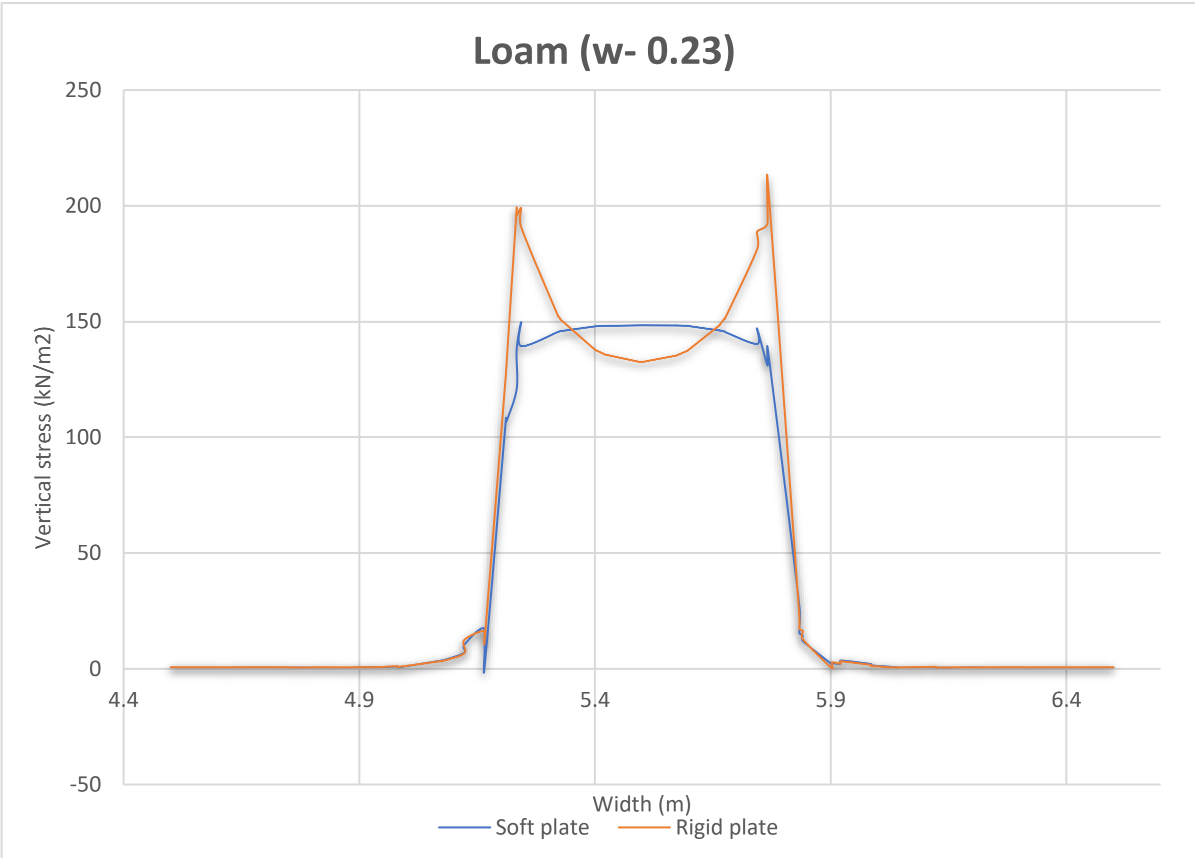


Figure 5 : Calculated vertical stress distributions on soil surface with a flexible (($\Re$ = 0.01 kNm^2) and rigid ($\Re$ = 8500 kNm^2) circular plate on loamy soil with w =0.23 gg^{-1}

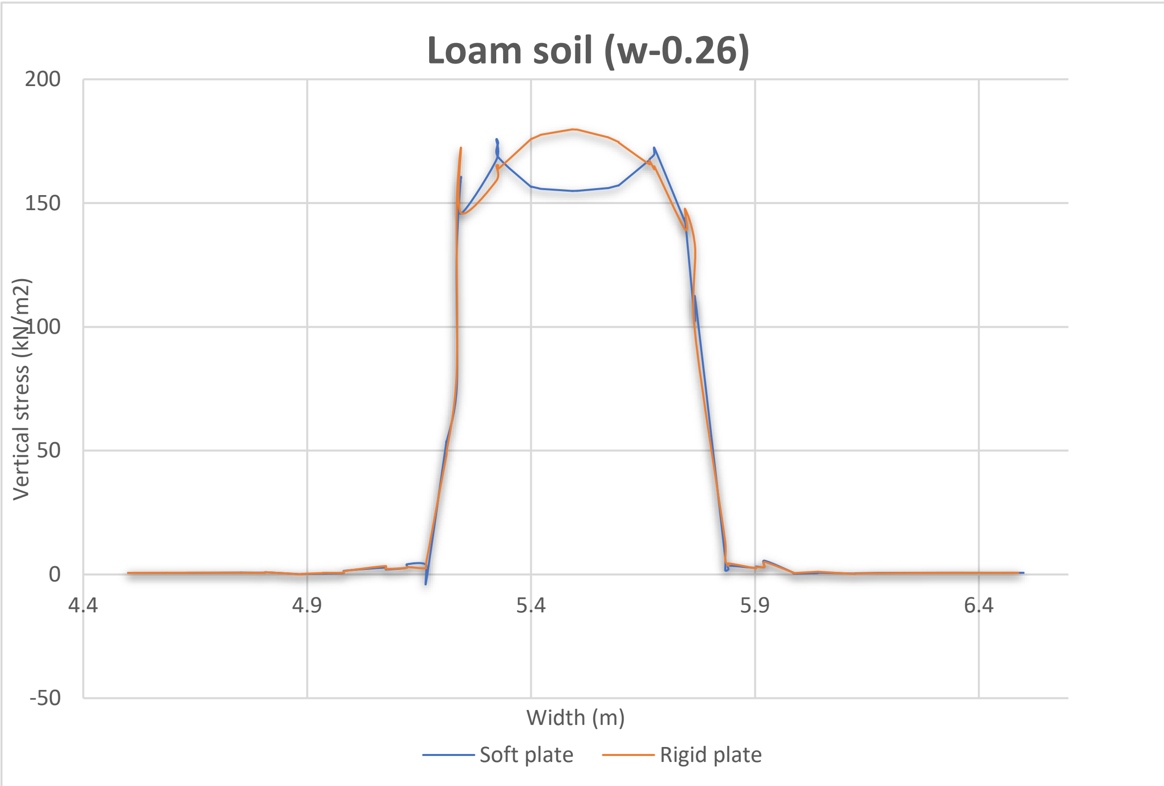
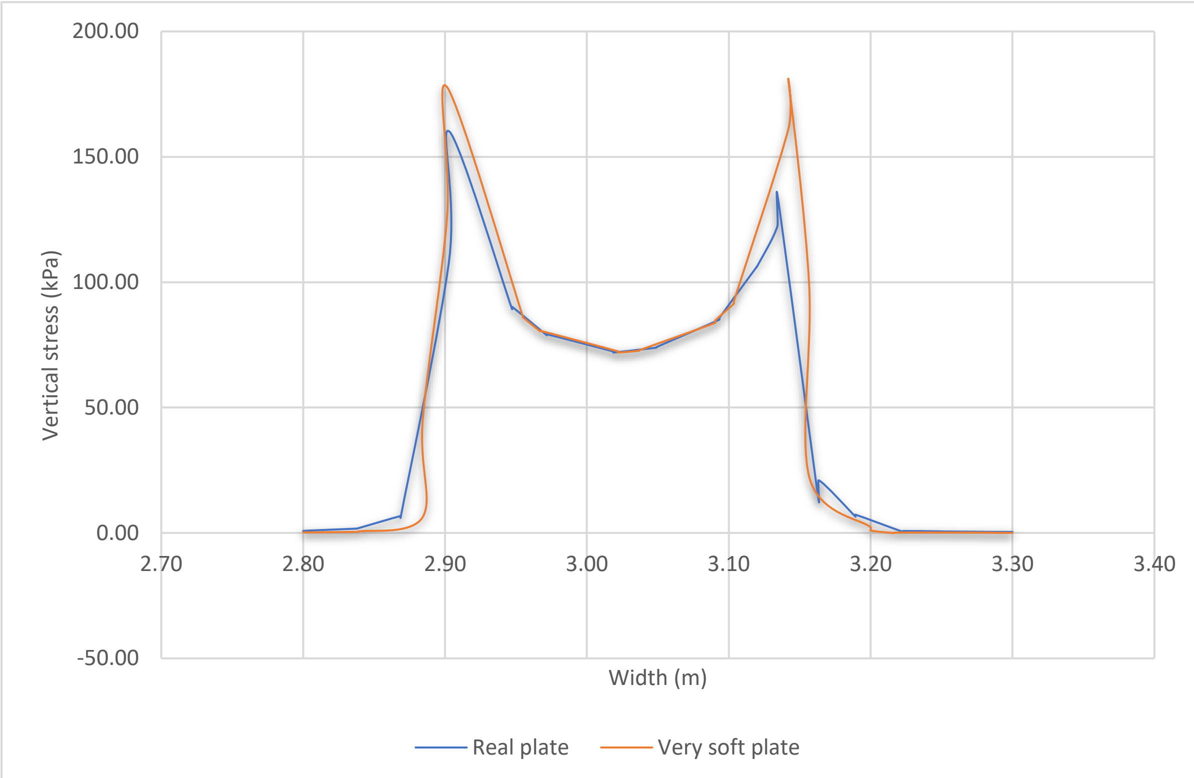


Figure 6 : Calculated vertical stress distributions on soil surface with a flexible (($\Re$ = 0.01 kNm^2) and rigid ($\Re$ = 8500 kNm^2) circular plate on loamy soil with w = 0.26gg^{-1}

Sinkage test

A. Pressure distribution on the surface

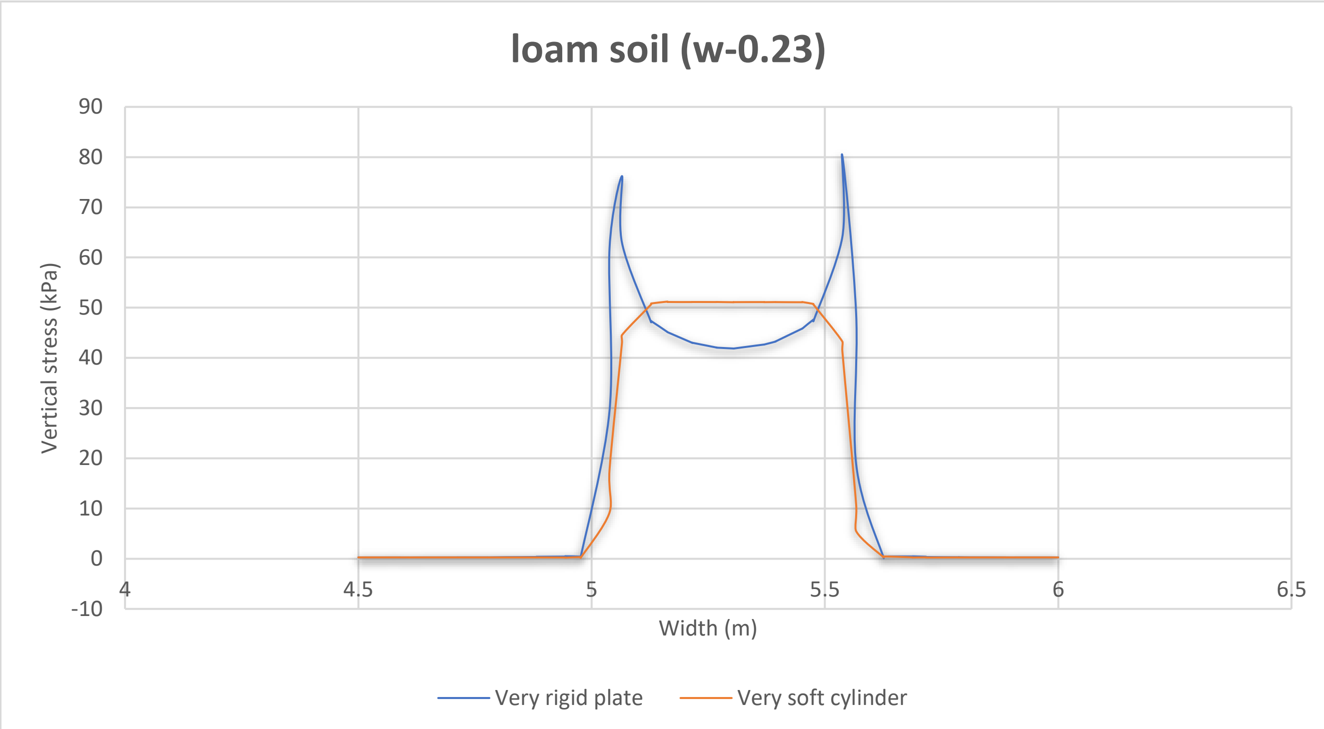
Figure 3 : Vertical stress distribution on loamy soil (w=0.23 gg-1) at surface with very soft ($\Re$ = 0.01 kNm^2) and

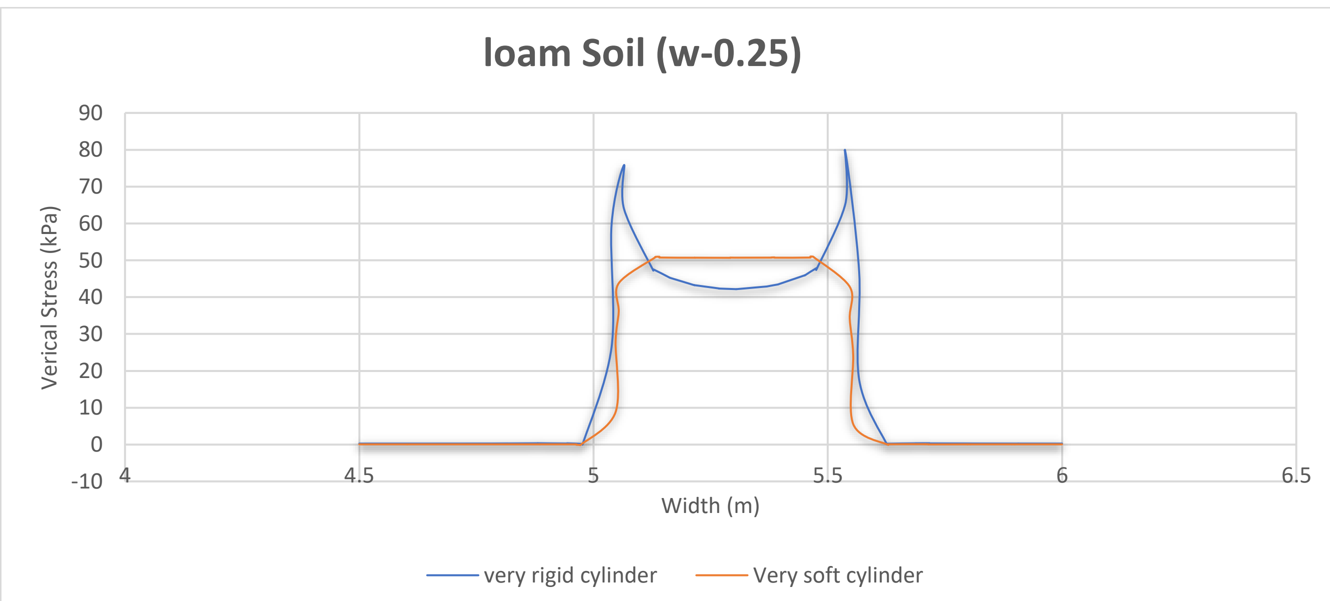


2. Wheeling test

A. Pressure distribution on loamy soil (w=0.23 gg^{-1})

- On soil surface





Conclusion

- Numerical modelling using the PLAXIS FEM model was proposed. It is based on the concept of a beam with a contact area, flexural rigidity and an applied uniform vertical stress above it to describe the soil/tyre interface.
- From the results, it can be depicted that this new approach can be implemented for the calculation of vertical stress distribution and thereby model compaction by considering soil type depending upon the mechanical parameters, the flexural rigidity of the beam and applied uniform vertical pressure.

- To improve the approach in this study, a quantitative relationship between flexural rigidity and different types of tyres used on the same soil.
- Soil properties, mechanical parameters, EI, and applied uniform vertical are used as input parameters.

References

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- Alexandrou, A., & Earl, R. (1995). In situ determination of the pre-compaction stress of a soil. *Journal of Agricultural Engineering Research*, *61*(1), 67-71.