Numerical investigation of soil behaviour under road structures

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Abstract: Methods of road structures for designing and reinforcing are not up to date and do not keep up with newer technical specifications. From a geotechnical perspective, approximations and simplifications are used to determine the design bearing capacity of the earthwork during the dimensioning of road structures

In the calculations, the soil characterized by a single modulus of bearing capacity only, so no take account the soil bearing capacity according to changes of depth. It is easy to see that the real behaviour of the subsoil is not properly taken into account in the design procedure.

In this article, we show how the behaviour of the subsoil under the given road structure layer has been tried to model in the most realistic way using Plaxis2D. Basically, we have investigated the ability of traffic loads on the roadway structure to influence the deformation caused by the stresses in the earthworks. These deformations affect the subsidence of the road structure, the extent of which is important to know in the design process, as excessive deformations can cause damage and failure of the road structure.

A HS-Small material model has been specified for modelling the subbase; this model takes into account the range of small strain and the increase stiffness that occurs within it, so that under the limit depth the extent of compression of the subbase is not overestimated. We use the term boundary depth, but this is also called the depth of the active compression zone.

In order to increase the efficiency of the modelling, the "Guidelines for mathematical dimensioning of foundations of traffic surfaces with a course asphalt surface" (RDO-Asphalt 09/E) were used to determine the loads on the road structure, and the stiffness of the asphalt concrete where to take into account the effect of climatic conditions on the stiffness.

Keywords: road structures; climatic conditions; HS-small material model; linear elastic

1. Introduction

In today's fast-paced lifestyle, there has been a clear increase in car use in recent years; according to the KSH 2020 data, there are nearly 4 million cars on the road, and the number of trucks has already crossed 500,000 since 2018 due to increased freight transport. Generally, traffic on domestic roads is increasing steadily, with capacity utilisation already exceeding 100 percent on some sections. In view of this, the construction of missing road network elements must be continued and existing road networks require continuous maintenance and upgrading. Developments must be planned using the most up-to-date methods possible, taking into account the need to optimise costs also, to this way achieve the best possible quality of service.

From a geotechnical point of view, when designing road structures, it is important to consider how and with what parameters are taken into account the behaviour of the soil under the structural layer. The choice of these inputs should be made with the aim of getting as close as possible to reality, while taking into account economic considerations.

In the sizing procedures, the subbase bearing capacity modulus can be obtained by laboratory testing for traffic load classes D, E and K, or by using a table for traffic load classes A, B and C. The soil is thus characterised by a single modulus of bearing capacity, ignoring the change of soil bearing capacity with depth. When examining the real behaviour of the subsoil, it has to be taken into account that in the compacted soil layers, stresses are created both by the self-weight of the subbase and by the vehicle loads, which cause deformations and subsidence. In addition, it should also be taken into account that the construction also has an impact on the subbase. These loads, together with the unloading - re-loading phenomenon, cause a change in the stiffness modulus of the soil layer. Finally, it is also worth noting that the simpler material models used in widely used finite element calculations, often overestimate the compression of the lower layers. They cannot be considered as completely realistic, as these models not take account the limiting depth concept, thus summing up the subsidence without a limit.

In the following, a Plaxis 2D model of a type of road structure of traffic load class R is presented and the resulting data are evaluated. In the modelling, we have tried to take into account the conditions listed above, e.g., to determine, for a given soil layer, the extent to which different loads and asphalt stiffnesses affect the stiffness values in a range of small deformations. In this article which based on master thesis, 4-4 type road structures for two traffic load classes with varying asphalt stiffnesses per quarter and 4 different load intensities were investigated. We made in total 128 finite element runs.

2. MODELLING

In finite element modelling, the choice of material models was influenced by whether the model type well approximates the physical properties of the material under investigation. Plaxis allows the use of several non-linear material models to describe the soil environment. As a result, the HSsmall material model was used for the subbase and the subgrade layers, while simpler linear models were used for other materials. For the asphalt concrete and FZKA layers, a Linear Elastic material model was chosen, and for the CKt base layers, a Mohr-Coulomb material model was chosen.

2.1. HS-Small material model

The HSsmall material model is a Hardening Soil model with small-strain stiffness. For conventional linear elasticity-based subsidence calculations, we can assume that stresses can be developed to infinite depth, from which deformations values are obtained to the same infinite depth, resulting in an infinite subsidence value from the summed deformations. In contrast, in the HSsmall material model, stresses that develop beyond the limiting depth no cause deformation, compression, and this is called the range of small strains. It should also be noted that at the beginning of the loading and unloading - reloading cycles, smaller deformations are produced, as shown in Fig. 1.

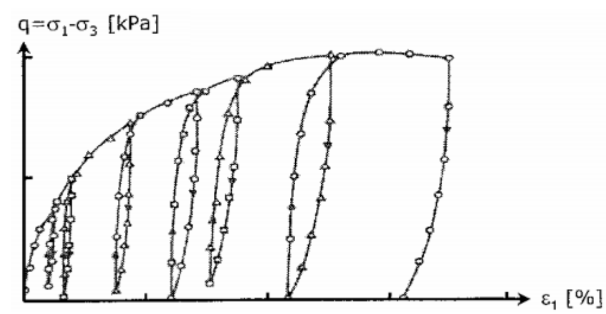

Figure 1 Modulus of the triaxial test interpreted in terms of σ-ε

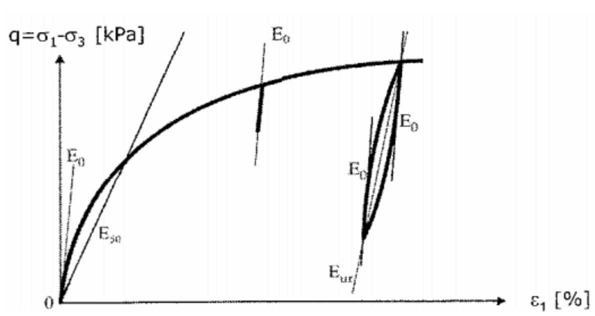

Figure 2 Stiffness and strength parameters of HS-Small model, right

For the HSsmall material model, the program calculates with the modulus G_0 at the beginning of the load changes (in the range of small strains) and then a gradually decreasing shear modulus as the shear strain increases. In the higher strain range, as is usual for the hardening soil model, the soil layer is characterised by a gradually increasing E modulus with increasing stress level (Figure 3).

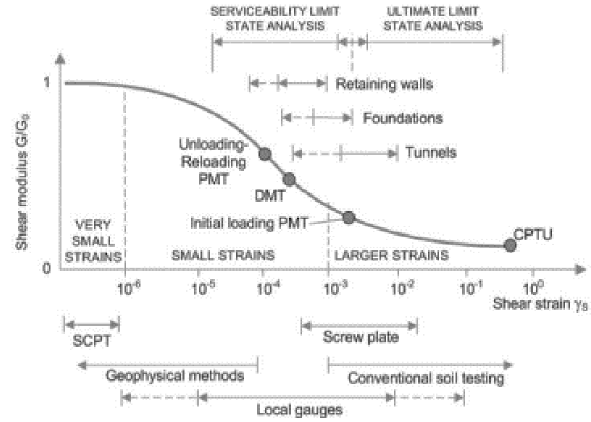

Figure 3 Characteristic stiffness-strain curve for soils

2.2. Model structure

Road structures of type K and R traffic load classes, defined according to the road technical specification ÚT 2-1.202:2005 "Design and reinforcement of asphalt pavement structures", were modelled using Plaxis 2D finite element software. The table below shows the semi-rigid road structure R1, where the asphalt layers are built on a base layer of hydraulic binder stabilisation, in this case CSG (cement-stabilised gravel).

Table 1 Road structure layers R1

semi-rigid (20 cm thick hydraulic binder stabilisation) road structure of traffic load class R1	
4 cm	wearing course AC11
11 cm	binder course AC22
12 cm	base layer AC22
20 cm	CSG base layer
60 cm	subbase
	natural subgrade

Figure 5 shows the layering scheme already modelled. The analysis was performed by building an axisymmetric model geometry. The load wheel in the present computational model is wide (super single) type, that is we calculated with a single heavy-duty vehicle wheel whose the load force distributed on a circular disc of radius r=0.1575 m. Note that for the calculation models, a surface of r=0,15 m was considered to take the load. The extent of the model space was defined so that the stress states in the road structures are not affected by the size of the "soil box" created in the modelling. The modelling was based on a 2x1 traffic lane roadway layering, so used for the width of the traffic lane size commonly was also considered.

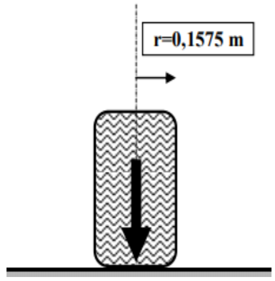

Figure 4 Diagram of a load wheel

Based on these data, the edge of the domain was defined at a distance of 3 m in the x-axis direction, while in the vertical direction the lower boundary of the model was defined at a depth of 2 m, as seen from the origin at coordinates (0, 0).

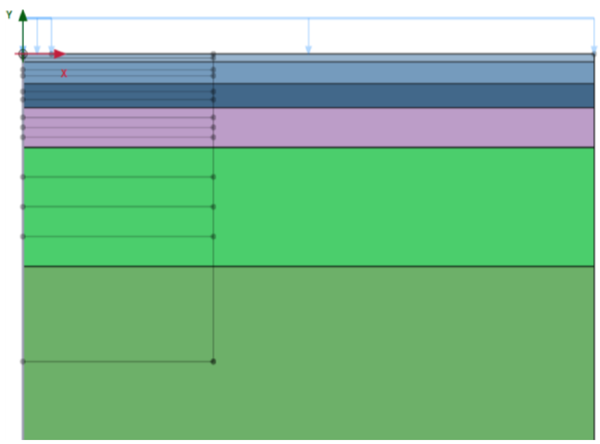

Figure 5 Plaxis 2D geometry model of the R1 road structure layer system

2.3. Defining load values

In the finite element modelling, the load phases acting on each pavement layer were split into two parts. For the load values, we separated the preload and the vehicle load acting on the track structure itself.

The preload was set to 150 kPa in each calculation run to allow for the effect of compaction during construction. The preload was activated or deactivated in the corresponding phases and the actual load values were only recorded after the deactivation phase.

Loads caused by vehicles with different axle weights were considered when determining the actual loads. The axle load classes were taken into account on the basis of the data provided, which was based on the German road structure sizing procedure (RDO Asphalt 09/E).

Axle weight distribution intervals:

– 0 - 4 tonnes → Axle weight load value of 2 tonnes considered
– 4 - 8 tonnes → Axle weight load value of 6 tonnes considered
– 8 - 12 tonnes → Axle weight load value of 10 tonnes considered
– 12 - 14 tonnes → Axle weight load value of 13 tonnes considered

The calculated values on the small distributed loads are given in the table below.

Table 2 Calculated values of distributed loads

Mean load value of pendulum weight distribution [tonnes]	2	6	10	13
Small surface area (0,15 m radius circle area) [m^2]	0.0707	0.0707	0.0707	0.0707
Weight distribution on the surface [tonnes /m^2]	28.2942	84.8826	141.4711	183.9124
tons-- kPa conversion	1	tons =	9.80665	kPa
Calculated distributed load value [kPa]	**277**	**832**	**1387**	**1804**

2.4. Defining soil physical parameters and calculation phases

The values of soil physical parameters used in the models were partly based on experience, recommendations and laboratory tests, and partly on the data available (Table 3).

In the resulting data service, the stiffness parameter for each asphalt concrete layer was given, interpreted for the middle of the layer, with separated quarterly.

Table 3 Subbase and natural subgrade physics parameters

		Subbase	**Natural subgrade**
Designation	Unit of measurement	**HS-Small**	**HS-Small**
γ_{unsat}	[kN/m^3]	18.50	18.00
γ_{sat}	[kN/m^3]	19.00	19.00
ν	[-]	0,3	0.20
E_{50}^{ref}	[kN/m^2]	28000	10000
E_{oed}^{ref}	[kN/m^2]	28000	10000
E_{ur}^{ref}	[kN/m^2]	84000	30000
power (m)	[-]	0,5	0.5
G_0^{ref}	[kN/m^2]	95000	80000
$\gamma_{0.7}$	[-]	2,00E-4	2.00E-04
c	[kN/m^2]	5.0	5.0
φ	[°]	32.0	28.0
ψ	[°]	3.0	0.0

Before running, the different (build) states must be defined to reproduce what happens in reality. The modelling included the following phases:

– Initial Phase
– Loading (pre-loading - compaction phase)
– UnLoading
  - Load_2_ton (vehicle axle load of 2 tons)
  - Load_6_ton (vehicle axle load of 6 tons)
  - Load_10_ton (vehicle axle load of 10 tons)
  - Load_13_ton (vehicle axle load of 13 tons)

3. MODELLING RESULTS

During the runs, different parameters were tested for the road structure layers. In each case, the results obtained from the runs were determined for horizontal sections of a given depth, taken in the immediate vicinity of the layer boundaries, and for the subbase was also taken at the soil centreline too. The figure below shows a schematic diagram of the roadway structure, marked with the depths at which sections were taken.

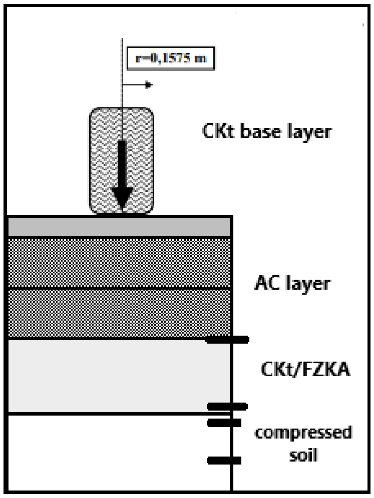

Figure 6 Location of calculation results for CKt/FZKA base course structures

For road structures constructed with CSG base layers, a horizontal section was taken at the following points:

1. in the immediate vicinity of the upper plane of the base course
2. in the immediate vicinity of the bottom plane of the base course
3. in the immediate vicinity of the upper plane of the compacted in the immediate vicinity of the upper plane of the subbase
4. in the middle of the subbase
5. in the immediate vicinity of the lower plane of the subbase
6. in the immediate vicinity of the upper plane of the subgrade
7. in the middle of the subgrade

From the data sets defined for the layers, charts were produced for each run, one by one, using Excel, taking the quarter into account. They are a good representation of the increase in soil stiffness values due to the phenomenon of unloading-reloading.

The diagrams below clearly show that in the loading zone, as the intensity of the load increases, the stiffness decreases and then, moving away from the axis, the stiffness gradually increases. It can also be clearly seen from the diagrams that at points 3 m from the axis, the soil stiffness values are almost the same for all 4 load cases. Consequently, the stiffness increase is much larger for the 13 tonnes load intensity than for the 2 tonnes load (Figure 7). In the latter case, there may be only a negligible increase in stiffness compared to the initial stiffness (Figure 8).

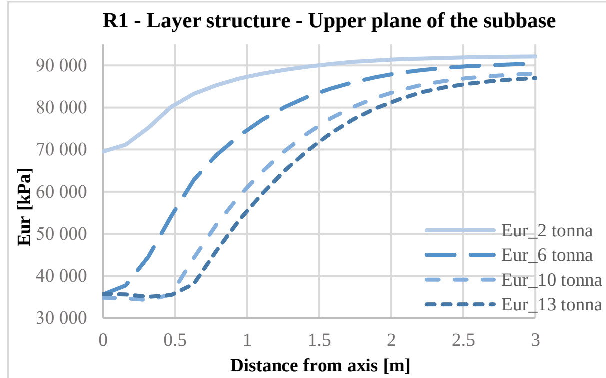

Figure 7 Road structure layer system R1, subbase top section, unloading/reloading modulus values

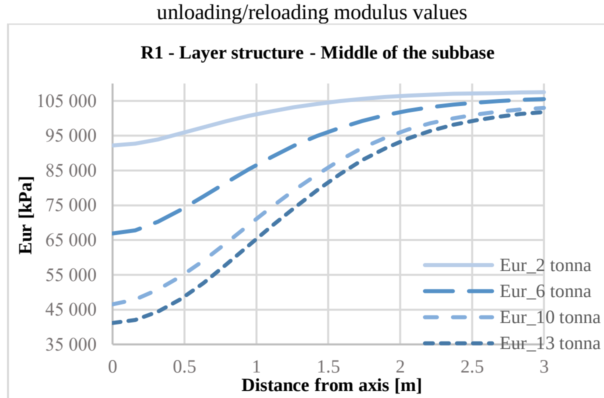

Figure 8 Road structure layer system R1, subbase centre section, unloading/reloading modulus values

In addition, it is clear from examining the series of diagrams that with increasing depth, the initial stiffness values show an increase in the loading zone and at a distance of 3 m from the loading zone. In the loading zone, the initial stiffness values show a larger increase, in contrast to the stiffness values at the edge of the model, where they change only minimally with increasing depth (Figure 9).

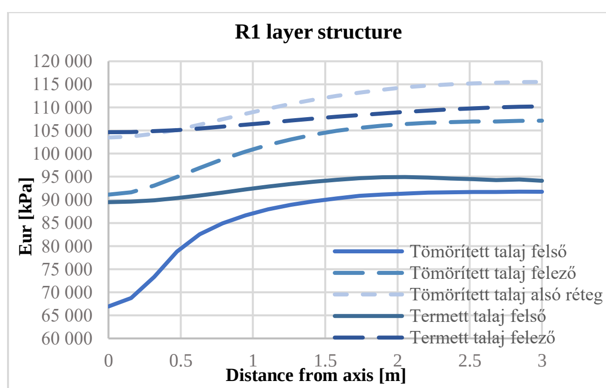

Figure 9 R1 stratification at 2 tonnes load at different depths value

4. CONCLUSIONS

From the previous diagrams, it can be seen that all distribution functions can be approximated relatively acceptably by three lines, as illustrated in the figure below.

Using the principle of approximation by linear stages, it is conceivable that a linear approximation should be used to solve the problem. In this computational case, it is possible to use simplifications for the materials to be modelled, and it is sufficient to use Linear Elastic or Mohr - Coulomb material models. The use of these material models simplifies the modelling process, as they are much easier to include the parameters to be input than the HSsmall material model, and it is also worth mentioning that in this case the finite element calculation is simplified, so that the time of the runs is much shorter.

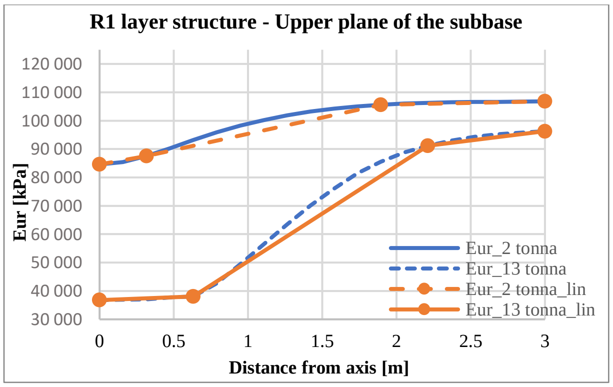

Figure 10 Approximation of curves by 3 linear sections

To make the calculation more accurate, we use E modulus that changes by depth, that is different sizes of zones were created both vertically and laterally, for which different elastic modules were defined. The values thus obtained allowed us to take into account both vertical and horizontal stiffness differences.

The following figure shows the geometry of the model under study.

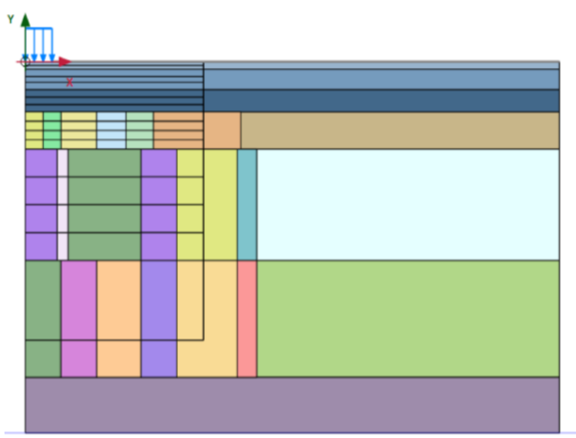

Figure 11 Geometric design usingLinear Elastic, Mohr - Coulomb material models

The results obtained from the models run with this geometry design were compared with the results calculated using the HSsmall material model, to see how well the soil behaviour described by the HSsmall material model can be approximated using a simpler material model.

The comparison was made taking into account two aspects, both of which relate to the deformation of the subbase layers. Both the subsidence in the road structure layer and the elongation of the asphalt's edge fibres are important factors, as their excessive development can lead to the failure of the road structure.

The extent of vertical displacements of the road structures was determined in the lower plane of the aggregate asphalt concrete layer. The resulting subsidence values are illustrated in the figures below, distinguishing for which model and material model the subbase layer was considered.

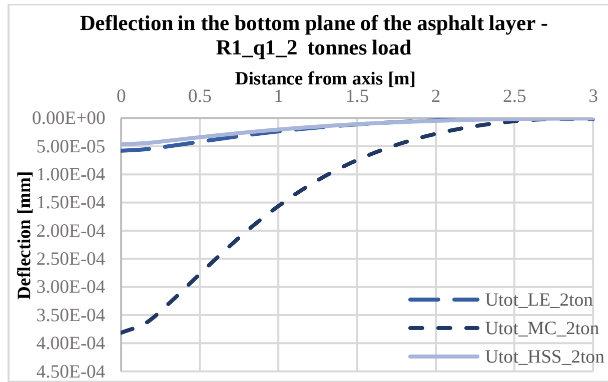

Figure 12 Diagram of the deflection of the R1 road structure in the bottom plane of the asphalt layer under a 13 t load in the first quarter

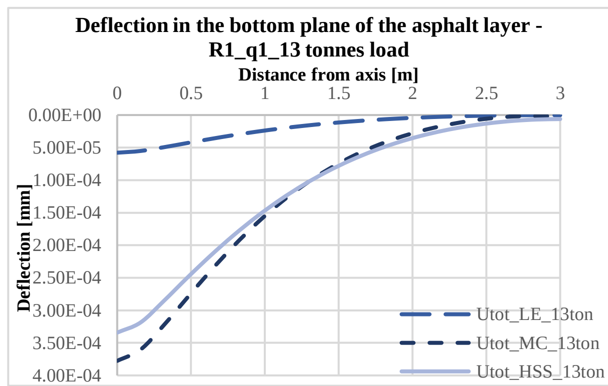

Figure 13 Diagram of the deflection of the R1 road structure in the bottom plane of the asphalt layer under a 2 t load in the third quarter

From the deflection plots, it can be seen that for the subsidence under a load of less than 2 tonnes, the value determined by the HSsmall material model is better reproduced by the Linear Elastic Material Model, but for the load of more than 13 tonnes, the reverse is true. Looking at the second case, where the soil behaviour described by the MC material model better approximates the behaviour of the original computational model, it can be said that in this case plastic deformations can develop in the soil.

The following table show the elongation values of the asphalt edge fibre. The values determined are along the x=0 axis. The values of the asphalt track stiffness in this case influence which material model better approximates the values originally calculated by the HS-Small material model. When looking at the first quarter, where the asphalt pavement stiffness value is the highest, the values calculated by the Mohr-Coulomb model better approximate the values of the HS-Small model. In the third quarter, the opposite is the case, where the Linear Elastic model better approximates the HS-small values, where the asphalt stiffness values are the lowest.

Table 3 Elongation values of the asphalt edge fibre of R1 type road structure layer systems

Elongation of asphalt edge fibre in X=0 axis				
			material model	**Elongation of edge fibre ε_x [-]**
R1 road structure layer	**Q1**	**2 t.**	Linear Elastic	2.7870E-05
			Mhor - Coulomb)	2.8650E-05
			HS - small	3.1850E-05
		13 t.	Linear Elastic	2.0550E-04
			Mhor - Coulomb)	2.3000E-04
			HS - small	2.5850E-04
	Q3	**2 t.**	Linear Elastic	6.2620E-05
			Mhor - Coulomb)	6.3240E-05
			HS - small	5.9660E-05
		13 t.	Linear Elastic	5.2450E-04
			Mhor - Coulomb)	6.7440E-04
			HS - small	5.8290E-04

All in all, this linearly flexible computational approach is a good starting point for simplifying the modelling.

5. SUMMARY

From the processing of the results obtained, it is clear that the stiffness values increase with increasing depth, that is stiffness increases can indeed occur in soils in the small strains range. This increase in stiffness is a consequence of the fact that in these soil zones, the deformation due to stresses is almost negligible. In the case of roadways, the determination of the subsidence values is not overestimated when this is taken into account.

In carrying out this task, the traffic loads and the stiffness modulus of the asphalt layers were determined on the basis of the German road structure sizing procedure, which in itself forms the basis for an innovative and novel sizing procedure. This new way of thinking is reinforced by our claim for subgrade sizing too, where we state that stiffness increases can be expected in deeper soil zones.

The scaling procedure for subbase can be simplified by using Linear Elastic models. The increase in stiffness due to the considered unloading-reloading can also be taken into account by using simpler material models. For this purpose, soil zones with different stiffnesses have to be defined. It can be clearly seen that these models approximate the results of the HS-Small model relatively well. This can be considered as a positive aspect from a computational point of view, as it avoids the need to perform costly CD triaxial tests to define the parameters of the HS-S mall models and also reduces the finite element run time of the models by using simpler material models. This is why it was worth considering the use of linear elastic and Mohr - Coulomb material models, where the necessary parameters do not require complex and costly laboratory tests.

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