Modulus of subgrade reaction for pipelines in a borehole installed by horizontal directional drilling

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Annotation
The pipe stress analysis for pipelines installed in the soil is based on the interaction between the pipeline and the surrounding soil. Stresses, which will develop in the pipeline, are largely dependent on the soil pipeline interaction, which is determined by the a modulus of subgrade reaction The current Dutch method for calculating modulus of subgrade reaction in a borehole is based on Schleicher's theory. Since the application of this calculation method for pipelines in boreholes is questioned, research based on finite element calculations is carried out. The moduli of subgrade reaction determined by Schleicher's equation are higher than the values calculated by finite element analysis for the sandy soil types In clayey soil types the moduli of subgrade reaction according Schleicher's equation are significantly lower than the finite element soil types. Therefore, caution is required for stress analysis in clayey soil types. The moduli of subgrade reaction determined by Schleicher's equation might be to advantageous in design calculations.

Keywords
HDD, Pipe stress analysis, Modulus of subgrade reaction, Borehole, Schleicher's theory

INTRODUCTION

The pipe stress analysis for pipelines installed in the soil is based on the interaction between the pipeline and the surrounding soil. Stresses, which will develop in the pipeline, are largely dependent on the soil pipeline interaction. Particularly the stiffness of the soil, which is often expressed as a modulus of subgrade reaction, is an important parameter for the soil pipeline interaction. The modulus of subgrade reaction gives the relation between soil reaction stress and displacement of the pipeline into the surrounding soil next to the borehole.

BACKGROUND

The modulus of subgrade reaction for pipelines surrounded by soil is investigated to some extent. The behavior of the soil pipeline combination is reasonably well understood. The behavior of a pipeline installed in a borehole made by horizontal directional drilling however, is not or only poorly investigated. Pipelines installed in trenches are surrounded and have a large contact area between the pipeline and the soil. When a pipeline is located in borehole, the contact area between pipeline and borehole wall is often initially relatively small. Due to bending or application of loads on the pipeline, the pipeline will be pushed into the borehole wall which leads to a higher contact area, which in turn influences the soil reaction stress.

The growth of the contact between the pipeline and the borehole wall area in combination with the ability of soil to deform in the direction of the annular space in the borehole leads to a significant different soil pipeline interaction and hence a different modulus of subgrade reaction then for pipelines installed in trenches.

CURRENT DUTCH PRACTICE

The formula of [1] considers a rectangular plate on an elastic halfspace. The plate has length L and width B. From the ratio of soil stiffness to beam bending stiffness EI the characteristic length is determined and this is considered to be L. B is considered to be equal to the diameter D. With these the stiffness can be calculated using:

$$k_v = \frac{E_{soil}}{m(1-\nu^2)\sqrt{A}} \quad with \quad L = \frac{\pi}{\lambda} \quad and \quad \lambda = \sqrt[4]{\frac{k_v D}{4E_{pipe} I}}$$

In which:

E_{soil}	Young’s modulus of the soil	[kPa]
A	Loaded area = L*D	[m^2]
ν	Poisson’s ratio	[-]
E_{pipe}	Bending stiffness of pipe, see equation	[kPa]
m	shape factor	[-]
I	Moment of inertia	[m^4]
k_v	Modulus of subgrade reaction	[KNm^3]

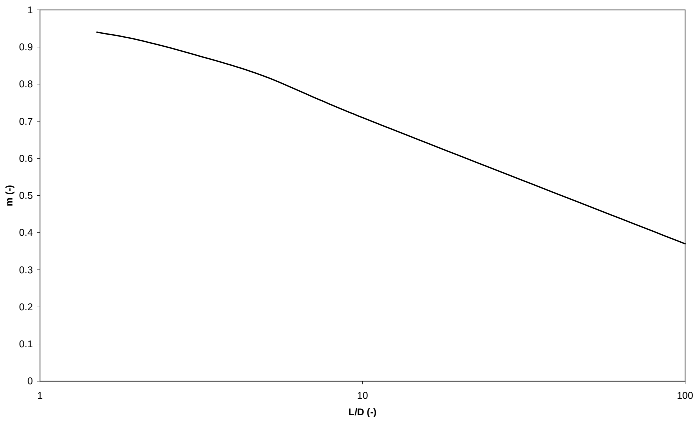

Figure.1: Value of m, which is related to L/D.

The dimension of k_v is [kN/m^3] whereas the dimension of the spring stiffness that is used in the code is [kN/m^2]. Schleicher’s spring stiffness needs to be multiplied by the width of the loaded area $k=k_vB$ to have a required stiffness per length unit.

The use of the characteristic length π/λ for L is not explained in Schleicher’s original theory. Schleicher derived his formula based on a plate on the surface with length L. The characteristic length is used in the Dutch requirements for pipeline installation [3] to estimate a value for L. It is based on an analytical solution for a beam on elastic springs [2]. In this solution, π/λ equals half the so-called wavelength.

The so called wavelength determines the length over which the pipeline penetrates the borehole wall under certain loading conditions. In contrary to the Schleicher formula which assumes a more or less constant deformation of the entire plate, the penetration distance of the pipeline is not constant. Beside constant deformation, the theory is based on linear elasticity and plastic deformations are neglected that are considered important. Furthermore there is the problem that the pipeline-load does not act on top of an elastic halfspace but inside a hole in the elastic halfspace, so that the soil above the borehole is not considered.

Due to the background of Schleicher's theory and the basic assumptions, the applicability of this theory was questioned.

FINITE ELEMENT MODELLING

Since analytical solutions for the determination of the modulus of subgrade reaction for a pipeline in a borehole is not known a finite element analysis was performed. The 2D finite element analysis is carried out for plane strain conditions. A circular borehole was created in the subsoil. A rigid pipeline inside the hole was pushed downward into the soil below the borehole. In the borehole a drilling fluid pressure preventing the hole from collapsing is present. The soil has been modeled as a homogeneous linear elastic Mohr-Coulomb plastic material. For various soil types the force displacement curves have been determined.

Two different pipeline installation depths are considered:

- A deep variant at 25 m below surface at an effective fluid pressure of 275 kN/m^2
- A shallow variant at 10 m below the surface at an effective fluid pressure of 110 kN/m^2.

Model calculations have been made for a borehole with a diameter of 1520 mm and a pipeline 1219 mm this will be called series 1 and a situation with a smaller hole of.600 mm with a pipeline diameter of 406 mm which will be called series 2.

The simulations have been performed for 8 soil types in deep and shallow variants for each series, resulting in 2 series * 8 soil types * 2 depths gives 32 simulations. The parameters for the deep and shallow variants are presented in the tables below.

simulation	soil	γ_{wet} [kN/m^3]	C_u [kPa]	C [kPa]	φ[˚]	E [kPa]	ν [-]	K_0 [-]	γ_{eff} [kN/m^3]
1	Sand	20	-	1	30	15000	0.35	0.5	10
2	Sand	21	-	1	35	50000	0.35	0.8	11
3	Clay	13	-	1	17.5	2000	0.45	0.7	3
4	Clay	13	40	0	0	2000	0.45	0.7	3
5	Clay	17	-	10	22.5	4000	0.45	0.6	7
6	Clay	17	75	0	0	4000	0.45	0.6	7
7	Clay	17	-	10	22.5	6000	0.45	1.5	7
8	Clay	17	150	0	0	6000	0.45	1.5	7

Table 1: soil parameters for the deep variant at a reference depth of 25 m below the surface.

simulation	soil	γ_{wet} [kN/m^3]	C_u [kPa]	C [kPa]	φ[°]	E [kPa]	ν [-]	K_0 [-]	γ_{eff} [kN/m^3]
1	Sand	20	-	1	30	10000	0.35	0.5	10
2	Sand	21	-	1	35	50000	0.35	0.8	11
3	Clay	13	-	1	17.5	1000	0.45	0.7	3
4	Clay	13	25	0	0	1000	0.45	0.7	3
5	Clay	17	-	10	22.5	2000	0.45	0.6	7
6	Clay	17	50	0	0	2000	0.45	0.6	7
7	Clay	17	-	10	22.5	6000	0.45	1.5	7
8	Clay	17	150	0	0	6000	0.45	1.5	7

Table 2: Soil parameters for the shallow variant at a reference depth of 10 m below the surface.

The simulation results are presented in figure 2 to 5. It can be seen that the general shape of the force displacement relationship shown in the figures for a specific soil type is similar regardless of the depth or diameter, there is merely a visible difference in scale of the vertical axis. Although all soils show a weaker response of the force with increasing displacement, it should be noted that the force required for pushing down the pipeline does not reach a maximum value in the sandy soils. In the clayey soils however a maximum value is reached after a relative small displacement.

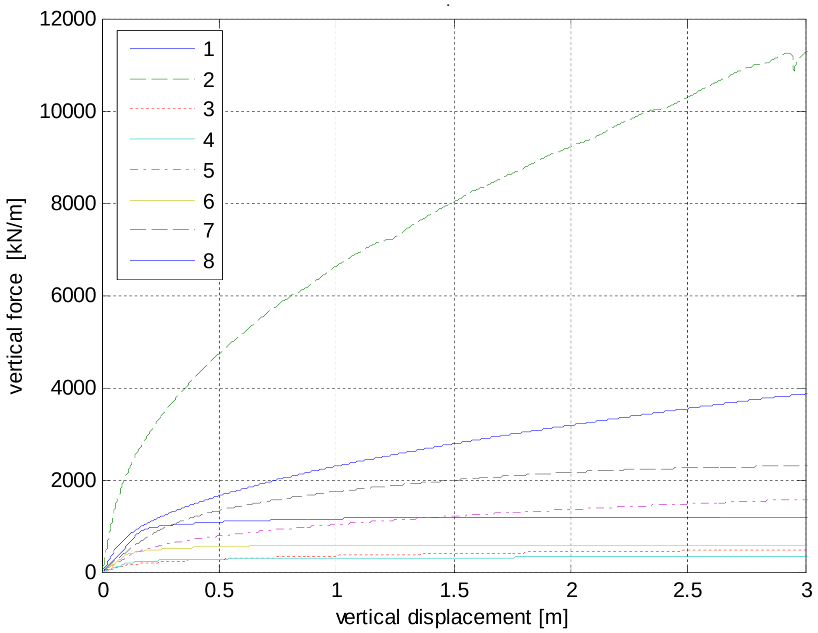

Figure 2: Vertical force versus displacement for the large diameter series 1, deep variant.

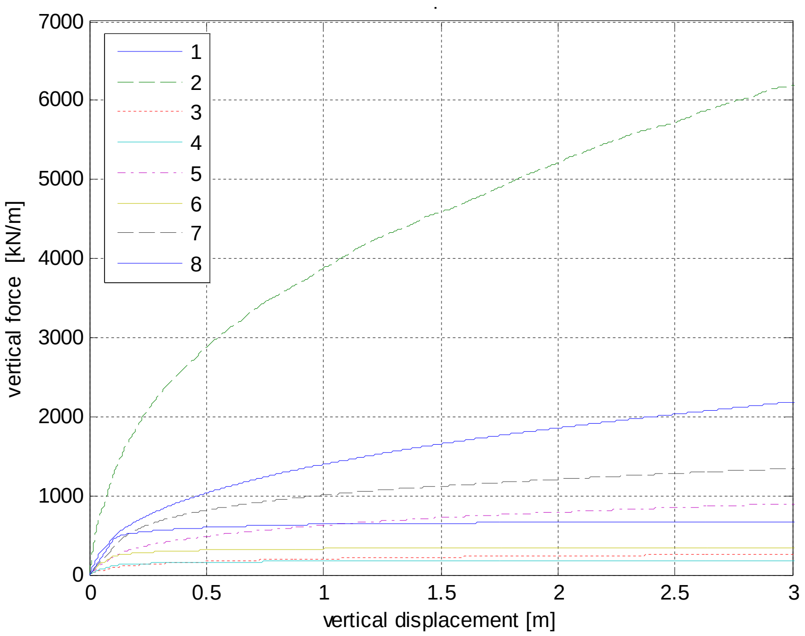

Figure 3: Vertical force versus displacement for the small diameter series 2, deep variant.

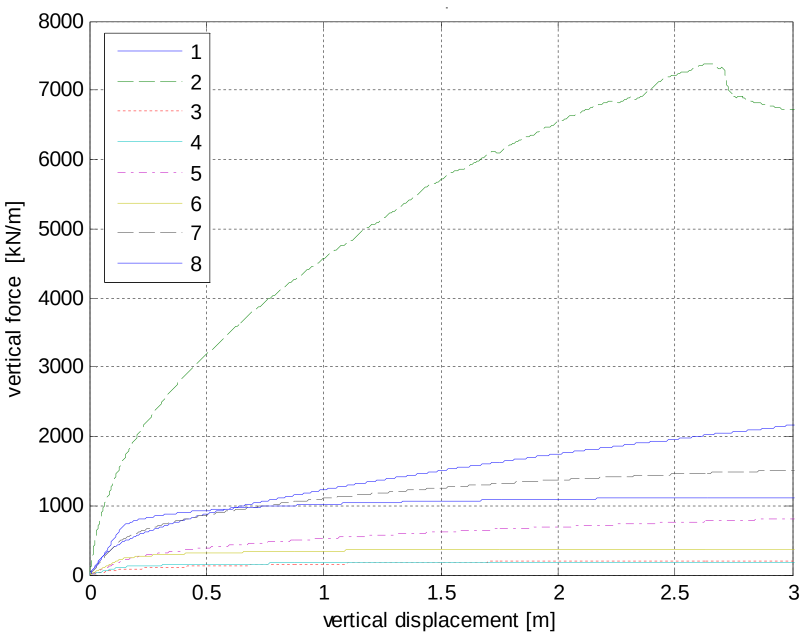

Figure 4: Vertical force versus displacement for the large diameter series 1, shallow variant.

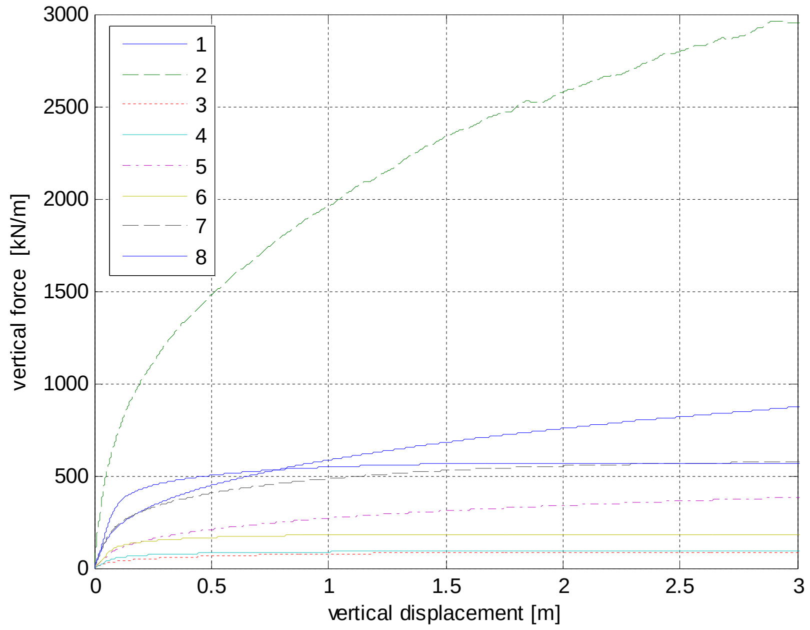

Figure 5 Vertical force versus displacement for the small diameter series 2, shallow variant.

The derivative of the force displacement figure for and soil type 8 (the deep and large diameter variant) is shown in figure 6.

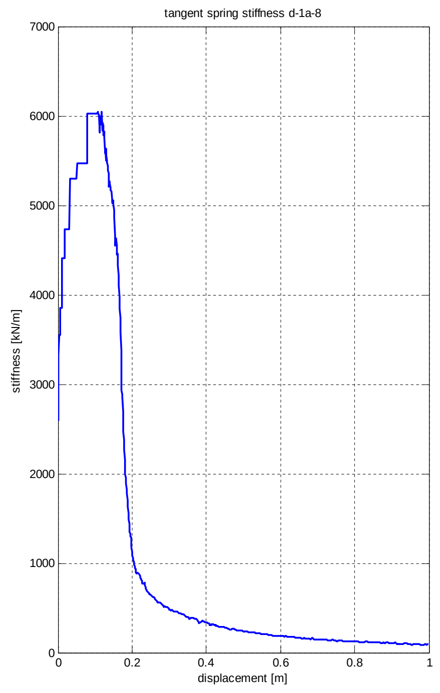

Figure 6: Derivative of the force-displacement curve (tangent modulus) of the deep large diameter variant for soil type 8.

It can be observed (figure 6) that the tangent modulus of subgrade reaction increases to a maximum and then decreases to a low value for a displacement of about 0.2 m. Such an increase of stiffness followed by a decrease is visible in the results of all simulations.

DISCUSSION

From the previous figures, it can be deduced that a linear schematization of the modulus of subgrade reaction fits quite well for vertical displacements up to about 0.1 m. For this relative small displacement, the secant modulus of subgrade reaction has been determined and presented in table 3. The values in the table give a good overview of the initial stiffness for the pipeline penetrating the borehole wall.

It should be noted that in most cases the displacement of pipelines relative to the bore wall is small, so that the secant modulus of subgrade reaction can be used. For clayey soils however, significant plastic behavior of the soil may occur after displacements exceeding 0.1 m. In case of larger displacements in clayey soils, it is necessary to use a bilinear modulus of subgrade reaction.

Using the soil parameters given in table 1 and table 2, the moduli of subgrade reaction according Schleicher's formula are calculated (table 4). The characteristic length is calculated after determination of λ. The graph shown in figure 1 is used to determine the shape factor m.

soil type	Soil spring stiffness of first 0.1 m borehole penetration [kN/m/m']			
	deep, large diameter	deep, small diameter	shallow, large diameter	shallow small diameter
1	7516	4323	3799	2115
2	21078	11433	12702	6815
3	1398	830	643	362
4	1756	1119	840	587
5	2924	2183	1417	1071
6	3508	2274	1624	1223
7	4172	3230	3861	2430
8	5267	4383	5028	3721

Table.3; Derived modulus of subgrade reaction from the FEM simulations

soil type	Soil spring stiffness [kN/m/m']			
	deep, large diameter	deep, small diameter	shallow, large diameter	shallow small diameter
1	5630	5810	3542	3655
2	22287	23000	22287	23000
3	628	648	284	293
4	628	648	284	293
5	1386	1431	628	648
6	1386	1431	628	648
7	1386	1431	628	648
8	1386	1431	628	648

Table.4: Moduli of subgrade reaction computed using Schleichers formula and m=0.72. The length L was calculated using the characteristic length.

Comparison of the values presented in table 3 and 4 shows that moduli of subgrade reaction determined by Schleicher's equation are higher than the values calculated by finite element analysis for the sandy soil types. The soil mechanical parameters and the stress level of the sandy soils are of importance for the value of the modulus of subgrade reaction. In clayey soil types, the moduli of subgrade reaction according Schleicher's equation are significantly lower than the finite element soil types.

Usually a higher modulus of subgrade reaction leads to higher stresses in the pipeline. Therefore, caution is required for stress analysis in clayey soil types. The moduli of subgrade reaction determined by Schleicher's equation might be to advantageous in design calculations.

CONCLUSIONS

The pipe stress analysis for pipelines installed in the soil is based on the interaction between the pipeline and the surrounding soil. Stresses, which will develop in the pipeline, are largely dependent on the soil pipeline interaction, which is largely determined by the modulus of subgrade reaction [4].

The current Dutch method for calculating modulus of subgrade reaction is based on Schleicher's theory. Since the application of this calculation method for pipelines in boreholes is questioned, research based on finite element calculations is carried out.

The moduli of subgrade reaction determined by Schleicher's equation are higher than the values calculated by finite element analysis for the sandy soil types. In clayey soil types the moduli of subgrade reaction according Schleicher's equation are significantly lower than the finite element soil types.

Usually a higher modulus of subgrade reaction leads to higher stresses in the pipeline. Therefore, caution is required for stress analysis in clayey soil types. The moduli of subgrade reaction determined by Schleicher's equation might be to advantageous in design calculations.

Since the 2D and 3D situation differ significantly, further research is recommended, because the assumed infinite contact length and uniform penetration over that length in the 2D finite element analysis can be questioned.

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