Numerical simulation of external loads on buried pipelines

by Johannes Brückner, Christian Engel, Ulrich Marewski and Michael Steiner

Within the scope of the presented work, a simulation model was developed which completely depicts the buried pipeline and the surrounding soil. The model was validated using a number of analytical methods. The bedding conditions of the pipe trench are described by means of a standardized criterion which takes into account the filled soil type and the degree of compaction. The modular design allows the application of any loads, e.g. earth loads, traffic loads or temperature strains. The result provides a three-dimensional deformation plot of the pipeline and the ground. The “extended elastic analysis” according to DIN EN 1594 is used as stress criterion for structural integrity assessment. The model can be used to answer specific engineering questions, e.g. in the framework of structural modifications or construction of high-pressure gas pipelines. The holistic assessment can also be provided to authorized technical experts to support the scope of expert opinions.

1. BACKGROUND

At the European level, the functional requirements for pipelines in public gas grids at operating pressures of above 16 bar are governed by EN 1594 [1]. According to Section 7.2, the internal pressure is supposed to be the leading load case for the dimensioning (“standard load condition”). The influence of additional loads and the interaction with the soil are not taken into consideration in this model. For pipeline sections where significant

![Figure 1: Simulated ovalization in comparison with analytical solution](image)
external loads may be encountered, a more extensive planning has to be performed using established analysis methods as specified by Section 7.3.

There are several technical assessment concepts available which utilize simplifications to address day-to-day engineering needs for standard cases of buried piping systems. VdTÜV Instruction Sheet 1063 [2] can be for example used to investigate ovalization of the pipeline’s cross-section subjected to traffic loads. The application of the DIN EN 1594 Annexes A to F enables the estimation of soil-induced shifts which may result in additional straining along the pipeline. The standardized methods consider individual sub-aspects, e.g. with regard to settlement, mining subsidence, frost heave or potential impact caused by earthquakes. Comparatively few assessment models are available for holistic investigations of complex and combined load profiles. As a possible approach, DIN EN 1594 specifies numerical simulation models in line with the finite element method (DIN EN 1594:2013, Section 7.3.3).

2. NUMERICAL ASSESSMENT APPROACH

The finite element method is basically suitable for the numerical solution of physical field problems which are described by differential equations. The method has become an efficient engineering tool against the background of the continuously increasing computing capacity of modern computers. The accuracy of each numerical model must be evidenced by means of comparisons with established methods (validation). Within the context of the work presented here, a finite element model has been developed which simulates the buried pipeline subjected to any load configuration. Validation has been performed step by step for the pipeline and the surrounding soil. All simulations have been carried out using the commercial software package ABAQUS, version 6.13-3.

First, three decisive base load cases were simulated on the straight pipe and compared with analytical solutions from technical literature. The ovalization load case (Figure 1) is shown exemplarily of this process step. Surface loads which correspond to the bedding conditions of the buried pipeline were applied to the outer surface of the pipe. The lateral soil pressure was varied as a relative component of the vertical load over the lateral pressure coefficient $\lambda$ along the lines of [2]. Maximum ovalization results from the theoretical case of the laterally unsupported pipe ($\lambda = 0$). The simulated circumferential stress very well matches the analytical solution as specified by [3]. Similar to this load case, the deflection of the pipe subjected to a bending load was simulated for an elastic bedded pipe and compared with the analytical solution according to [4]. The internal pressure load case was validated with reference to [5].

The structural stress sustained by a buried pipeline under influence of external loads is strongly related to the interaction with the surrounding soil. In particular the settlement profile of the soil has a major effect on the expected pipeline shift. The deformation behaviour of soil is generally described by the soil stiffness which estab-
lishes proportionality between stress and deformation. Compared to the classic elasticity theory, this ratio is not necessarily linear. However, linearization within the expected stress range is regularly usual in civil engineering to formally apply linear-elastic assessment methods. For the purpose of validating the soil mechanical model used here, simple load cases were initially simulated on a quadratic body and compared with analytical solutions for stress propagation in the elastic half-space. Elementary basic variables are given by a perpendicularly effective point load in line with [6] and a square load with a constant surface pressure in line with [7]. As an example, Figure 2 shows the simulated vertical soil stress below a three-axle 60-tonne truck as per DIN 1072 [8]. The finite element results (red dots) very well concur with the analytical solution (coloured polygonal surface, superimposition of [7] in line with the 60-tonne truck geometry as per [8]). The simulated maximum value of 0.052 MPa below the centre truck wheel also well concurs with the 60-tonne truck load curve in line with VdTÜV Instruction Sheet 1063 [2].

For the purpose of validating the simulated deformation of soil, a comparison with a standardized settlement calculation was carried out in accordance with DIN 4019 [9] (Figure 3). Thus, the following equation applies:

\[ s = \sigma_{z0} \cdot b \cdot \frac{f}{E^*} \quad \text{with} \quad E^* = \frac{E_z}{1 - \nu^2} \cdot \left(1 \cdot \frac{2\nu}{1 - \nu^2} \right) \]

where:
- \( s \) = settlement,
- \( \sigma_{z0} \) = nominal surface stress,
- \( b \) = foundation width, \( f \) = settlement coefficient,
- \( E^* \) = calculation modulus

The coefficient \( f \) considers the specific character of the foundation form and the calculation depth of the compressible ground layer (in this case the coefficient for a slack rectangular load as per Kany [10]). The calculation modulus \( E^* \) is derived from the soil stiffness modulus which can be established by means of dynamic probing with economically justifiable work as per [11]. In the model, simulation for soil stiffness of 5 MN/m² results in a maximum settlement of 23.1 mm (see Figure 3). Settlement at the characteristic point of the square load (74% of the semi-axis) is 16.9 mm according to the FE calculation and 18.4 mm in line with DIN 4019 [9]. The settlement curve below the identifying point can be calculated using coefficients according to Steinbrenner [12]. Comparison across the depth shows, that the simulation sufficiently concurs with the standardized settlement calculation and, as from a referenced depth \((z/b)\) of 0.5, forecasts negligibly greater settlement. This is to be rated as conservative, particularly with reference to typical soil cover heights above high-pressure gas pipelines. The assumption of a linearized soil consistency modulus can therefore be applied as a suitable material law for this assessment concept.

For the simulation of the pipeline statics, the sub-models of pipe and soil are merged to a combined model (Figure 4). The properties of the actual pipe (diameter, wall thickness, internal pressure) and the soil parameters (cover, soil stiffness, specific weight, layer composition) are freely variable. As an external load, a 60-tonne lorry load is positioned on a rotatable base, so that traversals at
Figure 4: Parametric pipe-soil-model under influence of a 60-tonne truck load.
Figure 5: Defined soil zones according to ATV-DVWK-A 127

- Load case 1: "Dead load"

- Load case 2: "Dead load + Traffic load"

- Load case 3: "Dead load + Traffic load + Pressure"

Vertical soil stress
Hoop stress in pipe wall

Max.

Figure 6: Simulated soil- and hoop stress caused by a 60-tonne truck load (pipe cross section)
different crossing angles to the pipeline can be simulated. Since the consistency of the lateral soil has an influence on the ovalization stress value (see Figure 1 with calculation of the lateral pressure coefficient), this parameter has been considered in the simulation model as a numerical bedding criterion. ATV-DVWK Code of Practice 127 [13] defines four soil zones which characterize the layer composition within the pipe trench (Figure 5). $E_1$ designates the cover fill above the pipe crown and $E_2$ the soil below the pipe. Soil zones $E_2$ and $E_3$ designate the lateral soil layer, with the possibility of distinction between the backfill in the trench and undisturbed soil ($E_2 \neq E_3$) or if viewed as an overall layer ($E_2 = E_3$). The effective vertical stiffness modulus is then quantified using coefficients which depend on the conditions encountered during construction work:

$$E_2 = f_1 \cdot f_2 \cdot \alpha_B \cdot E_{20}.$$  

$E_2$ = effective stiffness modulus, $f_1$ = coefficient for consideration of creep properties, $f_2$ = coefficient for consideration of the degree of compaction, $\alpha_B$ = reduction factor for consideration of the trench width, $E_{20}$ = global soil stiffness

For global soil stiffness $E_{20}$ [13] specifies conservative minimum values depending on the backfilled soil type. For the purpose of assessing already laid pipelines, this

---

Figure 7: Simulated soil- and longitudinal stress caused by a 60-tonne truck load (pipe longitudinal section)
value can be substituted by results from dynamic probing, e.g. in line with [11]. The effective lateral soil stiffness then follows from reduction via the coefficients $f_1$, $f_2$, and $\alpha_B$. For detailed application and classification, see [13]. By varying the coefficients, the lateral bedding conditions can be simulated and systematically investigated (e.g. soil consistency, Proctor density, size and sheeting of the pipe trench, etc.).

The numerical solution for the defined model parameters is carried out in three load cases which build on each other step by step. In load case 1, the unpressurized pipeline is subjected to the system’s dead weight only (basic status after pipelaying). In load case 2, the impact of the local additional load is superimposed with the first load case. In the given example, the unpressurized pipeline is traversed by a 60-tonne truck. In load case 3, the internal pressure is also applied so that the structural stress at nominal conditions is simulated (here, traversal of the pressurized pipeline). Figures 6 and 7 show the numerical results for the described load cases in the pipeline’s cross-section and longitudinal section (calculated parameters: nominal diameter 900, wall thickness 12.5 mm, DP 675, frictionless pipe, specific soil weight 19.6 kN/m$^3$, $E_s,14 = 20$ MN/m$^2$, $E_s,23 = f_1 \cdot f_2 \cdot \alpha_B \cdot E_s,14 = 0.8 \cdot 0.75 \cdot 0.85 \cdot 20$ MN/m$^2 = 10.2$ MN/m$^2$, soil cover 1 m, 60-tonne truck load at a crossing angle of 90°). The middle diagrams show the simulated soil stress for different depth sections. The hump-shaped load profile below the truck load falls away rapidly with increasing depth. The structural stresses within the pipe wall are plotted in the right-hand diagram row. Figure 6 shows the hoop stresses on the outer and inner fibre of the pipe wall. The cross section is shown perpendicular below the truck load (index UM) and the at the model end, i.e. outside the impact caused by the traffic load (index U0). The characteristic shape caused by the pipe ovalization is visible. The magnitude of the circumferential stress in load case 3 (pipeline subjected to nominal pressure) shows that the internal pressure involves the decisive stress mode for this load configuration. Similarly, Figure 7 shows the longitudinal stresses along the pipeline. The curves show a bending-typical variant below the additional load, i.e. compressive stress at the pipeline’s crown (index L12) and tensile stress at the bottom (index L6).

The developed simulation model can be optionally varied and supplemented by the parametric structure. In particular, separation of the surrounding soil from the load modulus on the terrain surface enables the static additional load to be freely modified. Figure 8 shows three examples of how the load module can be modified (railway load LM 71 according to [14]). Furthermore, ABAQUS features the possibility of defining further addi-

Figure 8: Variable application options due to modular concept
tional loads, e.g. due to thermal expansion or subjected to allowable pipe bending stress due to laying. Furthermore, the soil-mechanical constitutive model can be expanded on demand. In this respect, it has to be considered that the number of soil parameters might be increased significantly. Notes on numerical implementation may be found, for example, in [15] and [16].

3. STRENGTH CRITERION

The influence of the external load results in a multi-axial stress condition in the pipe wall which can be calculated to an equivalent stress in line with the "extended elastic analysis" as per DIN EN 1594 [1], Section 7.4.1. For structural strength assessments, a stress level up to the specified minimum yield strength (SMYS) of the pipe material is permitted, if all additional loads have been considered in the calculation:

$$\sigma_{vGEH} = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2 - \sigma_x \sigma_y - \sigma_y \sigma_z - \sigma_z \sigma_x + 3 (\tau_x^2 + \tau_y^2 + \tau_z^2)} \leq R_{0.5}$$

$$\sigma_{vGEH} = \text{Mises equivalent stress},$$  
$$\sigma_x, \sigma_y, \sigma_z = \text{normal stresses},$$  
$$\tau_x, \tau_y, \tau_z = \text{shear stresses},$$  
$$R_{0.5} = \text{specified minimum yield strength (SMYS)}$$

For the purposes of practical application, the given concept provides an approach for structural assessment of any load configuration against a standardized strength criterion.

4. PRACTICAL EXAMPLE

As a practical example, the construction of a motorway slip road is shown which was to be banked up above an existing pipeline of the German network operator Open Grid Europe. The crossing situation was modelled as shown in Figure 9 for the following calculation parameters: nominal diameter 800, wall thickness 14.2 mm, DP 100, material grade L 485 MB as defined by [17] with SMYS 485 MPa, ramp 4.7 m high and 30 m wide, soil cover without ramp 1.9 m, specific soil weight 21 kN/m³, exact modelling of the soil layer stiffness in line with the subsoil survey, 60-tonne truck load as per [8]. For the purpose of considering all potential loads, a thermal longitudinal pipeline expansion for a temperature difference of 25°C and an additional elastic laying stress in line with DVGW Code of Practice G 463 [18], Section 6.6, were applied. These load assumptions are to be considered as very conservative.

Figure 9 shows the vertical soil stresses and the von Mises equivalent stress for the nominal pipe pressure condition. Deformation has been scaled by a factor of 20 for

![Figure 9: Simulation of the pipeline statics underneath a motorway slip road](image-url)
visualisation purposes. The maximum equivalent stress is 390.0 MPa and lies perpendicular below the centre of the 60-tonne truck load on the inner pipe wall side at 12 o’clock position. Since the maximum equivalent stress is less than the specified minimum yield strength of the pipe material (390.0 MPa < 485 MPa), the pipeline’s structural design fulfils the formal requirements according to DIN EN 1594 [1] and is thus acceptable in terms of strength.

5. SUMMARY

The presented simulation model can be used to investigate specific engineering questions which are not covered by the validity of simplified approaches. The modular structure allows any loads to be applied, e.g. as a result of earth banks, traffic loads, canals or railway lines. Further additional loads, e.g. caused by temperature expansion or pipelaying, can also be considered. The simulated stress level is assessed by a standardized criterion in line with the “extended elastic analysis” as defined by [1]. For practical applications, it provides an efficient tool for use by experts which enables a holistic assessment of modifications or construction of high-pressure gas pipelines. The result can also be provided to assessors as part of their statements.

REFERENCES

[1] DIN EN 1594: Gas infrastructure – Pipelines for maximum operating pressure over 16 bar - Functional requirements: German version EN 1594: 2013
[18] DVGW G 463 (A): High Pressure Gas Steel Pipelines for a Design Pressure of more than 16 bar; Construction: 2016

AUTHORS

Johannes Brückner, M.Sc.
Open Grid Europe GmbH,
Essen
Phone: +49 201 3642 18447
Email: johannes.brueckner@open-grid-europe.com

Dipl.-Ing. Christian Engel
TÜV Nord Systems GmbH & Co. KG,
Essen
Phone: +49 201 825 2677
Email: cengel@tuev-nord.de

Dr.-Ing. Ulrich Marewski
Open Grid Europe GmbH,
Essen
Phone: +49 201 3642 18389
Email: ulrich.marewski@open-grid-europe.com

Dr.-Ing. Michael Steiner
Open Grid Europe GmbH,
Essen
Phone: +49 201 3642 18290
Email: michael.steiner@open-grid-europe.com