

GUIDELINE FOR THE SEISMIC DESIGN OF HIGH-PRESSURE GAS PIPELINES

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Abstract: *The paper highlights the crucial role of seismic design in ensuring the functionality of buried pipeline systems, particularly in the context of future energy supply with the integration of LNG infrastructure and hydrogen-based energy sources. It is therefore important to design new buried pipeline systems to be earthquake-resistant based on comprehensible calculation principles and constructive rules. However, the current European and international codes for the seismic design of pipelines are only of limited suitability for practical use due to the complexity of the calculation approaches, the lack of connection to the pipeline standards in use, and the incompleteness for special pipeline situations. To address these issues, a research project funded by the DVGW (German Technical and Scientific Association for Gas and Water) has been initiated to develop a design guideline for high-pressure gas pipelines that can withstand earthquake actions based on DIN EN 1998.*

The contributions introduce the contents and principles of the new guideline that allows a practical approach for designing spatially distributed pipeline systems with suitable computational models and design concepts for seismically induced ground movements. The contributions in this guideline cover wave types and wave propagation in soil that cause particle movements in the soil and subsequently forced deformations on buried pipelines. Building upon this, a multi-level verification concept with increasing accuracy is proposed for the load case seismic wave propagation. The study pays particular attention to the direction of seismic waves, installation depth, and other important considerations such as pipe bends, traffic infrastructure crossings, and culvert structures for crossing rivers. Finally, the application of the developed guideline is demonstrated on a typical pipeline configuration that showcases tangible evidence of its effectiveness in practice.

1. Introduction

The transportation of natural gas, a crucial energy source, is indispensable for sustaining urban living standards. This key contribution to today's economic infrastructure is facilitated through the extensive, globally interconnected pipeline networks which are regularly extended with additional kilometres each year (Cozzi and Gould, 2015). Welded steel pipes remain the favoured choice for long-distance, pressurized gas transmission, primarily for their economic efficiency and reliability (Sextos et al., 2019). Additionally, they are often buried underground for enhanced safety and environmental protection (Kirkham, 2021). When these pipelines span vast territories, traversing earthquake-prone zones often becomes a necessity. Given their characteristics, even brief stretches through such hazardous areas can pose a threat to the entire supply system's functionality. In earthquake-prone regions, buried or underground high-pressure gas pipelines experience stresses due to

relative ground displacements stemming from seismic wave propagation. Assessing the seismic structural integrity of such lifelines is complex due to influencing factors such as pipeline properties connections, operational pressures, temperature differences, varying geotechnical conditions, and seismic hazards along the pipeline greatly influence the seismic behaviour and vulnerability of such networks (O'Rourke and Liu, 1999). Additionally, these pipelines are also subjected to permanent ground deformations which include phenomena such as faulting, ground liquefaction, lateral shifts, and slope failures (ASCE, 1984). In the realm of buried pipeline design, seismic effects are usually measured by the resulting stresses or axial strains in the pipeline wall. This design approach based on strain has been evolving and in practical use for many decades. Various national annexes and guidelines, such as PRCI (2004), ALA (2001), AFPS (2020), IITK (2007), and ASCE (1984), specifically tackle seismic effects using strain-based methodologies. In Germany, the design or verification of pipelines is carried out according to the specifications outlined in Eurocode 8 (EN 1998). The recent amendment to the National Annex for Germany (DIN EN 1998-1/NA, 2021) herald a transition from the former seismic zones to a more continuous spectrum of seismic loading. As a result, the seismic requirements in numerous regions have increased, leading to significant challenges in implementing DIN EN 1998. These include ambiguities in safety level definitions, overly complex and expensive calculation methods, and the exclusion of existing standards like DIN EN 1594 and DIN ISO 3183. Within the purview of a research initiative endorsed by the DVGW, there is an ongoing development of a simplified guideline for the seismic design of buried high-pressure gas steel pipelines. The project would provide recommendations on seismic investigations that are actually necessary in the safety analyses when planning gas pipelines in Germany, a country with low to moderate seismicity. This paper delineates the outcomes from the initial phase of this research, which deals with basic development of detailed and simplified models, parametric study, and formulation of a hierarchical verification concept in compliance with the normative specifications for the load case of seismic wave propagation on welded high-pressure gas pipelines. After the completion of the project, this verification paradigm will be assimilated into the DVGW's set of standards and regulations, aiming for maximal practical application, thereby fortifying the safety of pipelines situated in Germany.

2. Failure modes and strain limits of buried pipelines under seismic action

The failure modes of buried pipelines subjected to seismic forces reveals crucial insights into their structural vulnerabilities. These failures often manifest in different forms for continuous or segmented pipelines, including but not limited to, tensile fracture, shell or beam mode buckling, and upheaval, cross-section ovalization (Sextos *et. al.* 2019) shedding light on the diverse challenges faced by underground pipelines during seismic events. O'Rourke and Liu (1999) found that burial depth also affects pipeline failure modes. Shallow trench installations may cause beam or up-heave buckling whereas deeper burial leads to shell-mode buckling or tension rupture as primary failure modes.

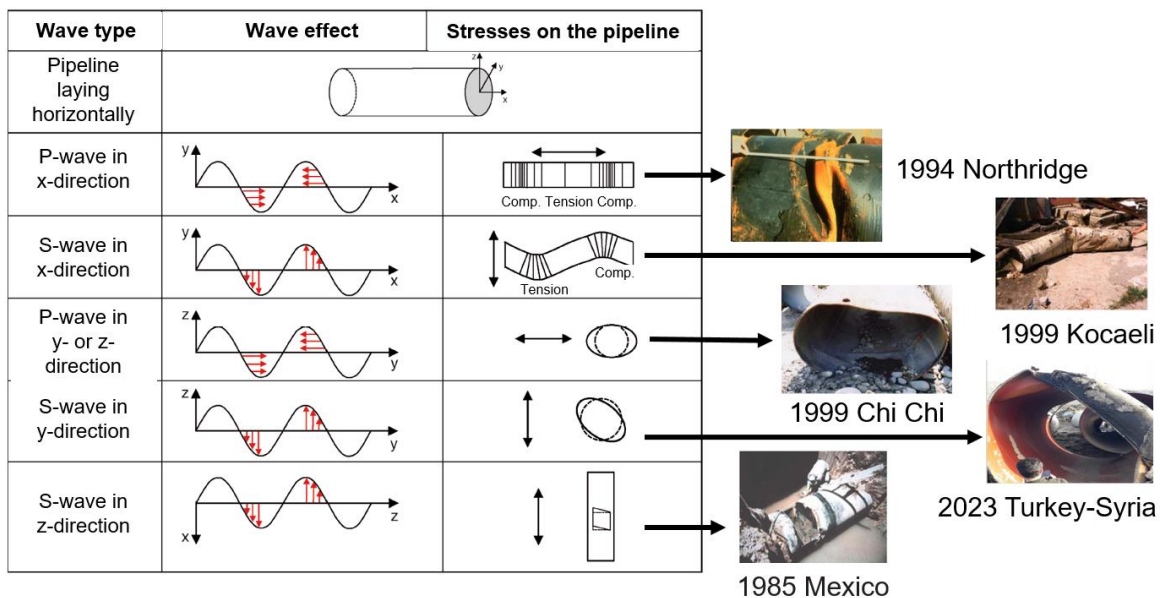


Figure 1. Damage to underground pipelines and associated stresses (Images from Flores and Liu (2003); Vazinram and Rasti (2006); Butenweg, Schmitt and Rosen (2014); Uckan *et al.* (2023)).

Figure 1 provides a representative illustration of such damages including the diverse nature of seismic waves. The propagation of seismic waves, notably P-waves in the axial direction, induces concurrent tension and compression within pipelines, resulting in wrinkling and rupture, exemplified by the impact of the 1994 Northridge earthquake. Additionally, the lateral movement of strike-slip faults during events such as the 1999 Kocaeli earthquake leads to S-waves causing lateral bending of pipelines. Instances like the 1999 Chi Chi and 2023 Turkey-Syria earthquakes demonstrate significant deformation, namely cross-section ovalization, in steel pipe segments traversing active fault lines. Furthermore, seismic waves' upward and downward movements provoke uplift and bearing stresses at specific pipeline sections, ultimately culminating in joint weakening and subsequent collapse, akin to observations during the 1985 Mexico City earthquake. While Germany is associated with a low to moderate seismicity, it is essential to note that during significant seismic events, buried pipelines are susceptible to substantial damage. These forces have the potential to induce plastic deformations in the pipelines (Kuhlmann, 2004).

Comprehending these pipeline failure modes drives the advancement of both numerical and analytical approaches incorporated within current codes and standards. The typical induce predominant loads on buried pipelines are through relative ground movement to the pipeline sometimes termed displacement-controlled loading (PRCI, 2004). The nonlinear analysis methods are often employed to explore strains surpassing the pipeline's yield strain. Therefore, various codes define a suitable limit state in particular for longitudinal strains within the nonlinear range. This is appropriate as it considers the available ductility and buckling behavior of steel pipes. Additionally, the tensile hoop stresses enhance resistance to local buckling, aiding the pipe in withstanding diametrical changes at the buckle (Liu et al., 2009). Concurrently with the release of the new European hazard map, the second generation of Eurocode standards is being developed. In juxtaposition with the prevailing standard DIN EN 1998-4 (2007), the preliminary draft of Part 4 of Eurocode 8, prEN 1998-4 (2022), encompasses meticulous provisions for the strain-based verification of buried pipelines. It also addresses the determination of consequential strains resulting from seismic loads, taking into account the interaction between soil and pipeline by means of nonlinear time history calculations. Table 1 presents the allowable strain limits for tension and compression as outlined in various seismic guidelines for both straight and bends/tees buried gas steel pipelines.

Table 1. Allowable strains limits for buried continuous pipelines in different codes.

| Code | Pipeline Case | Allowable strains | |
|--------------------|---------------------------|-------------------|--------------------------|
| | | Tension | Compression |
| prEN 1998-4 (2022) | Straight | 3% | min (1%, 0.4 t/D) |
| | Bend or Tees | 1% | 0.35 t/D |
| ASCE (1984) | Straight | 2 – 5% | 0.35 t/D |
| | Bend or Tees | - | 0.35 t/D |
| ALA (2001) | Pressure integrity limits | 4% | 1.76 t/D |
| PRCI (2004) | Pressure integrity limits | 2 – 4% | 1.76 t/D |
| IITK (2007) | Straight | 3% | 0.175 t/D – 0.35 t/D |
| | Bend or Tees | 1% | 0.175 t/D – 0.35 t/D |
| AFPS (2020) | Straight | 2 – 5% | min (1%, 0.4 t/D) |

For seismic action considerations, the new continuous earthquake map of Germany, as defined by DIN EN 1998-1/NA (2021), quantifies earthquake intensity in relation to the spectral response acceleration on rock, denoted as $S_{aP,R}$. For a more detailed classification or grouping into different levels of seismic action, the draft from the second-generation standards, specifically in the general rules and seismic action, prEN 1998-1-1 (2021), introduces a classification predicated on the spectral response acceleration. This division encompasses four classifications: very low, low, moderate, and high (as tabulated in Table 2). Subsequently, these classifications along with axial strain limits are subsequently utilized within the paper to evaluate the seismic safety of diverse underground pipelines.

Table 2. Range of $S_{aP,R}$ to define seismicity levels for a return period of 475 years.

| Seismicity level | $S_{aP,R}$ [m/s^2] |
|------------------|---------------------------|
| Very low | $S_{aP,R} < 1.0$ |
| Low | $1.0 \leq S_{aP,R} < 2.5$ |
| Moderate | $2.5 \leq S_{aP,R} < 5.0$ |
| High | $5.0 \leq S_{aP,R}$ |

3. Methodology

The initial stage involves generating the acceleration response spectrum in accordance with DIN EN 1998-1/NA (2021). This process entails considering the mean values of the four seismicity levels. To ensure an adequate safety margin, the response spectra envelope for each seismicity level is created by accounting for various soil factors and control time periods. The utilization of the PEER ground motion database (Ancheta et al., 2013) facilitates the acquisition of relevant real earthquake data time-histories. For the modelling of the seismic loading of the pipelines within the framework of a nonlinear time history calculation, spectrum-compatible acceleration time histories are checked with respect to the comparable energy content to the underlying response spectrum and the least standard deviations of the records resulting in the identification of ten records for each seismicity level. Figure 2 depicts an example of the envelope or target response spectrum for moderate seismicity levels. This representation considers various soil conditions and spectrum-compatible records with mean values and standard deviations in comparison to the target spectrum.

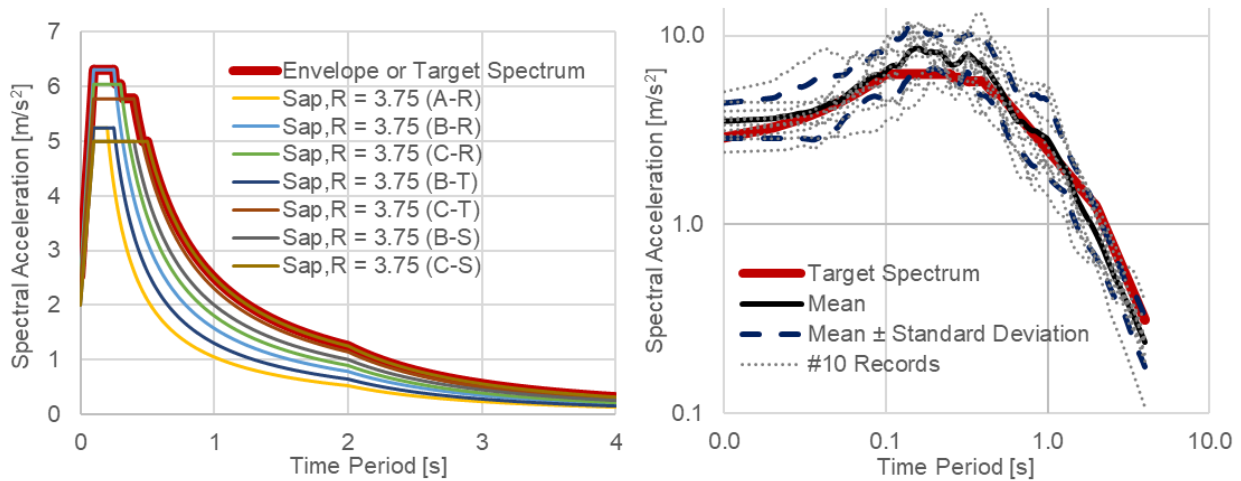


Figure 2. Response spectrum of moderate seismicity level (left) and response spectrum of selected records (right) showcasing compatibility.

Regarding the modelling of the buried pipeline, ANSYS® (2022) software was utilized. The numerical solution utilized a 3D Finite-Element (FE) Model, employing thick-walled beam elements (PIPE288) to represent the pipeline that also allows the introduction of internal gas pressure with temperature loadings. The axial strains generated by the internal pressure and temperature were calculated statically in the numerical solution and these were combined simultaneously in time with the upcoming strains produced from the seismic displacements. The analysis employed stress-strain non-linear Hollomon curves for different steel grades (Ramberg and Osgood, 1943). By referencing the stress-strain curve specific to each material, the analysis computed both elastic and plastic strains induced by seismic loads. For the seismic wave propagation loading, the paper employs a simplified combination of different wave types based on the so-called apparent wave velocity. This velocity corresponds to the speed the wave front achieves, and it serves as the foundation for mapping the spatial wave progression. This progression imposes time- and location-dependent ground displacements on the pipeline in three spatial directions. The calculation of the lengths of different pipeline configurations relied on the relationship between the separation distance and the preponderant wavelength

(O'Rourke and Liu, 1999). An essential point in the modelling of seismically stressed pipelines is the representation of the interaction of soil and pipeline. The individual directions of action of the interaction are represented by several spring characteristics describing the nonlinear behaviour of the soil (Kuhlmann, 2004). The interaction between the surrounding soil and the pipe were simulated using non-linear spring elements (COMBIN40) in longitudinal, horizontal, vertical directions along with an additional torsional spring. Figure 3 illustrates a modelling of a realistic buried pipeline, featuring straight sections, crossing structures, and sharp bends along with the exemplary locations of critical stresses or strains resulting from the propagation of wavefronts along the pipeline.

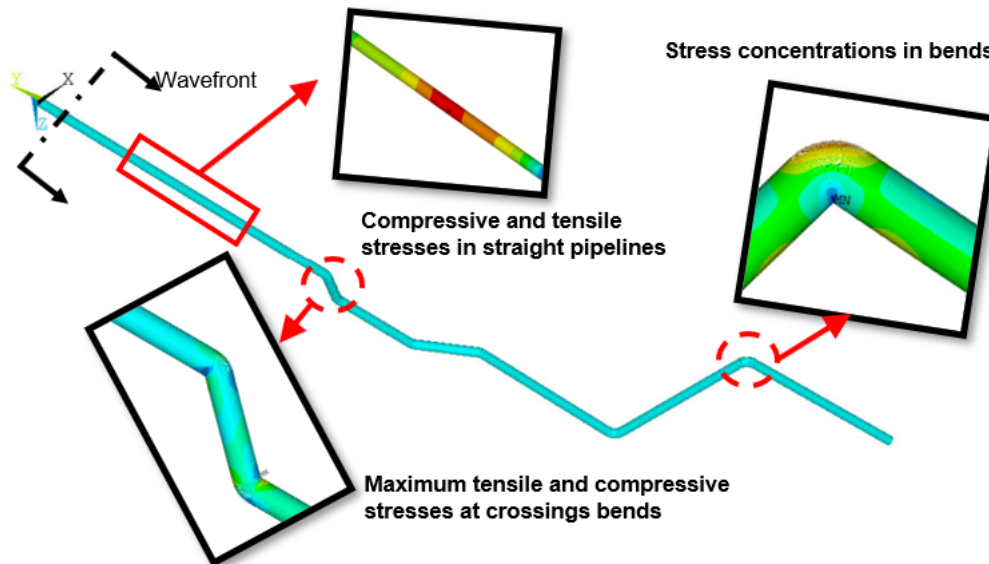


Figure 3. Seismic wave propagation along the buried pipelines and exemplary stress distribution at critical points.

4. Parametric Study

The strain-based verification according to DIN EN 1998-4 (2007) or prEN 1998-4 (2022) basically allows plastic deformation of the pipeline, but limits it to ensure sufficient safety against pipeline failure. In addition to compliance with the limits for the axial tensile strain, a limitation of the resulting compressive strains in the axial direction is prescribed to avoid a stability failure (denting). Hence, the assessment of strains relies on the numerical calculation model, considering all pertinent load cases within the parametric study. For realism and conservative analysis in the study, a mixed surrounding soil i.e. a combination of sand and clay or low plasticity clay was chosen. This soil type possesses a cohesion value (c) of 35 kN/m^2 , an angle of internal friction (ϕ) measuring 28° , and an effective unit weight of 9.5 kN/m^3 , alongside a pipeline coating friction factor (f) of 0.6. The initial phase of the examination primarily focused on the numerical calculation model applied to the straight section's pipelines with the non-linear time history analysis. The application of earthquake actions representative of Germany revealed no substantial violations of permissible normative limit values. Consequently, attention shifted towards the bends and the crossing structures along the pipeline due to the pronounced concentration of stresses in sharp bend regions. Due to extensive ten earthquake time histories per seismicity level, the calculations were computationally time and data exhaustive. Consequently, a simplified calculation model based on a sinusoidal load approach of the ground motion was also developed in parallel to the parametric study (Figure 4).

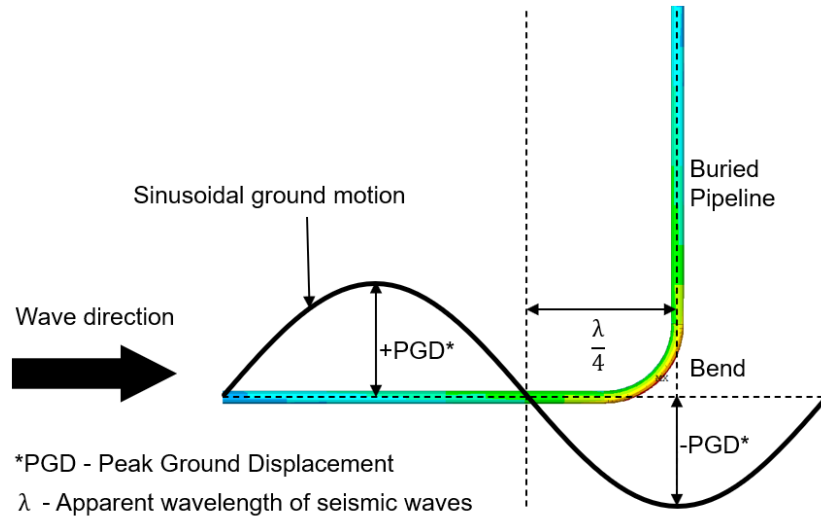


Figure 4. Simplified computational model (Chatterji et al., 2023)

This model involves the transmission of a sinusoidal wavefront along the buried pipeline, with the maximum magnitude of Peak Ground Displacement (PGD) from the time history allocated in one direction and 30% distributed across two other directions. The total time duration of the sinusoidal ground motion is determined based on covering the entire pipeline concerning the apparent velocity and wavelength. For instance, if the pipeline length measures 150 m based on a quarter of the wavelength (O'Rourke and Liu, 1999), the total wavelength will be 600 m and for an apparent wave velocity of 1000 m/s, the calculated total time duration is 0.6 s. This approach significantly reduces computation time to approximately 10 minutes, providing greater control over the parametric study. The simplified approach's validation involves comparing the axial strains (both tensile and compression) with those obtained from PEER ground motion time histories calculation across various pipeline diameters, material grades, operating pressures, bend radii, and configurations. This comparison between the time histories and sinusoidal motion yielded an approximate 90% confidence value for the axial strains.

For the next configuration, a 90-degree bend is selected as the unfavourable geometry with a segment length of both as 150 m. The consideration of the minimum requirements of the regulations, the most unfavourable configurations, and past experiences in designing pipelines in Germany were taken into account. Based on these, a total of 17 representative pipeline configurations for bends consisting of different diameters DN or outer diameter D , thickness (t), steel grades (yield strength, $R_{t0.5}$ or ultimate strength, R_m), operating pressures (DP) and temperature (T), buried depth of the pipeline at the centreline (H), and bend radius (R_{min}) are selected, which are compiled in Table 3.

Table 3. Realizations of the pipeline geometry (90-degree bend) for the parametric study.

| # | DN | D [mm] | t [mm] | $R_{t0.5}$ [MPa] | R_m [MPa] | DP [bar] | T [K] | H [m] | R_{min} |
|---|-----|--------|--------|------------------|-------------|----------|-------|-------|----------------|
| 1 | 100 | 114.3 | 3.6 | 245 | 415 | 16 | 20 | 1.5 | $3 \times D$ |
| 2 | 100 | 114.3 | 3.6 | 360 | 460 | 16 | 20 | 1.5 | $3 \times D$ |
| 3 | 300 | 323.9 | 6.3 | 360 | 460 | 16 | 20 | 1.5 | $3 \times D$ |
| 4 | 300 | 323.9 | 6.3 | 360 | 460 | 70 | 20 | 1.5 | $3 \times D$ |
| 5 | 300 | 323.9 | 6.3 | 290 | 415 | 16 | 20 | 1.5 | $3 \times D$ |
| 6 | 300 | 323.9 | 6.3 | 415 | 520 | 16 | 20 | 1.5 | $3 \times D$ |
| 7 | 300 | 323.9 | 6.3 | 360 | 460 | 16 | 20 | 1.5 | $1.2 \times D$ |
| 8 | 300 | 323.9 | 6.3 | 360 | 460 | 16 | 20 | 1.5 | $1.5 \times D$ |
| 9 | 600 | 610.0 | 6.3 | 415 | 520 | 16 | 20 | 1.5 | $3 \times D$ |

| | | | | | | | | | |
|----|------|--------|------|-----|-----|-----|----|-----|-------|
| 10 | 600 | 610.0 | 9.1 | 415 | 520 | 70 | 20 | 1.5 | 3 x D |
| 11 | 1000 | 1016.0 | 19.9 | 360 | 460 | 80 | 20 | 1.5 | 3 x D |
| 12 | 1000 | 1016.0 | 12.9 | 415 | 520 | 60 | 20 | 1.5 | 3 x D |
| 13 | 1000 | 1016.0 | 17.3 | 415 | 520 | 80 | 20 | 1.5 | 3 x D |
| 14 | 1000 | 1016.0 | 21.6 | 415 | 520 | 100 | 20 | 1.5 | 3 x D |
| 15 | 1000 | 1016.0 | 16.0 | 485 | 570 | 80 | 20 | 1.5 | 3 x D |
| 16 | 1000 | 1016.0 | 17.3 | 415 | 520 | 80 | 20 | 1.0 | 3 x D |
| 17 | 1400 | 1422.0 | 25.8 | 485 | 570 | 100 | 20 | 1.5 | 3 x D |

Similarly, within the depicted 2-D crossing structure shown in Figure 5 aligning with the characteristics of realization number three detailed in Table 3, the alteration in the crossing depth (ΔH) of the crossing section emerged as a principal parameter due to change in the soil resistances. The crossing depth (ΔH) were varied at 2.0, 4.0, and 8.0 m. The smoother bend radius of $5 \times D$ is employed. The midsection pipeline length remained constant at 30 m, while the incoming and outgoing straight pipelines were set to a length of 150 m each.

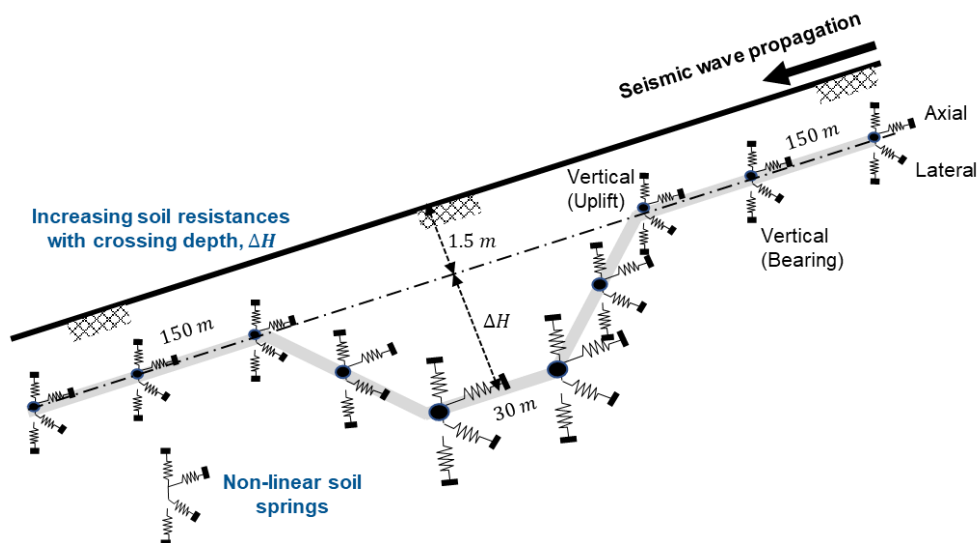


Figure 5. Traffic crossing structure model

5. Results

Drawing from the results of the computational investigations using the simplified load approach, the following conclusions can be drawn:

- Configurations - Compared to bend pipelines (90-degree bend and traffic crossing structures), straight pipe sections tend to be less vulnerable to the earthquake effects expected in Germany.
- Diameter - Smaller pipe diameters experience higher strains compared to larger diameters due to the lower section modulus.
- Pipeline wall thickness - As expected, a significant reduction in strain can be achieved by increasing the wall thickness.
- Material grade - Increasing material strength notably enhances earthquake resistance, particularly in the presence of plastic strains anticipated in moderate to strong earthquakes. However, for pipelines experiencing strains within the elastic range, the impact of material strength is not substantial.
- Bend radius - By increasing the bending radii, a strong reduction of the elongations in the bends can be achieved, especially for small pipeline diameters. Compared to increasing the material grade, a higher bending radius is a more effective measure.

- Surrounding soil - Changes in soil properties, specifically cohesion and friction angle, significantly impact soil-pipeline interaction. Higher cohesion and friction angle lead to reduced relative deformations between soil and pipeline, causing larger pipeline deformations. This effect is more pronounced in smaller diameter pipes due to their lower resistance to surrounding soil deformation.
- Seismic angle of incidence - The combination of the earthquake components of the seismic ground motion in the three spatial directions results in a different governing angle of incidence of the wave on the pipeline depending on the dominant component. Therefore, a variation of the angle of incidence plays a crucial role.

Concerning the 2D crossing structures, Figure 6 displays the plotted results revealing an approximate exponential increasing trend corresponding to the increase in PGD or seismicity level for various crossing depths. At very low or low seismicity levels, indicated by low PGD values, the most unfavourable strain values occurred at a crossing depth of 2.0 m. This phenomenon arises due to increased global system moments and bending stresses near the bends supported by prolonged pipelines which significantly outweigh the relatively lower stiffness provided by the soil springs owing to reduced overall soil depth. In contrast, for moderate and high seismicity levels, denoted by high PGD values, the most unfavourable strain values were observed at a crossing depth of 8.0 m. This can be attributed to the overall increase in soil stiffness. The crossing depth of 4.0 m does not decisively impact strain values due to the combination of low bending moment and low soil resistance. The normative limits are attained at a PGD value ranging between 8.0-10 cm, aligning with a moderate seismicity level.

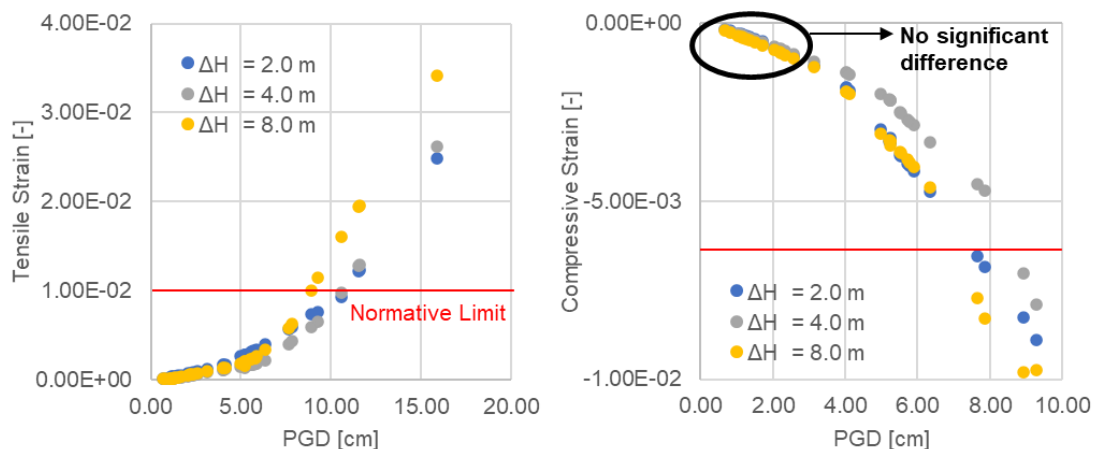


Figure 6. Variation of tensile and compressive strains with increasing PGD for different crossing depths.

When comparing the axial strain values obtained from various configurations (straight, 90-degree bends, 2D crossings, 3D spatial crossings combined with 90-degree bends), 90-degree pipe bend results in larger strains both in tension and compression for all seismic levels. Therefore, to adopt a conservative approach, the 90-degree bends serve as the foundation for the development of the multi-level or hierarchical verification concept.

6. Multi-level verification concept

A critical aspect of infrastructure design in earthquake-prone areas is the establishment of reliable verification frameworks. In pursuit of a simplified application within earthquake-prone regions of Germany, a three-stage verification framework characterized by ascending levels of precision has been formulated. The first two levels of verification are founded on verification tables contingent upon primary influencing parameters. These tables draw upon numerical simulation results pertaining to the most unfavourable combination of diameter and influence variations. To facilitate normative verification, the ultimate limit state employs the axial strain limit values stipulated in DIN EN 1998-4 (2007) and prEN 1998-4 (2022) as verification criteria. This approach yielded a total of 18 tables for the second stage, along with one table for the first stage. In cases where specific pipeline diameter and wall thickness combinations were not explicitly addressed, it is necessary to categorize them under the next less favourable configuration, either a smaller diameter or reduced wall thickness. An overview of the devised procedure is depicted in Figure 7. Additionally, the simplified verification table (stage

1) and, by way of illustration, a diameter-specific table (stage 2) for a DN 600 pipeline featuring a bending radius of $3D$ are shown.

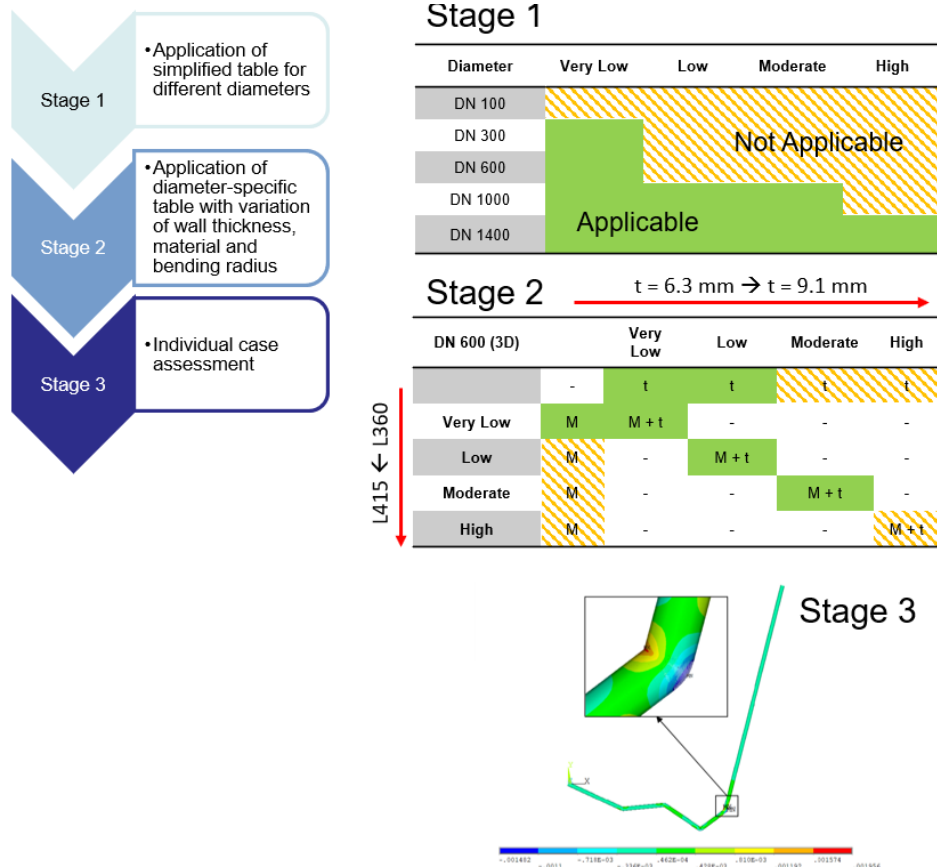


Figure 7. Hierarchical verification concept based on the four seismic action classes (Chatterji et al., 2023)

Stage 1: Simplified table for different diameters In the first stage, a blanket assessment is made based on five pipe diameters. If a direct classification via the pipe diameter is not possible, the next smaller diameter is to be selected. According to the grouping of the impact action levels very low, low, moderate or high in the columns that is decisive for the pipeline under consideration, a blanket statement can be made in accordance with the colour coding on the fulfilment of the verification (see Figure 7). A green marking corresponds to an allowable combination of diameter and action with compliance with the normative strain criteria. The shaded area indicates combinations for which the blanket verification in stage 1 is not applicable.

Stage 2: Diameter-specific table In addition to the diameter, the second stage also includes a variation of the pipe wall thickness, the material grade and the bending radius, starting from the most unfavourable constellation in stage 1. An example of a tabular representation for a specific combination of diameter and bending radius is given in Figure 7. In contrast to stage 1, the table is divided into the four action levels both in column and row directions. The individual columns contain in the first row the consideration of an increased wall thickness, t (e.g. 9.1 mm instead of 6.3 mm), whereas the different rows in the first column show the increase of the material grade, M (e.g. L415 instead of L360). A combination of the variation of both properties ($M + t$) is shown on the diagonal of the table. Analogous to stage 1, a cell with a green background represents a permissible combination of diameter and action for which the normative strain limits are observed. A shaded cell marks a combination for which the verification with the diameter-specific table is not applicable for a given bending radius in the second stage. In this case, an increase of the bending radius can be considered and the check can be performed using the corresponding table of the higher bending radius. Alternatively, an individual consideration can be carried out in stage 3.

Stage 3: Individual case assessment If verification is not possible by varying the pipe wall thickness, material grade and the bending radius for a specific diameter, an individual case analysis is required (stage 3). Here, for example, by applying the simplified calculation approach with sinusoidal load application, a more accurate

determination of the resulting strains for a representative 90-degree pipe bend can be made (Figure 4). Alternatively, the actual pipe geometry or section can be considered in a nonlinear time history calculation to allow for additional load reserves in the normative verification. Details on how to perform time history calculations can be found in DIN EN 1998 (2007) and prEN 1998-4 (2022).

7. Application

The application of the multi-level verification concept is shown with an example considering the real natural gas buried pipeline part of which run through the seismic hazards site in Germany. The seismic analysis is carried out for representative pipeline situations for the pipeline sections with the highest seismic impacts as shown in Figure 8. This pipeline is characterized by a diameter of DN 400 and a wall thickness measuring 9.4 mm, features factory bend radii of 10 times the diameter (10D) and a soil covering height of 1.2 m operating under a temperature of 25°C and designed for an internal pressure of 100 bar. The pipeline is composed of L 360 ME/NE material. The seismicity level according to prEN 1998-4 (2022) is classified as Low to Moderate, denoted by a $S_{aP,R}$ of 2.5 m/s². Additionally, the properties of the soil include a cohesion of 0 kN/m², a soil friction angle of 32.5°, and a soil density of 19 kN/m³. Additionally, the coefficient considering the pipe material was set at 0.6. The detailing non-linear time history analysis with the three spectrum-compatible synthetic time histories yielded tensile (ϵ_t) and compressive (ϵ_c) axial strains of +0.112% and -0.079% respectively which are well below the normative limits of 1% and -0.92% respectively as per prEN 1998-4 (2022).

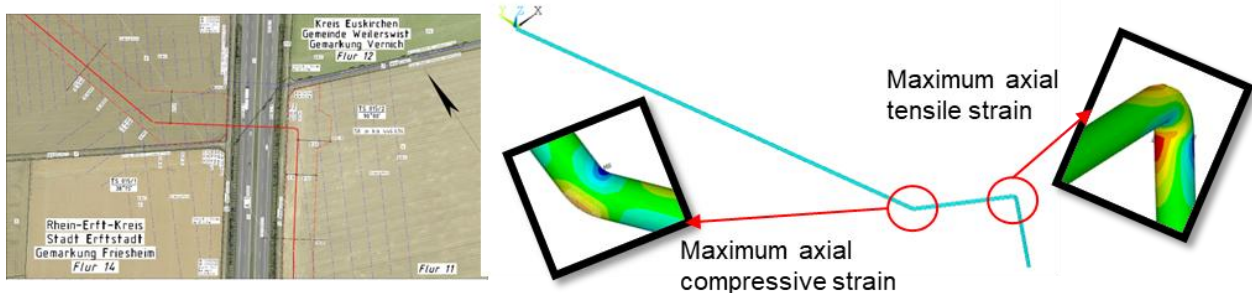


Figure 8. Plan, modelling and computational seismic analysis of a natural gas buried pipeline laid in Germany

The hierarchal verification concept initiates at stage 1 employing a simplified table for different diameters. Given that DN 400 falls between DN 300 and DN 600, both diameters are situated in the shaded area signifying that blanket verification in stage 1 is inapplicable for low and moderate seismicity levels, prompting the transition to stage 2 as shown in Figure 9. As smaller pipe diameters experience higher strains compared to larger diameters, DN 300 with a 10D bending radius is selected from an existing table established through parametric study for stage 2. Considering the same material grade (L360) but with a wall thickness of 8.0 mm instead of given 9.4 mm only the respective table row is examined. This analysis reveals the green region as marked in Figure 9 denoting an allowable combination of diameter and action complying with the normative strain criteria for both low and moderate seismicity levels. Consequently, individual consideration (stage 3) is not required, affirming that the pipeline adheres to the safety norms outlined in prEN 1998-4 (2022).

Stage 1

| Diameter | Very Low | Low | Moderate | High |
|----------|----------|-----|----------|------|
| DN 300 | | | | |
| DN 600 | | | | |

Stage 2

t = 6.3 mm → t = 8.0 mm

| | DN300 (10D) | Low | Moderate |
|----------|-------------|-------|----------|
| L360 | | t | t |
| L415 | M | M + t | |
| Moderate | M | | M + t |

Figure 9. Multi-level verification for DN400 natural gas buried pipeline.

To extensively utilize the multi-level verification concept and substantiate its efficacy, an individual assessment (stage 3) is conducted for DN 400 using the same soil parameters employed in the parametric study as well as with the soil parameters present in the site. The resulting axial strains obtained through a simplified calculation approach (sinusoidal wave propagation) are tabulated for both low and moderate seismicity levels in Table 4.

Table 4. Individual case assessment (stage 3) for DN400 pipeline for different soil conditions.

| DN400 (10D) | Soil properties as used in the parametric study | | Soil properties as present in the site | |
|---|--|------------------|---|------------------|
| | ϵ_t [%] | ϵ_c [%] | ϵ_t [%] | ϵ_c [%] |
| Non-linear time history analysis | – | – | 0.112% | –0.079% |
| Simplified calculation approach (low seismicity) | 0.174% | –0.201% | 0.153% | –0.113% |
| Simplified calculation approach (moderate seismicity) | 0.226% | –0.302% | 0.175% | –0.142% |

A comparison of the axial strains derived from the simplified calculation approach using soil properties from the parametric study demonstrates closer yet larger strain values. This observation indicates that the multi-level verification concept tends toward a conservative and safer estimation. Furthermore, when altering the soil properties to match the site conditions, reflected in the third and fourth columns of the table, the axial strains obtained from the simplified calculation approach become notably closer but still larger in comparison to the detailed and time-consuming non-linear time history analysis. The strains comply with the norms in all the cases. Such simplified multi-level verification tables and models prove instrumental in providing a rapid and preliminary assessment of buried pipelines under seismic hazards. These simplified models provide a foundational understanding of the pipeline's response to seismic actions which also aids in identifying critical parameters that may necessitate further detailed analysis. This enables engineers to make informed decisions, allocate resources and thereby streamlining the overall seismic design and evaluation process.

8. Summary

The paper addresses the complex challenges and propose simplified framework in assessing seismic structural integrity for buried high-pressure gas pipelines. The earthquake load case is crucial for planning new pipelines and converting existing ones for alternative transport, especially due to regional earthquake effects and verification according to the new hazard map for Germany. In the course of a research project, investigations were carried out on different pipeline configurations with the aim of deriving a simplified verification concept for the most practical application possible. The contributions of this paper introduce the principles of the new guideline, offering a practical approach for designing spatially distributed pipeline systems using computational models and design concepts for seismically induced ground movements. The paper covers various aspects of pipeline and soil parameters including angle of incidence of waves, propagation in soil, different configurations of buried pipeline. The result of the first part of the project is a hierarchical multi-level verification concept for the load case of wave propagation that enables verification of pipelines in earthquake-prone areas in Germany based on three stages for different seismic action classes defined in prEN 1998-1-1 (2021). The multi-level verification concept demonstrates simplified estimations of axial strains, offering rapid preliminary assessments crucial for seismic design in buried pipelines.

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