Second Generation of Eurocode 8

Webinar 4.4: **Above ground and buried pipelines**

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SCOPE FOR ABOVE-GROUND PIPELINES

Continuous pipelines

- Steel
- Unreinforced concrete
- Reinforced concrete

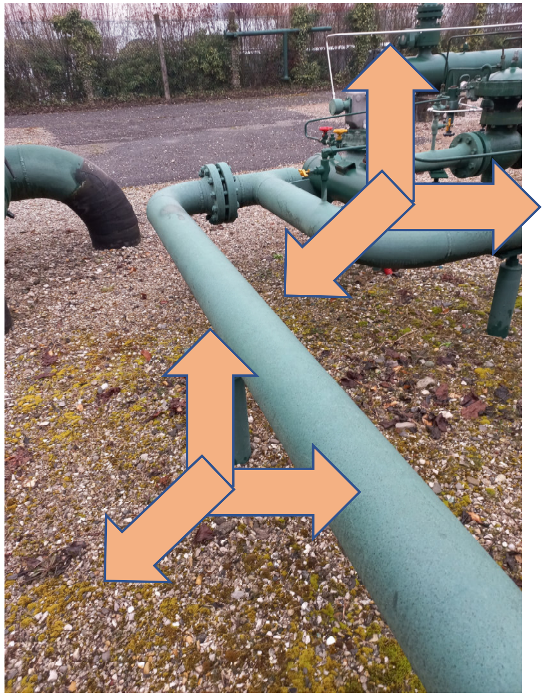
Seismic actions

- Transient and permanent ground deformations

Examples of above-ground pipelines (© C. Fernandez)

DESIGN CONCEPT - KEY POINTS

- Pipeline systems with straight and bended sections and ancillary elements are classified in singles lines and redundant networks.
- A pipeline should be considered as a single line when its behaviour during and after a seismic event is not influenced by other pipelines
- Above-ground pipelines should be designed for the dynamic structural response under the three components of the seismic actions. The variability of ground motion due to wave passage, local site effects and incoherence should be considered.
- Differential displacements due to the structural response of different substructures along the pipeline should be considered



DESIGN CONCEPT - KEY POINTS

- The design should include ancillary elements such as valves, pumps or instrumentation and their connections to the pipeline.
- The design should consider the influences of crossings to associated facilities due to connecting pipes and differing types of foundation.
- The principles of the seismic analysis procedures may also be applied to above-ground pipelines made of other materials (e.g. glass fibre-reinforced plastic/polymer (GFRP), high density polyethylene (HDPE) or polyethylene (PE)).
- Above ground pipelines should be designed in DC1 or DC2. Substructures of above-ground pipelines may be designed according to ductility classes DC1, DC2 or DC3.

DESIGN FOR PERMANENT GROUND DEFORMATION

The seismic design should consider seismic induced permanent ground deformations

- fault crossings
- liquefaction induced phenomena
- slope stability
- landslides
- local soil settlements

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MODELLING

- The dynamic calculation model should consider
  - strength, damping, pipeline geometry, stiffness and mass properties
  - foundations and soil stiffness
  - mass of the fluid inside the pipeline
  - dynamic characteristics of the substructures
  - type of connection between pipeline and substructure
- Soil-structure interaction should be taken into account using EN 1998-5, 8
- A pipeline may be considered straight when the radius of curvature is 20 times the outer diameter of the pipeline. Straight pipelines may be idealised by beam models with distributed mass.
- Special elbow or shell elements may be used instead of beam elements if out of roundness or warping behaviour are expected

STRUCTURAL ANALYSIS

Force-based approach

- Response spectrum analysis according to EN19981-1, 6.4.3

Displacement-based approach

- Elevated pipeline with supporting structures may be analyzed by means of non-linear static analysis according to EN 1998-1-1, 6.5
- Analysis of permanent ground motions may be carried out by static analysis with imposed displacements to the pipeline supports

ACTIONS AND COMBINATIONS OF ACTIONS

- The design values of seismic actions should be calculated separately for seismic action effects due to dynamic structural response and permanent ground deformations.

- The design values of the seismic actions should be superimposed with the permanent actions due to self-weight and variable actions. Existing variable actions (e.g. internal operational pressure) should be considered as permanent actions.

- If the design values of the seismic actions occur simultaneously along of the pipeline, they should be superimposed in the seismic design situation.

BEHAVIOUR FACTOR

- Welded steel pipelines

Structural ductility class	r/t	q_R	q_S	q_D	q
DC1	$100 \leq \frac{r_p}{t_p}$	1,0	1,5	1,0	1,5
DC2	$\frac{r_p}{t_p} < 50$	1,0	1,5	2,0	3,0
DC2	$50 \leq \frac{r_p}{t_p} < 100$	1,0	1,5	$1,0 + \frac{1,0}{50}\left(\frac{r_p}{t_p} - 50\right)$	$1,5\ q_D$

- Reinforced concrete above-ground pipelines should be design in DC1 with: q_R = 1,0, q_D = 1,0, q_S = 1,5

- Unreinforced concrete above-ground pipelines should be design with: q_R = 1,0, q_D = 1,0, q_S = 1,0

- Substructures should be design in DC1, DC2 or DC3 according to EN 1998-1-2

- The behaviour factor q_v for vertical seismic actions should be applied as min(q, 1,5), where q is behaviour factor for the horizontal component.

Seismic loads

- The seismic analysis shall take into account the spatial variability of the ground motions due to wave passage, local site effects and incoherence.

- If response spectrum analysis is applied, the spatial variability may be taken into account according to EN 1998-1-1, 5.2.3.2, by applying local site-specific response spectra at every support along the pipeline.

- Alternatively, a response-spectrum or time history analysis with uniform excitation of all supports may be applied if the design quantities are increased as follows:

  - **10 %** for uniform soil conditions with shear wave velocities varying not more than 200 m/s

  - **20 %** for of soil conditions with shear wave velocities varying more than 200 m/s

  - **30 %** for soil conditions with shear wave velocities varying more than 200 m/s and geological discontinuities, heterogenous soil conditions, non-negligible topographic/basin effects

PERMANENT GROUND DEFORMATION

- Fault crossings
- Liquefaction induced phenomena
  - exceedance of the load bearing capacity
  - settlements of foundations
  - instability of foundations
  - lateral spreading
- Slope stability
- Landslides
- Soil settlements

VERIFICATION TO LIMIT STATES

SD limit state

- Global stability (overturning, position on supports, etc.)
- Pipeline (steel: EN 1594, unreinforced + reinforced concrete: EN 1992-1-1)
- Substructures of elevated pipelines
- Foundations
- Anchorage systems

DL limit state

- Verified, if the all elements of the pipeline system remain in the elastic range

OP limit state

- Verify that the deformations are acceptable to maintain the functionality

SCOPE FOR BURIED PIPELINES

Continuous pipelines

- steel
- unreinforced concrete, reinforced concrete and prestressed precast reinforced concrete pipeline systems

Seismic Actions

- transient
- permanent ground movement

DESIGN CONCEPT - KEY POINTS

- The effects of seismic action considered on buried pipelines should be seismic induced stresses or strains in the pipeline wall.

- Buried pipelines restrained by the surrounding soil should be designed for ground motion due to the seismic wave propagation.

- The seismic design should consider the spatial variability of ground motion due to wave passage, local site effects and incoherence.

- The seismic design should consider seismic induced permanent ground deformations:
  - fault crossings
  - liquefaction induced phenomena
  - lateral spreading and landslides
  - slope stability
  - local soil settlements

DESIGN CONCEPT - KEY POINTS

- The seismic design of buried pipelines should consider the influences of crossings to associated subsystems (e.g. compressor stations) with connecting pipes, pipeline routing over single foundations and foundation slabs and transition areas to above-ground pipelines.

- The seismic design of a buried pipeline should include ancillary elements such as valves, tanks, pumps or instrumentation and their connections to the pipeline.

- Informative **Annex C** provides additional general design considerations for buried pipelines.

- The concepts may also be applied to buried pipelines made of other materials (e.g. Glass fibre-reinforced plastic/polymer (GFRP), High density polyethylene (HDPE) or Polyethylene (PE)).

ANNEX C: GENERAL DESIGN CONSIDERATIONS FOR BURIED PEPLINES

- Within 50 m on each side of the fault, relatively thick-walled pipeline and a coating allowing the lowest possible friction with the surrounding soil should be used. An exchange of the surrounding soil by a special low friction and high compressibility backfill may also be considered.
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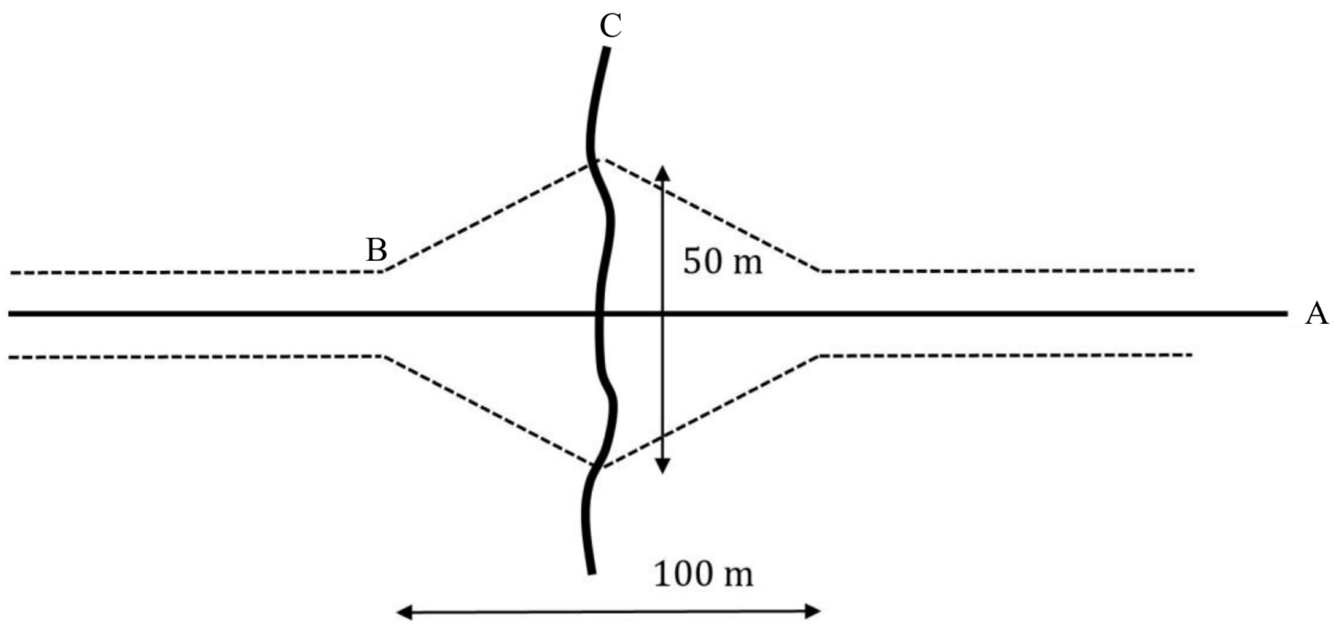
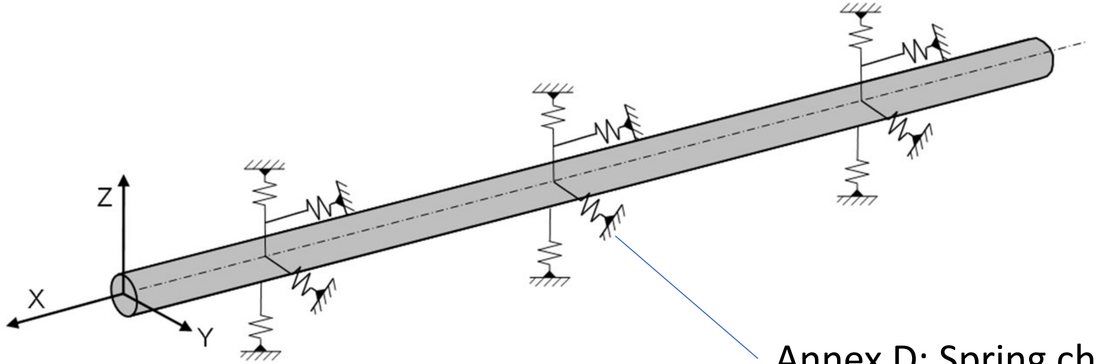


Trench design at fault crossing (A: pipeline; B: trench; C: fault)

MODELLING – ANALYTICAL AND NUMERICAL APROACHES

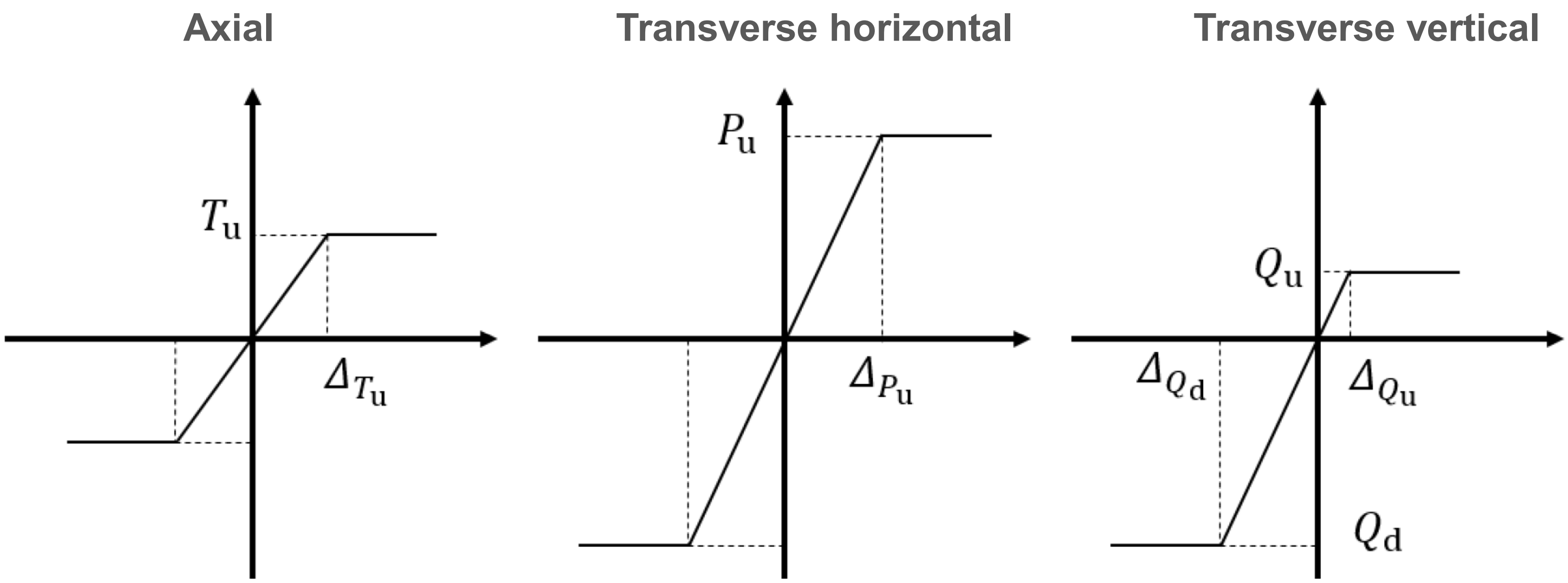
- A pipeline may be considered as a straight pipeline when the radius of curvature is greater than 20 times the outer diameter of the pipeline.
- A simple analytical model may be used for a no-slippage straight pipeline to get an upper bound estimate of the strains in the pipeline for wave propagation. If detailed modelling is required to capture out of round and warping effects, a hybrid model approach may be applied.
- Pipeline sections with or without bends may be modelled with beam elements. The interaction with the surrounding soil may be modelled by non-linear spring elements (Annex D). Inertia effects may be neglected.



Annex D: Spring characteristics

ANNEX D: SOIL-STRUCTURE INTERACTION EFFECTS

Spring characteristics



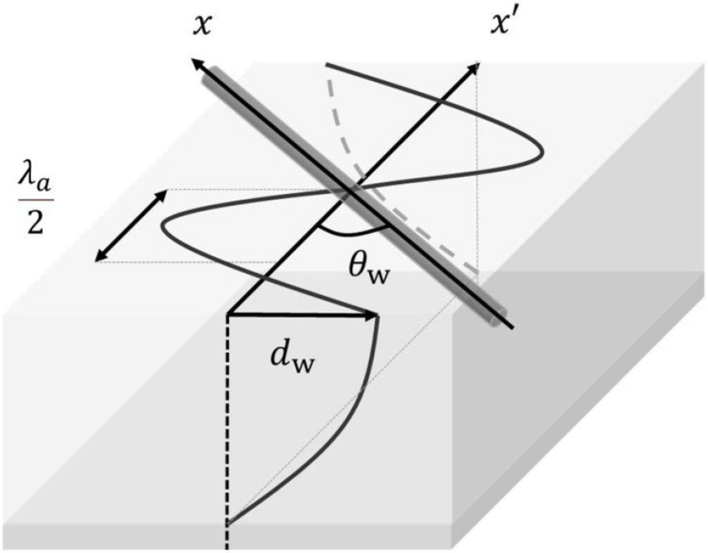
STRUCTURAL ANALYSIS

- Straight buried pipelines subjected to wave propagation may be analysed by strain analysis without considering soil structure interaction effects
- Buried pipelines with or without bends may be analysed by non-linear response-history analysis according to EN 1998-1-1, 6.5 and 6.6
- Permanent ground deformations may be analysed with static analysis by imposing displacements to the non-linear pipeline model.

SEISMIC LOADS: WAVE PRPOAGATION FOR STRAIGHT PIPELINES

Strain analysis with a sinusoidal wave according to EN 1998-5:2022, Table H.2

$$u(x,t) = d_{\mathrm{W}} \sin \left(\frac{2\,\pi}{\lambda_a} (x - V_{\mathrm{app}} t) \right)$$



Maximum axial strain

$$\varepsilon_{\mathrm{a}}^{\mathrm{p}} \leq \frac{PGV}{V_{\mathrm{app}}}$$

Maximum curvature

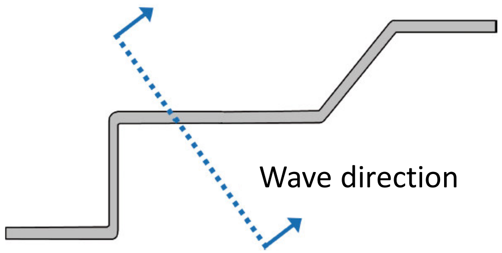
$$\chi^{\mathrm{p}} \leq \frac{PGA}{V_{\mathrm{app}}^2}$$

Apparent wave velocity

$$V_{\mathrm{app}} = 1000 \ \mathrm{m/s}$$

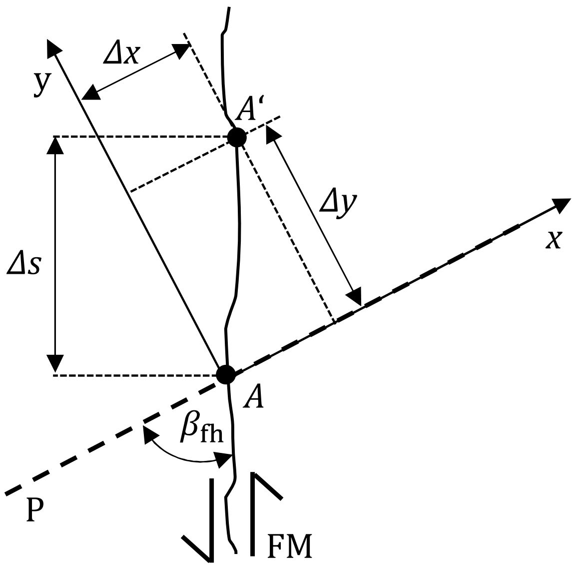
SEISMIC LOADS: NON-LINEAR RESPONSE TIME HISTORY ANALYSIS

- The seismic ground motion should be represented by displacement time-histories derived by integration from accelerograms fulfilling the criteria of EN 1998-1-1, 5.2.3.1
- The seismic wave propagation should be applied as displacement time-histories to the pipeline with the apparent wave velocity. Each set of seismic ground motions should be simultaneously applied in all three directions considering the time offset to cover wave passage effects.
- Different incident angles should be investigated to cover the directional dependence, especially in the areas of bends.
- As for PGV and PGA all design quantities may be increased by 20 or 30% with respect to the variation of the shear wave velocities and topographic discontinuities.

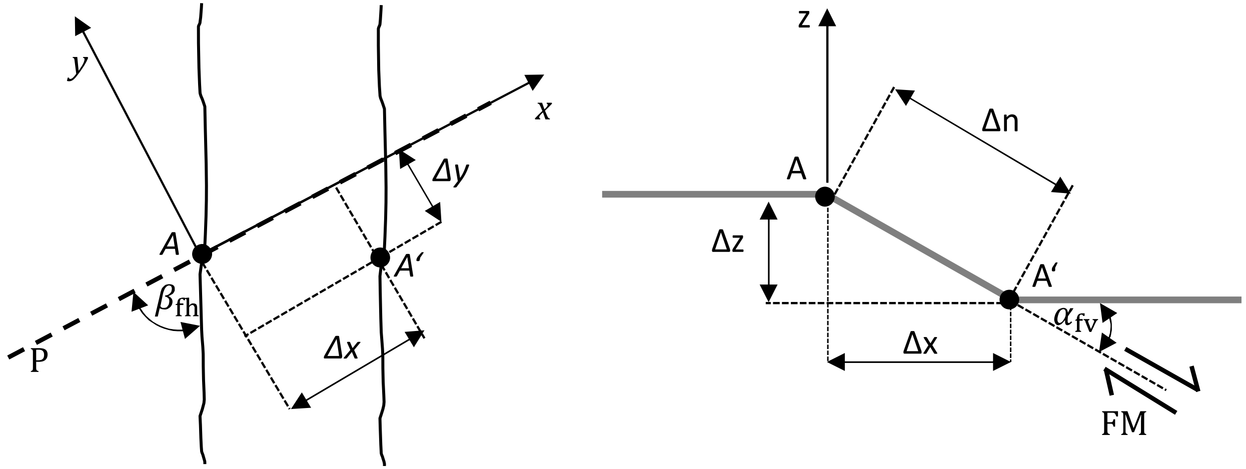


FAULT CROSSING FOR STRAIGHT PIPELINES

The fault-pipeline crossing is described by the crossing angle in the horizontal plane, β_{fh}, and the fault dip angle, α_{fv}. It is assumed, that the strike−slip faults only slip horizontally and dip−slip (i.e. normal or reverse) faults only slip vertically. The fault movements Δs and Δn may be estimated by site−specific investigations or using Annex E.



Strike−slip fault



Normal slip fault in plan and elevation

FAULT CROSSING FOR STRAIGHT PIPELINES

Fault movements in axial and transverse direction to the pipeline Δx and Δy due to the transverse (strike-slip) fault Δs

$$\Delta x = \Delta s \cos \beta_{\mathrm{fh}}$$

$$\Delta y = \Delta s \sin \beta_{\mathrm{fh}}$$

The components of fault movements in axial, transverse and vertical direction to the pipeline Δx, Δy and Δz due to the normal slip Δn

$$\Delta x = \Delta n \ \cos \alpha_{\mathrm{fv}} \sin \beta_{\mathrm{fh}}$$

$$\Delta y = \Delta n \ \cos \alpha_{\mathrm{fv}} \cos \beta_{\mathrm{fh}}$$

$$\Delta z = \Delta n \ \sin \alpha_{\mathrm{fv}}$$

FAULT CROSSING FOR STRAIGHT PIPELINES

The average axial strain ε_a^f in the pipeline due to the components of fault movements in axial and transverse direction of the pipeline:

$$\varepsilon_a^f = 2\left[\frac{\Delta x}{2L_A} + \frac{1}{2}\left(\frac{\Delta y}{2L_A}\right)^2\right]$$

L_A is the effective unanchored length:

$$L_A = \frac{E\,\varepsilon_y \pi\, D_p\, t_p}{T_u}$$

ε_y is the yield strain;

E is the Young's modulus;

T_u is the ultimate force per unit length at the soil-pipeline interface. => Annex D

LIQUEFACTION INDUCED PHENOMENA: BUOYANCY

The buoyant force per unit length of the pipeline, V_{BU}, in liquified soils is calculated as:

$$V_{\mathrm{BU}} = \frac{\pi D_{\mathrm{op}}^2}{4}(\gamma_{\mathrm{s}} - \gamma_{\mathrm{c}}) - \pi D_{\mathrm{op}} t_{\mathrm{p}} \gamma_{\mathrm{p}}$$

D_{op} is the outer diameter of the pipeline;

γ_{s} total unit weight of the soil;

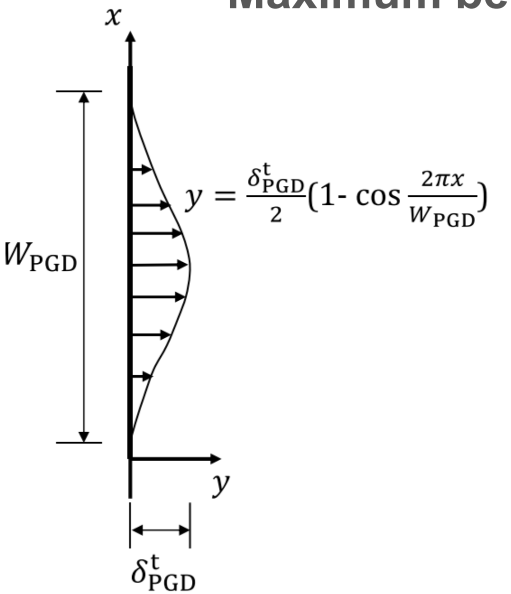
γ_{c} unit weight of the pipeline content;

γ_{p} unit weight of the pipeline material.

LIQUEFACTION INDUCED PHENOMENA: LATERAL SPREADING

Permanent ground displacements in the transverse and axial directions due to lateral spreading and landslides. W_{PGD}, L_{PGD} are the width and length of the permanent ground deformation zones, and $\delta^{t}_{\mathrm{PGD}}$, $\delta^{a}_{\mathrm{PGD}}$ the corresponding maximum amplitudes.

Maximum bending strain

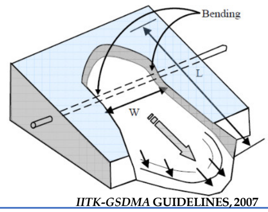


Flexible pipeline

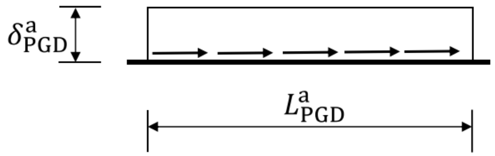
$$\varepsilon_b = \pm \frac{P_u \, (W_{\mathrm{PGD}})^2}{3\,\pi\,E\,t_p\,(D_{op})^2}$$

Stiff pipeline

$$\varepsilon_b = \pm \frac{\pi^2 D_{op}\,\delta^{t}_{\mathrm{PGD}}}{(W_{\mathrm{PGD}})^2}$$

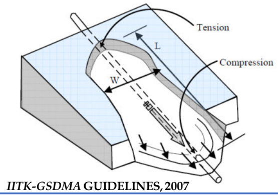


Maximum axial strain



$$\varepsilon_a = \frac{\tan^{-1}\left(\frac{\delta^{a}_{\mathrm{PGD}}}{L_{\mathrm{PGD}}}\right) L_{\mathrm{PGD}}}{2\,L_{em}} \qquad L_{\mathrm{PGD}} \leq 4\,L_{em}$$

$$\varepsilon_a = \frac{\tan^{-1}\left(\frac{\delta^{a}_{\mathrm{PGD}}}{L_{\mathrm{PGD}}}\right) L_{\mathrm{PGD}}}{\sqrt{L_{\mathrm{PGD}}\,L_{em}}} \qquad L_{\mathrm{PGD}} > 4\,L_{em}$$



LIQUEFACTION INDUCED PHENOMENA

Slope stability

The slope stability in the area of the pipeline routing should be analysed along the entire pipeline.

Soil settlements

Potential soil settlements and soil densification should be evaluated under free-field conditions according to EN 1998-5:2022, 9.4.2.1.4, along the entire pipeline.

ACTIONS AND COMBINATIONS OF ACTIONS

- The design values of seismic actions should be calculated separately for seismic action effects due to dynamic structural response and permanent ground deformations.

- The design values of the seismic actions should be superimposed with the permanent actions due to self-weight, soil covering and variable actions. Existing variable actions (e.g. internal operational pressure) should be considered as permanent actions.

- If the design values of the seismic actions occur simultaneously along of the pipeline, they should be superimposed in the seismic design situation.

VERIFICATION AT SD LIMIT STATE

Steel pipelines

- tensile strain in straight-line pipelines: 3 %;
- tensile strain in bends or tees of pipelines: 1 %;
- compressive strain straight-line pipelines: min {1 %; 0,4 t_p/D_p};
- compressive strain in bends or tees of pipelines: 0,35 t_p/D_p;

In welded steel pipelines, the ovaling O_v should not be greater than 2,5 %:

$$O_v = \frac{D_{max} - D_{min}}{D_{mean}}$$

O_v	is the out-of-roundness value of the pipeline;
D_{max}	is the greatest outer diameter of the pipeline after its out-of-roundness;
D_{min}	is the smallest outer diameter of the pipeline after its out-of-roundness;
D_{mean}	is the mean outer diameter of the pipeline before out-of-roundness.

VERIFICATION AT SD LIMIT STATE

Unreinforced & reinforced concrete and prestressed precast reinforced concrete

- To be verified according to EN 1992-1-1

Integrity requirement and ancillary elements:

- Buried pipeline systems should satisfy the integrity requirements and maintain their supplying capability as a global servicing system
- Anchorages of ancillary elements (e.g. valves, pumps or instrumentation) should be verified in the design seismic situation

VERIFICATION AT DL AND OP LIMIT STATE

DL limit state

- Verified, if the all elements of the pipeline system remain in the elastic range

OP limit state

- Verify that the deformations are acceptable to maintain the functionality

Annex E: Design differential surface displacement at pipeline – fault crossing

- Define the design differential displacement that can be used for designing pipelines, or other elongated structures, crossing a fault at a specified location.

- Informative Annex E provides an approximation of fault surface displacement for given return periods based on gross fault characteristics.

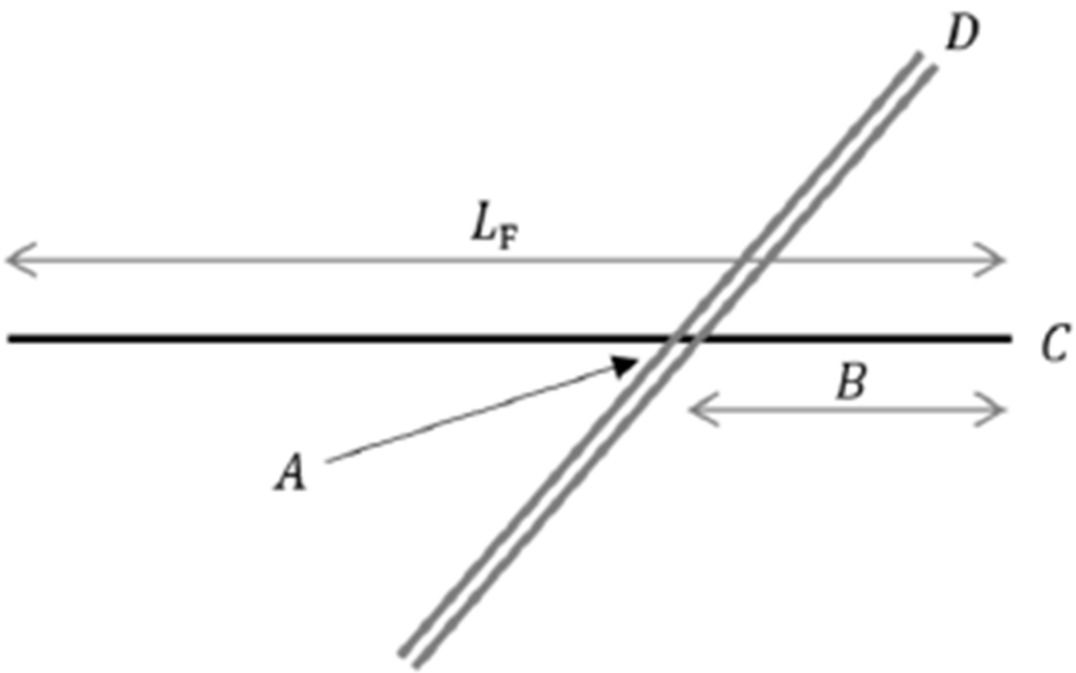
- The design differential displacement estimated via Annex E only concerns principal faulting. It does not incorporate any additional differential displacement appearing at sites away from the fault trace due to distributed/secondary faulting.

Annex E: Design differential surface displacement at pipeline – fault crossing

Motivation:

- Middle ground between the simpler approach (i.e., deterministic via the scaling relations) and the more “accurate” probabilistic approach (i.e., fault displacement hazard analysis).
- Fill the gap in European codes for estimating the design fault displacement for pipelines at fault crossings in a hazard-consistent manner.

Annex E: Design differential surface displacement at pipeline – fault crossing



A: crossing point
B: distance to closest fault-end
C: fault trace
D: pipeline

Annex E: Design differential surface displacement at pipeline – fault crossing

- 1st step: Fault mechanism and length & fault crossing site
- 2nd step: Recurrence rate v_F (from fault database or via simplified approach)
- 3rd step: Return period (T_R) for given fault displacement (Δ_F) or vice-versa:

$$T_R(\Delta_F) = \frac{1}{C_F v_F f_L(\Delta_F, L_F, X_L)}$$

where:

C_F = confidence factor

$f_L(\Delta_F, L_F, X_L)$ = function depending on the fault mechanism, fault length, and crossing point; estimated using tables

THANK YOU FOR YOUR ATTENTION!