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Earthquake- and subsidence-resistant design of ductile iron pipelines

Conception de canalisations en fonte ductile résistant aux tremblements de terre et aux affaissements

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Foreword

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Introduction

Buried pipelines are often subjected to damage by earthquakes. It is therefore necessary to take earthquake resistance into consideration, where applicable, in the design of the pipelines. In reclaimed ground and other areas where ground subsidence is expected, the pipeline design must also take the subsidence into consideration.

Even though ductile iron pipelines are generally considered to be earthquake-resistant, since their joints are flexible and expand/contract according to the seismic motion to minimize the stress on the pipe body, nevertheless there have been reports of the joints becoming disconnected by either a large quake motion or major ground deformation such as liquefaction.

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Earthquake- and subsidence-resistant design of ductile iron pipelines

1 Scope

This International Standard specifies the design of earthquake- and subsidence-resistant ductile iron pipelines suitable for use in areas where seismic activity and land subsidence can be expected. It provides a means of determining and checking the resistance of buried pipelines and also gives example calculations. It is applicable to ductile iron pipes and fittings with joints that have expansion/contraction and deflection capabilities, used in pipelines buried underground.

2 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

2.1
burying
placing of pipes underground in a condition where they touch the soil directly

2.2
response displacement method
earthquake-resistant calculation method in which the underground pipeline structure is affected by the ground displacement in its axial direction during an earthquake

2.3
liquefaction
phenomenon in which sandy ground rapidly loses its strength and rigidity due to repeated stress during an earthquake, and where the whole ground behaves just like a liquid

2.4
earthquake-resistant joint
joint having slip-out resistance as well as expansion/contraction and deflection capabilities

3 Earthquake-resistant design

3.1 Seismic hazards to buried pipelines

In general, there are several main causes of seismic hazards to buried pipelines:

a) ground displacement and ground strain caused by seismic ground shaking;

b) ground deformation such as a ground surface crack, ground subsidence and lateral spread induced by liquefaction;

c) relative displacement at the connecting part with the structure, etc.;

d) ground displacement and rupture along a fault zone.

Since ductile iron pipe has high tensile strength as well as the capacity for expansion/contraction and deflection from its joint part, giving it the ability to follow the ground movement during the earthquake, the stress generated on the pipe body is relatively small. Few ruptures of pipe body have occurred during earthquakes in the past. It is therefore important to consider whether the pipeline can follow the ground displacement and ground strain without slipping out of joint when considering its earthquake resistance. The internal hydrodynamic surge pressures induced by seismic shaking are normally small enough not to be considered.

3.2 Qualitative design considerations

3.2.1 General

To increase the resistance of ductile iron pipelines to seismic hazards, the following qualitative design measures should be taken into consideration.

a) Provide pipelines with expansion/contraction and deflection capability.

EXAMPLE Use of shorter pipe segments, special joints or sleeves and anti-slip-out mechanisms according to the anticipated intensity or nature of the earthquake.

b) Lay pipelines in a firm foundation.

c) Use smooth back fill materials.

NOTE Polyethylene sleeves and special coating are also effective in special cases.

d) Install more valves.

3.2.2 Where high earthquake resistance is needed

It is desirable to enhance the earthquake resistance of parts connecting the pipelines to structures and when burying the pipes in

a) soft ground such as alluvium,

b) reclaimed ground,

c) filled ground,

d) suddenly changing soil types (geology) or topography,

e) sloping ground,

f) near revetments,

g) liquefied ground, and/or

h) near an active fault.

3.3 Design procedure

To ensure earthquake-resistant design for ductile iron pipelines:

a) select the piping route;

b) investigate the potential for earthquakes and ground movement;

c) assume probable earthquake motion (seismic intensity);

d) undertake earthquake-resistant calculation and safety checking;

e) select joints.

Solid/firm foundations should be chosen for the pipeline route.

When investigating earthquakes and ground conditions, take into account any previous earthquakes in the area where the pipeline is to be laid.

3.4 Earthquake resistance calculations and safety checking

When checking the resistance of pipelines to the effects of earthquakes, the calculation shall be carried out for the condition in which the normal load (dead load and normal live load) is combined with the influence of the earthquake.

The pipe body stress, expansion/contraction value of joint, and deflection angle of joint are calculated by the response displacement method. Earthquake resistance is checked by comparing these values with their respective allowable values. The basic criteria are given in Table 1.

A flowchart of earthquake resistance determination and safety checking is shown in Figure 1. The basic equations only for earthquake resistance calculation are given in 3.5. A detailed example of calculation is given in Annex A.

Table 1 — Basic earthquake resistance check criteria

Load condition	Criterion	
Load in earthquake motion and normal load	Pipe body stress	⩽ Allowable stress (proof stress) of ductile iron pipe
	Expansion/contraction value of joint	⩽ Allowable expansion/contraction value of ductile iron pipe joint
	Deflection angle of joint	⩽ Allowable deflection angle of ductile iron pipe joint

3.5 Calculation of earthquake resistance — Response displacement method

3.5.1 General

This method shall be used except when the manufacturer and the customer agree on an alternative recognized method.

3.5.2 Design earthquake motion

The design acceleration for different seismic intensity scales can be determined according to the relationship between the several kinds of seismic intensity scales and the acceleration of ground surface, as given in Annex B.

3.5.3 Horizontal displacement amplitude of ground

The horizontal displacement amplitude of the ground is calculated using Equation (1) (see Annex A):

$$U_{\mathrm{h}}(x) = \left(\frac{\quad}{\pi}\right)^2 \cdot a \cdot \cos\frac{\pi \cdot x}{2H} \qquad (1)$$

where

$U_{\mathrm{h}}(x)$ is the horizontal displacement amplitude of the ground x m deep from the ground surface to the centre line of the pipe, in metres (m);

x is the depth from the ground surface, in metres (m);

T_{G} is the predominant period of the subsurface layer, in seconds (s);

a is the acceleration on the ground surface for design, in metres per second squared (m/s^2);

H is the thickness of the subsurface layer, in metres (m).

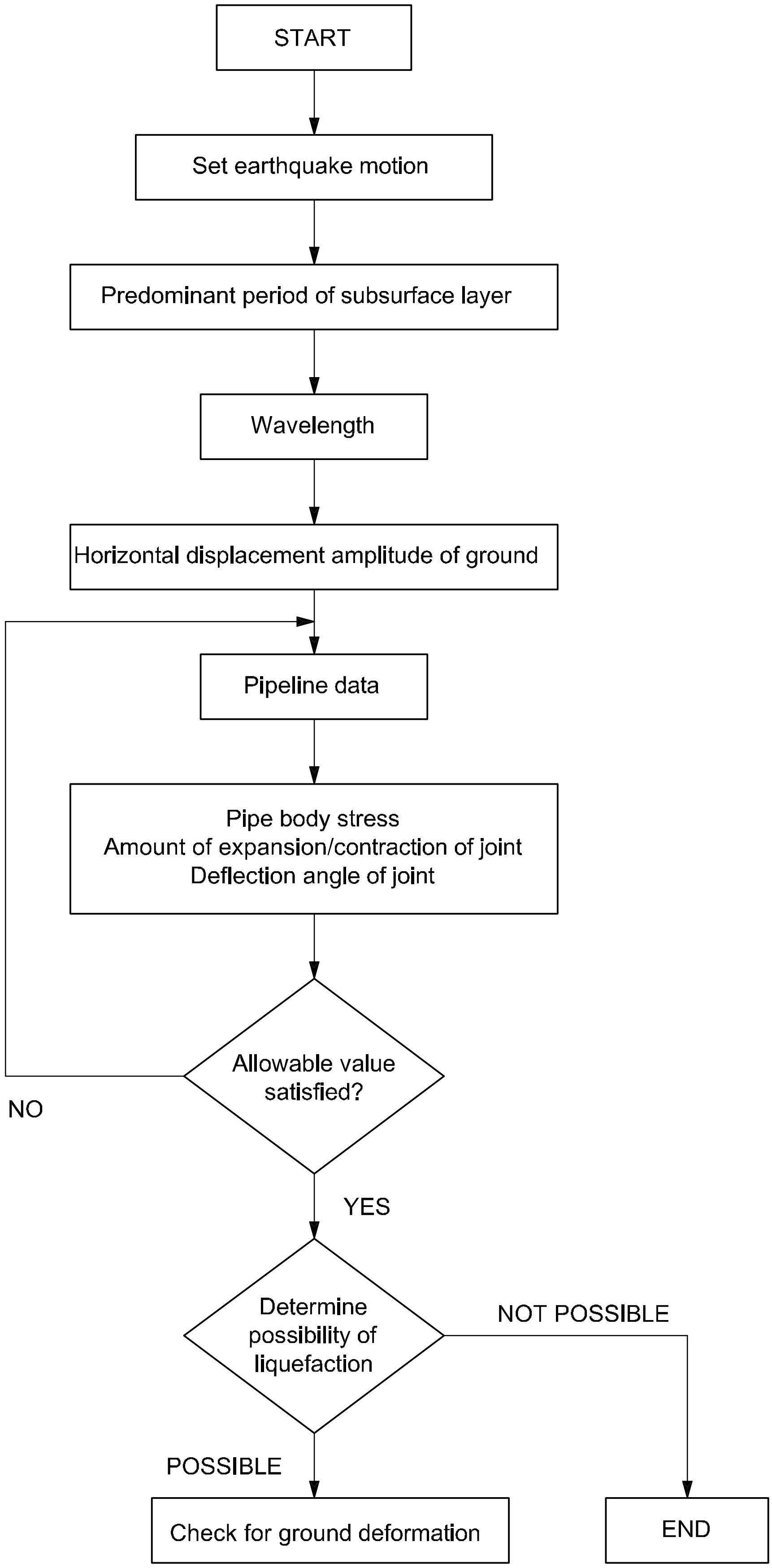


Figure 1 — Flowchart for calculation of earthquake resistance of buried pipelines

3.5.4 Pipe body stress

Pipe body stress is calculated using Equations (2), (3) and (4).

Axial stress:

$$\sigma_L = \xi_1 \cdot \alpha_1 \cdot \frac{\pi \cdot U_h(x)}{L} \cdot E \quad (2)$$

Bending stress:

$$\sigma_B = \xi_2 \cdot \alpha_2 \cdot \frac{2\pi^2 \cdot D \cdot U_h(x)}{L^2} \cdot E \quad (3)$$

Combined stress:

$$\sigma_x = \sqrt{3.12 \cdot \sigma_L^2 + \sigma_B^2} \quad (4)$$

where

σ_L, σ_B are the axial stress and the bending stress, respectively, in pascals (Pa);

σ_x is the combination of the axial and bending stresses, in pascals (Pa);

ξ_1 is the correction factor of axial stress in the case of expansion flexible joints;

ξ_2 is the correction factor of the bending stress in the case of expansion flexible joints;

α_1, α_2 are the transfer coefficient of ground displacement in the pipe axis and pipe perpendicular directions, respectively;

$U_h(x)$ is the horizontal displacement amplitude of ground x m deep from the ground surface, in metres (m);

L is the wavelength, in metres (m);

D is the outside diameter of the buried pipeline, in metres (m);

E is the elastic modulus of the buried pipeline, in pascals (Pa).

3.5.5 Expansion/contraction of joint in pipe axis direction

The amount of expansion/contraction of the joint in the pipe axis direction is calculated using Equation (5) (see Annex A):

$$u = \pm \varepsilon_G \cdot l \quad (5)$$

where

u is the amount of expansion/contraction of the joint in the pipe axis direction, in metres (m);

ε_G is the ground strain $= \frac{\pi \cdot U_h}{L}$

L is the wavelength, in metres (m);

U_h is the horizontal displacement amplitude of ground x m deep from the ground surface, in metres (m);

l is the pipe length, in metres (m).

3.5.6 Joint deflection angle

The joint deflection angle is calculated using Equation (6) (see Annex A):

$$\theta = \pm \frac{4 \cdot \pi^2 \cdot ' \cdot U_\mathrm{h}}{L^2} \quad (6)$$

where

- θ is the joint deflection angle, in radians (rad);
- l is the pipe length, in metres (m);
- U_h is the horizontal displacement amplitude of ground x m deep from the ground surface, in metres (m);
- L is the wavelength, in metres (m).

The above calculations, such as the amount of expansion/contraction of joint by the response displacement method, are based on the assumption that the ground will deform uniformly. However, since strain can be concentrated locally during an earthquake (due to the heterogeneity of the ground) and there is a possibility that the value can be greater than the calculation result, a certain value of safety margin — for instance, twice as much — is recommended.

4 Design for ground deformation by earthquake

4.1 General

Large-scale ground deformation such as ground cracks, ground subsidence and lateral displacement near revetments and inclined ground can be generated by liquefaction during an earthquake. Since such ground deformations can affect the buried pipeline, it is necessary to consider this possibility and to take it into account in the pipeline design.

4.2 Evaluation of possibility of liquefaction

The possibility of liquefaction shall be evaluated for soil layers when the following conditions are present:

a) saturated soil layer $\leqslant$ 25 m from the ground surface;

b) average grain diameter, D_{50}, $\leqslant$ 10 mm;

c) content by weight of small grain particles (with grain diameter $\leqslant$ 0,075 mm) $\leqslant$ 30 %.

The possibility of liquefaction can be evaluated by calculating the liquefaction resistance coefficient, F_L, using Equation (7):

$$F_\mathrm{L} = R/L \quad (7)$$

where

- R is the dynamic shear strength ratio indicating the resistance to liquefaction;
- L is the ground shear stress ratio during an earthquake, which indicates the generated shear stress in ground due to the earthquake.

When $F_\mathrm{L} < 1{,}0$, the layer is considered to be liquefied.

A detailed example of the evaluation of liquefaction assessment is given in Annex C.

4.3 Checking basic resistance

For ground deformation such as lateral displacement and ground subsidence induced by liquefaction, the basic resistance of the pipeline shall be checked by observing whether it can absorb the ground movement by the expansion/contraction and deflection of joints.

A detailed example of safety checking is given in Annex D.

5 Design for ground subsidence in soft ground (e.g. reclaimed ground)

5.1 Calculating ground subsidence

When burying pipes in soft ground, the amount of ground subsidence is estimated by calculating the increased earth pressure at the bottom of the trench in considering the weight of pipes, the weight of water in the pipes and the earth pressure of back-fill, using Equations (8), (9) and (10):

$$\delta_c = \frac{e_0 - e}{1 + e_0} \cdot H_c \tag{8}$$

$$\delta_c = {}_v \cdot \Delta \cdot H_c \tag{9}$$

$$\delta_c = \frac{C_c}{1 + e_0} \cdot H_c \cdot \log \frac{P + \Delta P}{p} \tag{10}$$

where

δ_c is the consolidation settlement, in metres (m);

e_0 is the initial void ratio of the undisturbed ground;

e is the void ratio after loading;

H_c is the thickness of consolidated layers, in metres (m);

m_v is the volume change ratio of the soil (coefficient of volume compressibility), in square metres per newton (m^2/N);

C_c is the compression index of the soil;

P is the pre-load of the undisturbed ground, in newtons per square metre (N/m^2);

ΔP is the increased load, in newtons per square metre (N/m^2), where

$$\Delta = {}_\sigma \cdot \Delta W \tag{11}$$

I_σ is the influence by depth value;

ΔW is the increased load, in newtons per square metre (N/m^2).

A detailed example of calculation of the amount of ground subsidence is shown in Annex E.

5.2 Basic safety checking

For ground subsidence in soft ground such as reclaimed ground, safety shall be checked by observing if the pipeline can absorb the ground movement by expansion/contraction and deflection of the joints. This way of safety checking is the same as for the ground deformation in the pipe perpendicular direction induced by liquefaction, which is given in Annex D.

6 Pipeline system design

6.1 Pipeline components

According to the results of calculations for expansion/contraction, slip-out resistance, and joint deflection, the pipeline system may be designed using the same joint for all pipes, or, alternatively, using a range/combination of pipeline components. If necessary, pipeline system components may be classified according to Table 2.

Table 2 — Classification of pipeline components

Parameter	Class	Component performance
Expansion/contraction performance	S-1	± 1 % of L or more
	S-2	± 0,5 % to less than ± 1 % of L
	S-3	Less than ± 0,5 % of L
Slip-out resistance	A	3 d kN or more
	B	1,5 kN to less than 3 kN
	C	0,75 kN to less than 1,5 kN
	D	less than 0,75 d kN
Joint deflection angle	M-1	± 15° or more
	M-2	± 7,5° to < 15°
	M-3	Less than ± 7,5°

L is the component length, in millimetres (mm)

d is the nominal diameter of pipe, in millimetres (mm)

6.2 Earthquake-resistant joints

In cases where pipelines are to be laid in locations where ground deformation could be induced by liquefaction during an earthquake, and where ground subsidence is anticipated in soft soil such as reclaimed ground, a pipeline having earthquake-resistant joints with slip-out resistance, as well as an expansion/contraction and deflection capability, should be used.

Annex A
(informative)

Example of earthquake resistance calculation

A.1 General

This annex presents an example of the calculation of the earthquake resistance of a pipeline, specified in A.2.

A.2 Specifications and conditions

The example pipeline and conditions are the following.

a) Type of pipe: 500 mm nominal diameter ductile iron pipe (K-9 class)

b) Outside diameter of pipe: $D = 0{,}532$ m

c) Standard thickness of pipe: $t = 0{,}009$ m

d) Calculated thickness of pipe [1)]: $t_1 = 0{,}007\,2$ m$(= t - 0{,}001\,8)$

e) Pipe length: $l = 6$ m

f) Soil covering above pipes: $h = 1{,}20$ m

g) Unit weight of soil: $\gamma_t = 17$ kN/m^3

h) Elastic modulus of ductile cast iron: $E = 1{,}6 \times 108$ kN/m^2

i) Design acceleration on the ground surface: $a = 0{,}94$ m/s^2 (corresponding to Modified Mercalli scale intensity of VII).

A.3 Ground model

See Figure A.1.

A.4 Various values of pipe profiles

A.4.1 Cross-sectional area, A_r

This is calculated using Equation (A.1):

$$A_r = \frac{\pi}{4}\cdot\left[\quad -(\quad - \quad \cdot \quad)\quad\right] = \frac{\pi}{\ }\times\left[\quad -(\quad - \quad \times \quad)\quad\right] = 1{,}187 \times 10^{-2}\ \text{m}^2 \qquad \text{(A.1)}$$

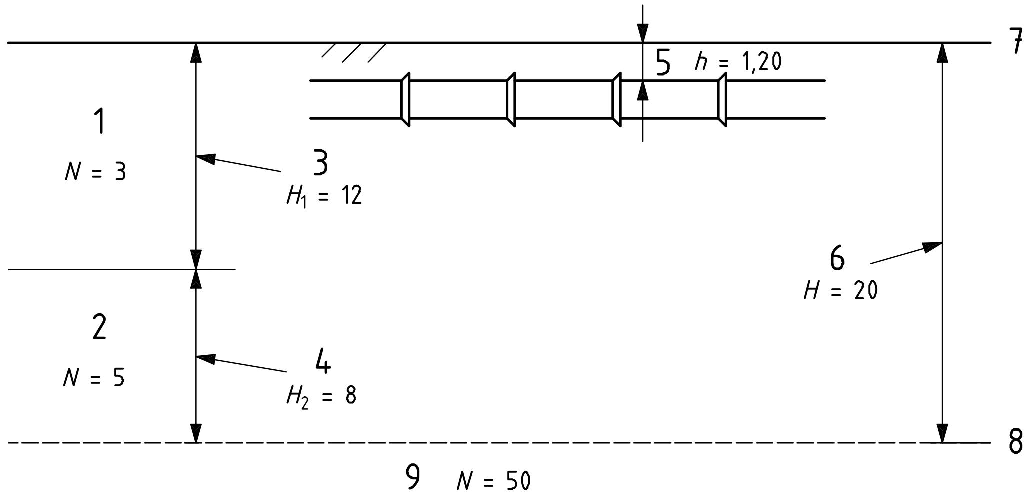
where

D is the outside diameter of pipe $= 0{,}532$ m;

t_1 is the calculated thickness of pipe $= 0{,}007\,2$ m.

1) The casting tolerance is subtracted from t.

Dimensions in metres



Key

1 first layer (alluvium sandy soil)
2 second layer (alluvium sandy soil)
3 thickness of layer
4 thickness of layer
5 soil covering
6 thickness of subsurface layer
7 ground surface
8 bedrock surface
9 diluvium sandy soil

Figure A.1 — Ground model

A.4.2 Moment of inertia of area, I

This is calculated using Equation (A.2):

$$I = \frac{\pi}{64}\cdot\left[\quad -(\quad - \quad\cdot\quad)\quad\right] = \frac{\pi}{\quad}\times\left[\quad -(\quad - \quad\times\quad)\quad\right] = \text{[illegible]}\times 10^{-4}\ \text{m}^4 \qquad \text{(A.2)}$$

A.5 Pipe body stress, expansion/contraction and deflection angle of joint due to earthquake motions

A.5.1 Calculation of seismic properties

A.5.1.1 Shear elastic wave velocity by layer

See Table A.1 for the shear elastic wave velocity and Table A.2 for the shear elastic wave velocity for different types of soil with respect to the shearing strain of the ground.

A.5.1.2 Average shear elastic wave velocity of surface layer, V_{DS}

This is calculated using Equation (A.3):

$$V_{DS} = \frac{\sum H_i}{\sum\left(\frac{\quad}{\quad}\right)} = \frac{20,0}{0,154\,0 + 0,092\,2} = 81,23\ \text{m/s} \qquad \text{(A.3)}$$

Table A.1 — Shear elastic wave velocity

Layer	Thickness of layer H_i m	Soil type	N value [a]	Average shear elastic wave velocity [b] V_{si} m/s	H_i/V_{si} s
First	12 $(= H_1)$	Alluvium sandy soil	3	$61,8 \cdot N^{0.211} = 61,8 \times 3^{0,211}$ $= 77,92 (V_{s1})$	0,154 0 $(= H_1/V_{s1})$
Second	8 $(= H_2)$	Alluvium sandy soil	5	$61,8 \cdot N^{0.211} = 61,8 \times 5^{0,211}$ $= 86,79 (V_{s2})$	0,092 2 $(= H_2/V_{s2})$
Bedrock	—	Diluvium sandy soil	50	$205 \cdot N^{0.125} = 205 \times 50^{0,125}$ $= 334,29 (V_{BS})$	—

[a] The N value is derived from the standard penetration test defined in JIS A-1219, ASTM D-1586 and BS 1377 test 19, etc.

[b] Japan Water Works Association, *Seismic Design and Construction Guidelines for Water Supply Facilities* (1997).

Table A.2 — Velocity of ground shearing elastic wave

Soil type		V_s m/s		
		10^{-3}	10^{-4}	10^{-6}
Diluvium	Clay	129 $N^{0,183}$	156 $N^{0,183}$	172 $N^{0,183}$
	Sand	123 $N^{0,125}$	200 $N^{0,125}$	205 $N^{0,125}$
Alluvium	Clay	122 $N^{0,077\,7}$	142 $N^{0,077\,7}$	143 $N^{0,077\,7}$
	Sand	61,8 $N^{0,211}$	90 $N^{0,211}$	103 $N^{0,211}$

NOTE 1 10^{-3}, 10^{-4} and 10^{-6} show the shearing strain of ground.

NOTE 2 Classified by composition ratio of sand and clay type soils.

NOTE 3 For the surface ground, use shearing strain of 10^{-3} level, and 10^{-6} for the bed rock.

NOTE 4 Table taken from *Seismic Design and Construction Guidelines for Water Supply Facilities* (1997), Japan Water Works Association.

A.5.1.3 Predominant period of subsurface layer, T_G

This is calculated using Equation (A.4):

$$T_G = 4 \cdot \sum \left(H_i / V_{si} \right) = 4 \times \left(0,154\,0 + 0,092\,2 \right) = 0,98 \text{ s} \tag{A.4}$$

A.5.1.4 Wavelength, L

This is calculated using Equation A.5:

$$L_1 = V_{DS} \cdot T_G = 81,23 \times 0,98 = 79,61 \text{ m}$$

$$L_2 = V_{BS} \cdot T_G = 334,29 \times 0,98 = 327,60 \text{ m}$$

$$L = \frac{2L_1 \cdot L_2}{L_1 + L_2} = \frac{2 \times 79,61 \times 327,60}{79,61 + 327,60} = 128,09 \text{ m} \tag{A.5}$$

where

V_{DS} is the average shear elastic wave velocity of subsurface layer = 81,23 m/s [Equation (A.3)];

V_{BS} is the shear elastic wave velocity of bedrock = 334,29 m/s (see Table A.1);

T_G is the predominant period of subsurface layer = 0,98 s [Equation (A.4)].

A.5.1.5 Apparent wavelength, L'

This is calculated using Equation (A.6):

$$L' = \sqrt{2} \cdot L = \sqrt{2} \times 128,09 = 181,15 \text{ m} \qquad \text{(A.6)}$$

where

L is the wavelength = 128,09 m [Equation (A.5)].

A.5.2 Calculation

A.5.2.1 Horizontal displacement amplitude of ground, $U_h(x)$

This is calculated using Equation (A.7):

$$U_h(x) = \left(\frac{2}{\pi}\right)^2 \cdot a \cdot T_G^2 \cdot \cos\frac{\pi x}{2H} = \left(\frac{2}{\pi}\right)^2 \cdot 0,94 \cdot 0,98^2 \cdot \cos\frac{\pi \times 1,47}{2 \times 20} = 2,27 \times 10^{-2} \text{ m} \qquad \text{(A.7)}$$

where

T_G is the predominant period of subsurface layer = 0,98 s [Equation (A.4)];

a is the design acceleration on the ground surface = 0,94 m/s^2 (corresponding to a Modified Mercalli scale intensity of VII);

H is the thickness of the subsurface layer = 20 m;

x is the depth of pipe centre $= z + D/2 = 1,20 + 0,532/2 = 1,47$ m.

A.5.2.2 Ground strain in pipe axis direction, ε_G

This is calculated using Equation (A.8):

$$\varepsilon_G = \frac{\pi \cdot U_h(x)}{L} = \frac{\pi \times 2,27 \times 10^{-2}}{128,09} = 0,000\,56 \qquad \text{(A.8)}$$

where

$U_h(x)$ is the horizontal displacement amplitude of ground = 2,27 × 10^{-2} m [Equation (A.7)];

L is the wavelength = 128,09 m [Equation (A.5)].

A.5.2.3 Rigidity coefficient of ground, K_{g1}, K_{g2}

This is calculated using Equations (A.9) and (A.10):

$$K_{g1} = C_{g1} \cdot \frac{\gamma_t}{g} \cdot V_{S1}^2 = 1,5 \times \frac{17}{9,8} \times 77,92^2 = 1,58 \times 10^4 \text{ kN/m}^2 \qquad \text{(A.9)}$$

$$K_{g2} = C_{g2} \cdot \frac{\gamma_t}{g} \cdot V_{S1}^2 = 3 \times \frac{17}{9,8} \times 77,92^2 = 3,16 \times 10^4 \text{ kN/m}^2 \qquad \text{(A.10)}$$

where

γ_t is the unit weight of soil = 17 kN/m^3;

g is the gravitational acceleration = 9,8 m/s^2;

V_{s1} is the shear elastic wave velocity of subsurface layer (first layer) in pipeline position = 77,92 m/s (see Table A.1);

C_{g1}, C_{g2} are the constants corresponding to the rigidity coefficient of layer per unit length in the pipe axis and pipe perpendicular directions of buried pipelines, where C_{g1} = 1,5 and C_{g2} = 3.

A.5.2.4 Transfer coefficient of ground displacement, α_1, α_2

This is calculated using Equations (A.11) and (A.12):

$$\alpha_1 = \frac{1}{1+\frac{E \cdot A_r}{K_{g1}}\left(\frac{2\pi}{L'}\right)^2} = \frac{1}{1+\frac{1{,}6\times 10^8 \times 1{,}187 \times 10^{-2}}{1{,}58\times 10^4}\left(\frac{2\pi}{181{,}15}\right)^2} = 0{,}873 \qquad \text{(A.11)}$$

$$\alpha_2 = \frac{1}{1+\frac{E \cdot I}{K_{g2}}\left(\frac{\pi}{\ }\right)^4} = \frac{1}{1+\frac{1{,}6\times 10^8 \times 4{,}087 \times 10^{-4}}{3{,}16\times 10^4}\left(\frac{\pi}{\ }\right)^4} = 1{,}000 \qquad \text{(A.12)}$$

where

K_{g1} is the rigidity coefficient of ground in pipe axis direction = 1,58 × 10^4 kN/m^2 [Equation (A.9)];

K_{g2} is the rigidity coefficient of ground in pipe perpendicular direction = 3,16 × 10^4 kN/m^2 [Equation (A.10)];

E is the elastic modulus of ductile cast iron = 1,6 × 10^8 kN/m^2;

A_r is the cross-sectional area of pipe = 1,187 × 10^{-2} m^2 [Equation (A.1)];

I is the moment of inertia of area = 4,087 × 10^{-4} m^4 [Equation (A.2)];

L' is the apparent wavelength = 181,15 m [Equation (A.6)];

L is the wavelength = 128,09 m [Equation (A.5)].

A.5.2.5 Stress correction factor for pipelines with expansion-flexible joints, ξ_1, ξ_2

This is calculated as follows, with the results expressed by Equations (A.13) and (A.14):

$$\xi_1 = \sqrt{\varphi_1^2 + \varphi_2^2} \Big/ \left[\quad (\ \cdot \lambda \cdot \ ) - \quad (- \ \cdot \lambda \cdot \ ) \right]$$

$$\xi_2 = \sqrt{\varphi_3^2 + \varphi_4^2}$$

where

$$\beta = \sqrt[4]{\frac{K_{g2}}{4EI}} = \sqrt[4]{\frac{3{,}16\times 10^4}{4\times 1{,}6\times 10^8 \times 4{,}087 \times 10^{-4}}} = 0{,}590/\text{m}$$

$$\nu = \ell / L = 6/128{,}09 = 0{,}047$$

$$\nu' = \ell / L' = 6/181{,}15 = 0{,}03$$

$$\mu = \frac{(l/2)}{L} = 3/128{,}09 = 0{,}023$$

$$\mu' = \frac{(l/2)}{L'} = 3/181{,}15 = 0{,}017$$

$$\lambda_1 = \sqrt{\frac{K_{g1}}{E \cdot A_r}} = \sqrt{\frac{1{,}58 \times 10^4}{1{,}6 \times 10^8 \times 1{,}187 \times 10^{-2}}} = 0{,}091\,2/\mathrm{m}$$

$$C_1 = \sin(\nu \cdot \beta \cdot \;) \cdot \;\; (\; \cdot \beta \cdot L) = -6{,}952$$

$$C_2 = \sin(\nu \cdot \beta \cdot \;) \cdot \;\; (\; \cdot \beta \cdot L) = -6{,}963$$

$$C_3 = \cos(\nu \cdot \beta \cdot \;) \cdot \;\; (\; \cdot \beta \cdot L) = -15{,}979$$

$$C_4 = \cos(\nu \cdot \beta \cdot \;) \cdot \;\; (\; \cdot \beta \cdot L) = -16{,}006$$

$$e_1 = \sin(\mu \cdot \beta \cdot \;) \cdot \;\; (\mu \cdot \beta \cdot L) = 2{,}717$$

$$e_2 = \sin(\mu \cdot \beta \cdot \;) \cdot \;\; (\mu \cdot \beta \cdot L) = 2{,}89$$

$$e_3 = \cos(\mu \cdot \beta \cdot \;) \cdot \;\; (\mu \cdot \beta \cdot L) = -0{,}459$$

$$e_4 = \cos(\mu \cdot \beta \cdot \;) \cdot \;\; (\mu \cdot \beta \cdot L) = -0{,}488$$

$$\Delta = (\;\; + \;\;) \cdot (\;\; - \;\;) + \;\;^2 = 303{,}506$$

$$f_1 = \frac{1}{\Delta}\left\{\left[\;\; \cdot (\;\; - \;\;) - \;\; \cdot (\;\; + \;\;) - \;\; \cdot \;\; (\; \cdot \pi \cdot \nu)\right] \cdot \frac{2 \cdot \pi}{\beta \cdot L} + (\;\; + \;\;) \cdot \;\; (\; \cdot \pi \cdot \nu)\right\} = -0{,}103\,36$$

$$f_2 = \frac{1}{\Delta}\left[\;\; \cdot (\;\; - \;\;) - \;\; \cdot (\;\; + \;\;) + (\;\; + \;\;) \cdot \;\; (\; \cdot \pi \cdot \nu) + \;\; \cdot \frac{2 \cdot \pi}{\beta \cdot L} \cdot \;\; (\; \cdot \pi \cdot \nu)\right] = -1{,}076\,25$$

$$f_3 = \frac{1}{\Delta}\left\{\left[\;\; \cdot (\;\; + \;\;) - \;\; \cdot (\;\; + \;\;) - \;\; \cdot \;\; (\; \cdot \pi \cdot \nu)\right] \cdot \frac{2 \cdot \pi}{\beta \cdot L} + (\;\; + \;\;) \cdot \;\; (\; \cdot \pi \cdot \nu)\right\} = -0{,}020\,22$$

$$f_4 = \frac{1}{\Delta}\left\{\left[\;\; \cdot (\;\; + \;\;) - \;\; \cdot (\;\; - \;\;) + (\;\; - \;\;) \cdot \;\; (\; \cdot \pi \cdot \nu)\right] \cdot \frac{2 \cdot \pi}{\beta \cdot L} - \;\; \cdot \;\; \cdot \;\; (\; \cdot \pi \cdot \nu)\right\} = 0{,}098\,92$$

$$f_5 = \frac{1}{\Delta}\left[(\;\; - \;\;)^2 + \;\; \cdot \;\; \cdot \;\; - \;\; \cdot \;\; \cdot \;\; (\; \cdot \pi \cdot \nu) - (\;\; - \;\;) \cdot \frac{2 \cdot \pi}{\beta \cdot L} \cdot \;\; (\; \cdot \pi \cdot \nu)\right] = 1{,}044\,2$$

$$\varphi_1 = \left[\exp(-\nu' \cdot \lambda_1 \cdot \;') - \cos(2 \cdot \pi \cdot \nu')\right] \cdot \exp(\mu' \cdot \lambda_1 \cdot \;') - \left[\exp(\nu' \cdot \lambda_1 \cdot \;') - \cos(2 \cdot \pi \cdot \nu')\right] \cdot \exp(-\mu' \cdot \lambda_1 \cdot L')$$
$$+ \;\; \cdot \;\; (\;' \cdot \lambda \cdot \;') \cdot \;\; (\; \cdot \pi \cdot \mu') = 0{,}046\,61$$

$$\varphi_2 = 2 \cdot \sin(2 \cdot \pi \cdot \;') \cdot \sinh(\mu' \cdot \lambda_1 \cdot \;') - 2 \cdot \sin(2 \cdot \pi \cdot \mu') \cdot \sinh(\;' \cdot \lambda_1 \cdot \;') = -0{,}004\,9$$

$$\varphi_3 = \;_3 \cdot \;_3 - \;_1 \cdot \;_2 - \;_4 \cdot \;_1 - \sin(2 \cdot \pi \cdot \mu) = -0{,}104\,79$$

$$\varphi_4 = \;_4 + \;_2 \cdot \;_3 - \;_2 \cdot \;_2 - \;_5 \cdot \;_1 - \cos(2 \cdot \pi \cdot \mu) = -0{,}710\,31$$

l	is the length between expansion flexible joints = 6 m, equivalent to pipe length;
K_{g2}	is the rigidity coefficient of the ground in the pipe perpendicular direction = 3,16 × 10⁴ kN/m² [Equation (A.10)];
E	is the elastic modulus of ductile cast iron = 1,6 × 10⁸ kN/m²;
I	is the moment of inertia of area = 4,087 × 10⁻⁴ m⁴ [Equation (A.2)];
L	is the wavelength = 128,09 m [Equation (A.5)];
L'	is the apparent wavelength = 181,15 m [Equation (A.6)];
K_{g1}	is the rigidity coefficient of ground in the pipe axis direction = 1,58 × 10⁴ kN/m² [Equation (A.9)];
A_r	is the cross-sectional area of pipe = 1,187 × 10⁻² m² [Equation (A.1)].

Consequently,

$$\xi_1 = 0{,}041\,02 \qquad \text{(A.13)}$$

$$\xi_2 = 0{,}718 \qquad \text{(A.14)}$$

A.5.2.6 Pipe body stress, $\sigma_L, \sigma_B, \sigma_x$

This is calculated using Equations (A.15) to (A.17):

Axial stress:

$$\sigma_L = \xi_1 \cdot \alpha_1 \cdot \frac{\pi \cdot U_h(x)}{L} \cdot E = 0{,}041\,02 \times 0{,}873 \times \frac{\pi \times 0{,}022\,7}{128{,}09} \times 1{,}6 \times 10^8 \text{ kN/m}^2$$
$$= 3{,}19 \times 10^3 \text{ kN/m}^2 = 3{,}19 \text{ MPa} \qquad \text{(A.15)}$$

Bending stress

$$\sigma_B = \xi_2 \cdot \alpha_2 \cdot \frac{2 \cdot \pi^2 \cdot D \cdot U_h(x)}{L^2} \cdot E = 0{,}718 \times 1{,}000 \times \frac{2 \times \pi^2 \times 0{,}532 \times 0{,}022\,7}{128{,}09^2} \times 1{,}6 \times 10^8 \text{ kN/m}^2$$
$$= 1{,}67 \times 10^3 \text{ kN/m}^2 = 1{,}67 \text{ MPa} \qquad \text{(A.16)}$$

Combined stress

$$\sigma_x = \sqrt{3{,}12 \cdot \sigma_L^2 + \sigma_B^2} = \sqrt{3{,}12 \times 3{,}19^2 + 1{,}67^2} = 5{,}88 \text{ MPa} \qquad \text{(A.17)}$$

where

α_1	is the transfer coefficient of ground displacement in the pipe axis direction = 0,873 [Equation (A.11)];
α_2	is the transfer coefficient of ground displacement in the pipe perpendicular direction = 1,000 [Equation (A.12)];
$U_h(x)$	is the horizontal displacement amplitude of the ground = 2,27 × 10⁻² m [Equation (A.7)];
L	is the wavelength = 128,09 m [Equation (A.5)];
D	is the outside diameter of pipe = 0,532 m;

E is the elastic modulus of ductile cast iron = $1,6 \times 10^8$ kN/m^2;

ξ_1 is the correction factor of axial stress when there are expansion flexible joints = 0,041 02 [Equation (A.13)];

ξ_2 is the correction factor of bending stress when there are expansion flexible joints = 0,718 [Equation (A.14)].

A.5.2.7 Amount of expansion/contraction of joint in pipe axis direction, u

This is calculated using Equation (A.18):

$$u = \pm \varepsilon_G \cdot \ell = \pm 0{,}000\ 56 \times 6 = \pm 0{,}003\ 36 \text{ m} \tag{A.18}$$

where

ε_G is the ground strain in pipe axis direction = 0,000 56 [Equation (A.8)];

l is the length between expansion flexible joints = 6 m, equivalent to the pipe length.

A.5.2.8 Deflection angle of joint, θ

This is calculated using Equation (A.19):

$$\theta = \pm \frac{4 \cdot \pi^2 \cdot l \cdot U_h(x)}{L^2} = \pm \frac{4 \times \pi^2 \times 6 \times 0{,}022\ 7}{128{,}09^2} = \pm \text{[illegible]} = \pm 0° 1' 08'' \tag{A.19}$$

where

l is the length between expansion flexible joints = 6 m, equivalent to pipe length;

$U_h(x)$ is the horizontal displacement amplitude of ground = $2,27 \times 10^{-2}$ m [Equation (A.7)];

L is the wavelength = 128,09 m [Equation (A.5)].

A.6 Summary of calculation results

Table A.3 shows the calculation results.

Table A.3 — Calculation results

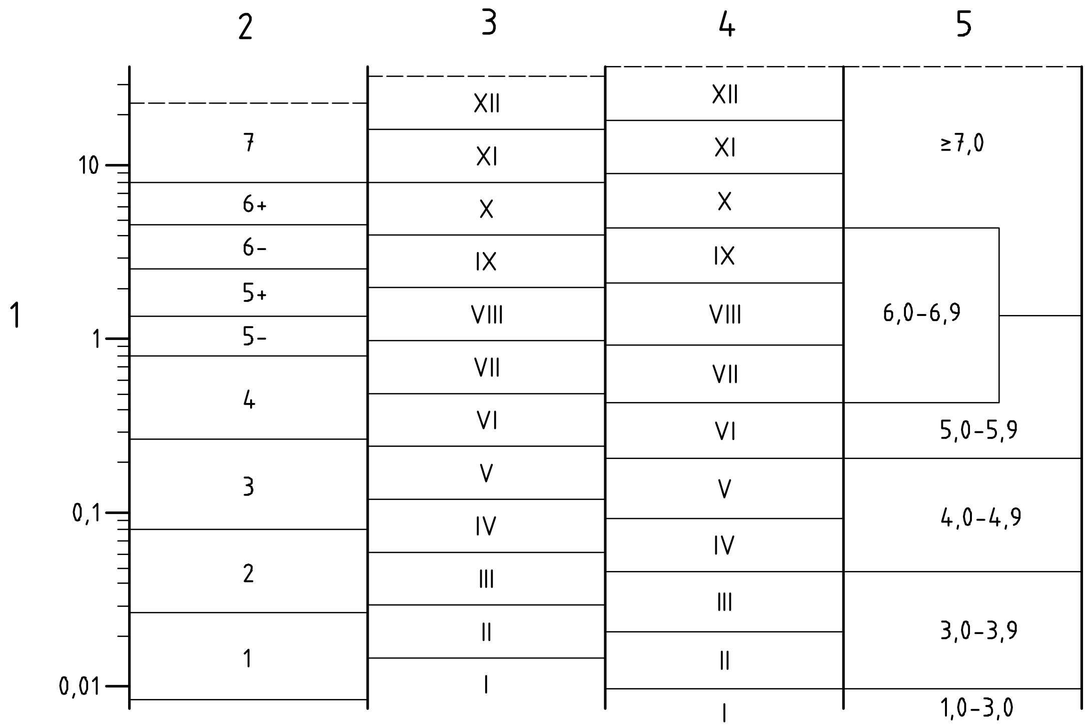
Pipe body stress (MPa)	5,88
Amount of expansion/contraction of joint (mm)	± 3,36
Deflection angle of joint	± 0° 1' 08"

Annex B
(informative)

Relationship between seismic intensity scales and ground surface acceleration

The Richter scale, the magnitude scale of earthquake size at the epicentre, is essentially different from seismic intensity scales such as the Modified Mercalli, JMA and MSK scales, which are measures of ground shaking at a particular site. See Figure B.1.

NOTE The relationship between the JMA, MSK and Modified Mercalli scales and acceleration is taken from [5]; that between the Richter and Modified Mercalli scales is taken from [6], given for locations near the earthquake epicentre.



Key

1 acceleration, α, m/s^2
2 JMA scale
3 MSK scale
4 Modified Mercalli scale
5 Richter scale

Figure B.1 — Relationship between seismic intensity scales and ground surface acceleration

Annex C
(informative)

Example of calculation of liquefaction resistance coefficient value

C.1 General

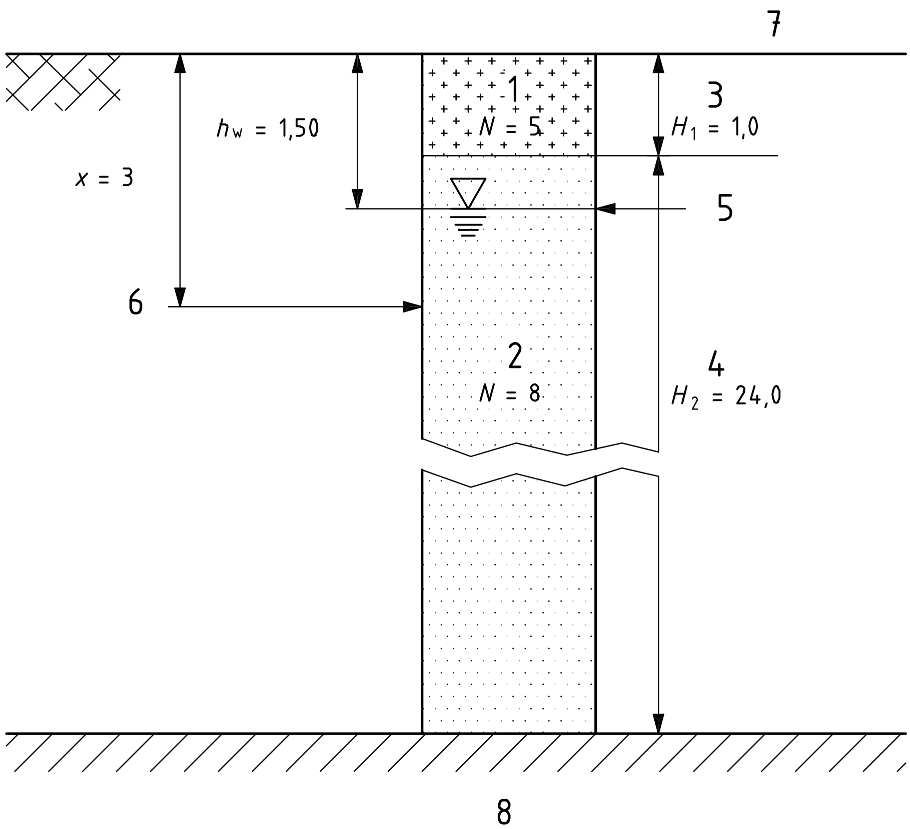
This annex presents an example calculation of the liquefaction resistance coefficient, F_L.

C.2 Calculation conditions

C.2.1 Soil layers model

The soil layers model is shown in Figure C.1. The calculation point is at a depth of 3 m.

Dimensions in metres
except for *N*



Key

1 first layer (alluvium clay)
2 second layer (alluvium sand)
3 thickness — first layer
4 thickness — second layer
5 ground water level
6 calculation point
7 ground surface
8 bedrock

Figure C.1 — Soil layers model

C.2.2 Ground acceleration for design

The maximum ground surface acceleration: $a = 2{,}02$ (m/s^2) (corresponding to a Modified Mercalli scale intensity of VIII).

C.3 Calculation of ground shear stress ratio during earthquakes

C.3.1 Reduction coefficient of shear stress along depth, γ_d

This is calculated using Equation (C.1):

$$\gamma_d = 1{,}0 - 0{,}015 \cdot x = 1{,}0 - 0{,}015 \times 3 = 0{,}955 \quad \text{(C.1)}$$

where

γ_d is the reduction coefficient of shear stress along the depth;

x is the depth of the calculation point from the ground surface = 3 m.

C.3.2 Correction factor for cyclic load of seismic motion, γ_n

This is calculated using Equation (C.2):

$$\gamma_n = 0{,}1 \cdot (M - 1) = 0{,}1 \times (7 - 1) = 0{,}6 \quad \text{(C.2)}$$

where

γ_n is the correction factor for the cyclic load of the seismic motion;

M is the magnitude of the subjected earthquake = 7.

C.3.3 Total load pressure at the calculation point, σ_x

This is calculated using Equation (C.3):

$$\begin{aligned}\sigma_x &= \gamma_{11} \cdot h_w + \gamma_{12} \cdot (x - h_w) = \gamma_{11c} \cdot H_1 + \gamma_{11s} \cdot (h_w - H_1) + \gamma_{12s} \cdot (x - h_w) \\ &= 13{,}73 \times 1{,}0 + 17{,}65 \times (1{,}5 - 1{,}0) + 19{,}61 \times (3{,}0 - 1{,}5) = 51{,}97 \text{ kN/m}^2\end{aligned} \quad \text{(C.3)}$$

where

σ_x is the total load pressure at the calculation point, in kilonewtons per square metre (kN/m^2);

γ_{11} is the unit weight of soil at the position above the ground water level, in kilonewtons per cubic metre (kN/m^3);

h_w is the depth of the ground water level from the ground surface = 1,5 m;

γ_{12} is the unit weight of soil at the position below the ground water level, in kilonewtons per cubic metre (kN/m^3);

x is the depth of the calculation point from the ground surface = 3 m;

γ_{11c} is the unit weight of clay at the position above the ground water level = 13,73 kN/m^3;

H_1 is the thickness of the clay layer (first soil layer) = 1,0 m;

γ_{11s} is the unit weight of sand at the position above the ground water level = 17,65 kN/m^3;

γ_{12s} is the unit weight of sand at the position below the ground water level = 19,61 kN/m^3.

C.3.4 Effective load pressure at calculation point, σ'_x

This is calculated using Equation (C.4):

$$\sigma'_x = \gamma_{11c} \cdot H_1 + \gamma'_{12} \cdot (x - h_\text{w}) = \gamma_{11c} \cdot H_1 + \gamma_{11s} \cdot (h_\text{w} - H_1) + \gamma'_{12s} \cdot (x - h_\text{w})$$
$$= 13,73 \times 1,0 + 17,65 \times (1,5 - 1,0) + 9,80 \times (3 - 1,5) = 37,26 \text{ kN/m}^2 \qquad \text{(C.4)}$$

where

σ_x is the effective load pressure at the calculation point, in kilonewtons per square metre (kN/m^2);

γ_{11} is the unit weight of soil at the position above the ground water level, in kilonewtons per cubic metre (kN/m^3);

h_w is the depth of the ground water level from the ground surface = 1,5 m;

γ'_{12} is the effective unit weight of soil at the position below the ground water level $= \gamma_{12} - \gamma_\text{w}$, in kilonewtons per cubic metre (kN/m^3), where

- γ_{12} is the unit weight of soil at the position below the ground water level, in kilonewtons per cubic metre (kN/m^3);

γ_w is the unit weight of water = 9,81 kN/m^3;

x is the depth of the calculation point from the ground surface = 3 m;

$\gamma_{11\text{c}}$ is the unit weight of clay at the position above the ground water level = 13,73 kN/m^3;

H_1 is the thickness of clay layer (first soil layer) = 1,0 m;

$\gamma_{11\text{s}}$ is the unit weight of sand at the position above the ground water level = 17,65 kN/m^3;

$\gamma'_{12\text{s}}$ is the effective unit weight of sand at the position below the ground water level $= \gamma_{12\text{s}} - \gamma_\text{w} = 9,80$ kN/m^3, where

- $\gamma_{12\text{s}}$ is the unit weight of sand at the position below the ground water level = 19,61 kN/m^3.

C.3.5 Ground shear stress ratio during earthquakes, L

This is calculated using Equation (C.5):

$$L = \frac{a}{g} \cdot \gamma_\text{d} \cdot \gamma_\text{n} \cdot \frac{\sigma_x}{\sigma'_x} = \frac{2,02}{9,81} \times 0,955 \times 0,6 \times \frac{51,97}{37,26} = 0,165 \qquad \text{(C.5)}$$

where

L is the ground shear stress ratio during earthquakes;

a is the maximum ground surface acceleration = 2,02 m/s^2;

g is the acceleration of gravity = 9,81 m/s^2;

γ_d is the reduction coefficient of shear stress along the depth = 0,955 [Equation (C.1)];

γ_n is the correction factor for the cyclic load of the seismic motion = 0,6 [Equation (C.2)];

σ_x is the total load pressure at the calculation point = 51,97 kN/m^2 [Equation (C.3)];

σ'_x is the effective load pressure at the calculation point = 37,26 kN/m^2 [Equation (C.4)].

C.4 Calculation of dynamic shear strength ratio, R

C.4.1 Equivalent N value, N_1

This is calculated using Equation (C.6):

$$N_1 = C_N \cdot N = 1{,}62 \times 8 = 13{,}0 \qquad \text{(C.6)}$$

where

N_1 is the equivalent N value;

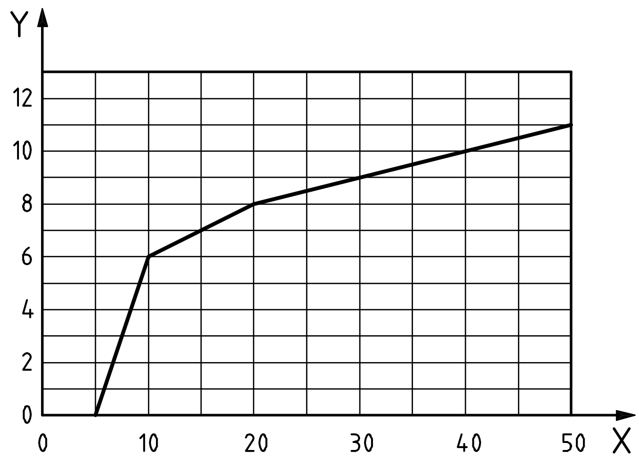
C_N is the coefficient of the equivalent N value $= \sqrt{10 \times 9{,}81/\sigma'_x} = 1{,}62$, where

σ'_x is the effective load pressure at the calculation point = 37,26 kN/m^2 [Equation (C.4)];

N is the N value at the calculation point = 8.

C.4.2 Added modified N value, ΔN_F

When the small grains content F_c is 5 % at the calculation point, added modified N value ΔN_F is 0 according to Figure C.2.



Key

X small grains content, F_c, %

Y added modified N value, ΔN_F

Figure C.2 — Relationship between F_c and ΔN_F

C.4.3 Modified N value, N_a

This is calculated using Equation (C.7):

$$N_a = N_1 + \Delta N_F = 13{,}0 + 0 = 13{,}0 \qquad \text{(C.7)}$$

where

N_a is the modified N value;

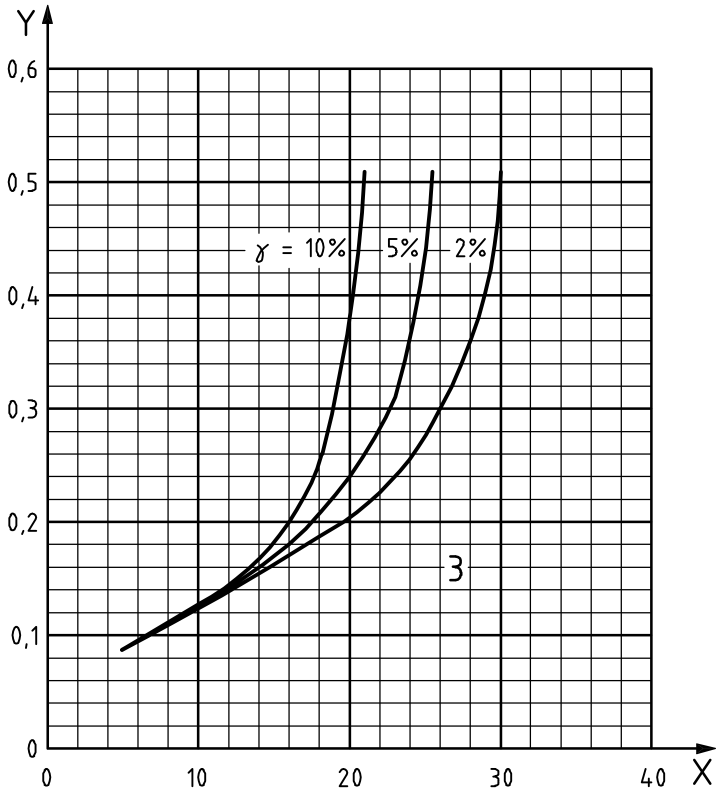
N_1 is the equivalent N value = 13,0 [Equation (C.6)];

ΔN_F is the added modified N value for small grains content = 0 [Figure C.2].

C.4.4 Dynamic shear strength ratio, R

Dynamic shear strength ratio R is determined by the modified N value N_a according to Figure C.3 and Equation (C.8). The shear strain of $\gamma = 5$ % is selected.

$$R = 0{,}15 \tag{C.8}$$



Key

X modified N value, N_a

Y dynamic shear strength ratio in saturated soil layer, R

γ shear strain

Figure C.3 — Relationship between N_a and R in saturated soil layer

C.5 F_L value calculation

This calculation of the value F_L is made using Equation (C.9):

$$F_L = R/L = 0{,}15/0{,}165 = 0{,}91 \tag{C.9}$$

where

F_L is the liquefaction resistance coefficient;

R is the dynamic shear strength ratio $=$ 0,15 [Equation (C.8)];

L is the ground shear stress ratio during the earthquake $=$ 0,165 [Equation (C.5)].

Consequently, the soil layer at the calculation point is evaluated to be liquefied for the assumed earthquake, because the liquefaction resistance coefficient F_L is less than 1,0.

Annex D
(informative)

Checking pipeline resistance to ground deformation

D.1 General

This annex presents examples of the safety checking of ductile iron pipelines for resistance to ground deformation caused by earthquake.

D.2 Example in pipe axis direction

D.2.1 Specifications and conditions

The example pipeline and conditions are the following.

a) Joint: earthquake-resistant joint

b) Amount of expansion/contraction of joint: $\beta = \pm$ 1 % (ratio for pipe length);

c) Number of joints: $n = 20$

d) Pipe length $l = 6$ m

e) Assumed ground strain in pipe axis direction: $\varepsilon_G = 0,5$ %

f) Reduction ratio of amount of expansion/contraction of joint for ground displacement: $f = 0,5$

D.2.2 Result of safety checking

D.2.2.1 Total amount of expansion/contraction of joint, E_ℓ

This is calculated using Equation (D.1):

$$E_\ell = \frac{\beta \cdot n \cdot l}{100} = \frac{1 \times 20 \times 6}{100} = 1{,}2 \text{ m} \tag{D.1}$$

where

β is the amount of expansion/contraction of the joint = ± 1 % of pipelength;

n is the number of joints = 20;

l is the pipe length = 6 m.

D.2.2.2 Ground displacement in pipe axis direction, δ_a

This is calculated using Equation (D.2):

$$\delta_a = f \cdot \varepsilon_G \cdot n \cdot l = 0{,}5 \times 0{,}5 \times 10^{-2} \times 20 \times 6 = 0{,}3 \text{ m} \tag{D.2}$$

where

f is the reduction ratio of the amount of expansion/contraction of the joint for the ground displacement = 0,5;

ε_G is the ground strain in pipe axis direction = 0,5 %.

D.2.2.3 Result of safety checking

When E_l exceeds δ_a ($E_l > \delta_a$), then the pipeline can absorb the ground displacement and has been safely designed for ground deformation in its axis direction.

D.3 Example in pipe perpendicular direction

D.3.1 Specifications and conditions

The example pipeline and the conditions acting upon it are as follows.

a) Joint: earthquake-resistant joint

b) Maximum deflection angle at joint: $\theta = 7^\circ$

c) Number of joints: $n = 12$

d) Pipe length: $l = 6$ m

e) Assumed ground displacement in pipe perpendicular direction: $\delta_r = 3$ m

D.3.2 Result of checking

D.3.2.1 Maximum amount of displacement in the pipe perpendicular direction, H_{max}

This is calculated using Equation (D.2):

$$H_{max} = l \times ([illegible] \theta + [illegible] \theta + [illegible] \theta + [illegible] \theta + [illegible] \theta) = 6{,}0 \times ([illegible]^\circ + [illegible]^\circ + [illegible]^\circ + [illegible]^\circ + [illegible]^\circ) = 7{,}0 \text{ m} \tag{D.3}$$

where

l is the pipe length = 6,0 m;

θ is the maximum deflection angle at joint = 7°;

Dimensions in metres

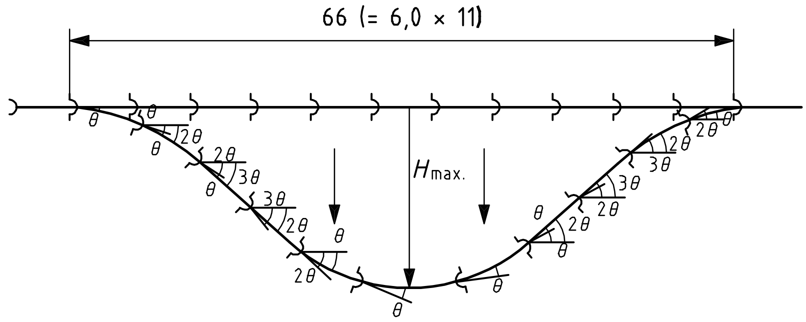


Figure D.1 — Maximum amount of displacement

D.3.2.2 Result of safety checking

When H_{max} exceeds δ_r $(H_{max} > \delta_r)$, then the pipeline can absorb the ground displacement and has been safely designed for the ground deformation in its perpendicular direction.

Annex E
(informative)

Example of ground subsidence calculation

E.1 General

This annex presents an example of the calculation of ground subsidence, using Equation (9). The end result varies depending on the number of layers chosen for the calculation and could be an under-estimation of the degree of subsidence. Where any doubt exists, a fully integrated solution should be carried out.

E.2 Specifications and conditions

The example pipeline and conditions are the following.

a) Kind of pipe: Ductile iron pipe, nominal diameter 1 000 mm (K-9 class pipe)

a) Outside diameter of pipe: $D = 1{,}048$ m

b) Standard thickness of pipe: $t = 0{,}013\ 5$ m

c) Inner diameter of pipe: $D_1 = 1{,}021$ m ($= D - 2t$)

d) Weight of pipes: $W_1 = 4{,}0$ kN/m (including cement mortar lining)

e) Soil covering above pipes: $h = 1{,}5$ m

f) Excavation width: $w = 2{,}2$ m

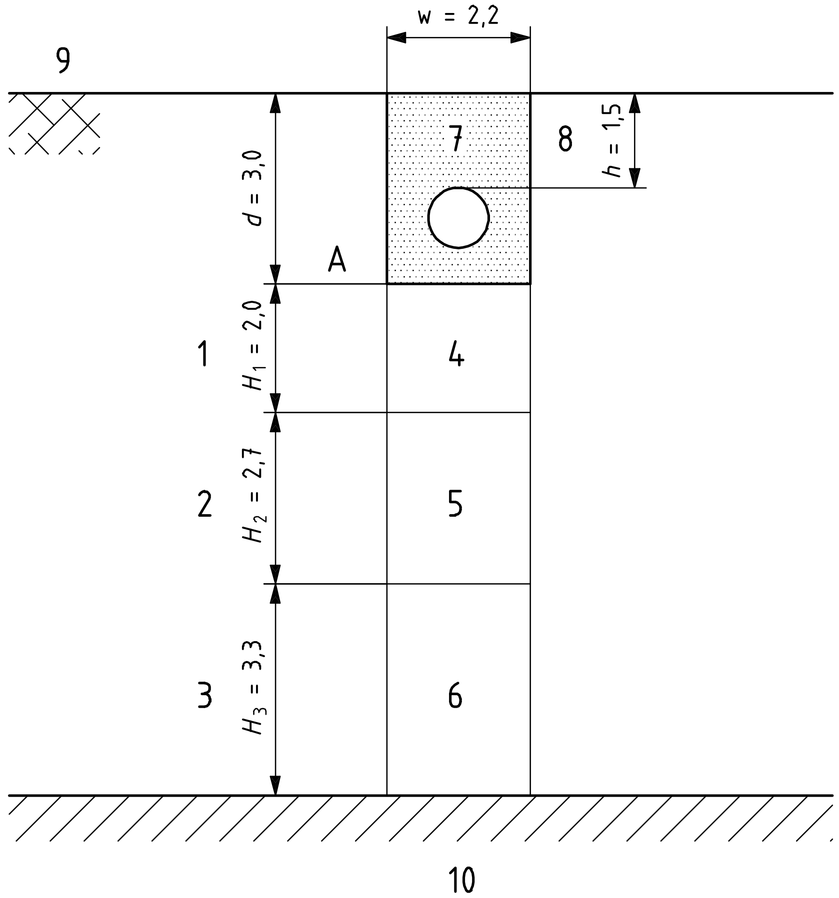
g) Excavation depth: $d = 3{,}0$ m

h) Unit weight of back-fill sand: $\gamma_s = 20$ kN/m^3

E.3 Ground model for investigation

See Figure E.1.

Dimensions in metres



Key

1 thickness of first layer
2 thickness of second layer
3 thickness of third layer
4 first layer (clay)
5 second layer (clay)
6 third layer (sand)
7 replace with sand
8 soil covering
9 ground surface
10 bedrock

Figure E.1 — Ground model

E.4 Soil layer data

See Table E.1.

Table E.1 — Soil layer data

Layer	Soil type	Thickness of layer H_i m		Unit weight of soil γ_i kN/m^3		Volume change ratio m_{Vi} m^2/kN	
First	Clay	H_1	2	γ_1	16	m_{V1}	$3,6 \times 10^{-3}$
Second	Clay	H_2	2,7	γ_2	16	m_{V2}	$2,1 \times 10^{-3}$
Third	Sand	H_3	3,3	γ_3	20	m_{V3}	$1,0 \times 10^{-4}$

E.5 Calculation of ground subsidence

E.5.1 Weight of excavated soil, W_2

This is calculated using Equation (E.1):

$$W_2 = w \cdot d \cdot \gamma = 2,2 \times 3,0 \times 16 = 105,6 \text{ kN/m} \tag{E.1}$$

where

w is the width of excavation = 2,2 m;

d is the depth of excavation = 3,0 m;

γ is the unit weight of excavated ground = γ_1 = 16 kN/m^3.

E.5.2 Weight of back-filling sand, W_3

This is calculated using Equation (E.2):

$$W_3 = \left(w \cdot d - \frac{\pi \cdot D^2}{4} \right) \cdot \gamma_s = \left(2,2 \times 3,0 - \frac{3,14 \times 1,048^2}{4} \right) \times 20 = 114,8 \text{ kN/m} \tag{E.2}$$

where

w is the width of excavation = 2,2 m;

d is the depth of excavation = 3,0 m;

D is the outside diameter of the pipe = 1,048 m;

γ_s is the unit weight of back-fill sand = 20 kN/m^3.

E.5.3 Weight of the water in pipes, W_4

This is calculated using Equation (E.3):

$$W_4 = \frac{\pi \cdot D_i^2 \cdot \gamma_w}{4} = \frac{3,14 \times 1,021^2 \times 9,81}{4} = 8,0 \tag{E.3}$$

where

D_1 is the inner diameter of the pipe = 1,021 m;

γ_w is the unit weight of water = 9,81 kN/m^3.

E.5.4 Increased load on face A, ΔW

This is calculated using Equation (E.4):

$$\Delta \; = (\;_1 + \;_2 + \;_3 - \;_4)/ \; = (\; + \; + \; - \;)/ \; = 9{,}6 \text{ kN/m}^2 \tag{E.4}$$

where

W_1 is the weight of the pipes (including cement mortar lining) = 4,0 kN/m;

W_2 is the weight of excavated soil = 105,6 kN/m [Equation (E.1)];

W_3 is the weight of back-filling sand = 114,8 kN/m [Equation (E.2)];

W_4 is the weight of water in the pipes = 8,0 kN/m [Equation (E.3)];

w is the width of excavation = 2,2 m.

E.5.5 Influence value by depth, X_i

The influence value by depth is determined as follows according to Figure E.2, in which depth ratio X_i is the value of the depth at the centre of each layer divided by the excavation width w. See Equations (E.5) to (E.7).

First layer:

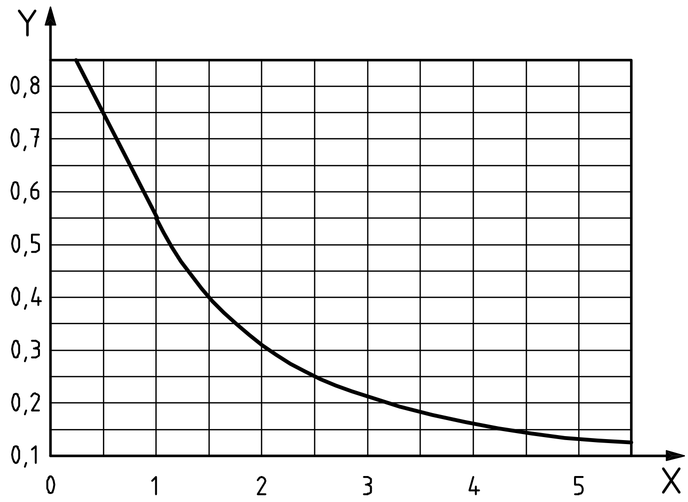
$$X_1 = \frac{H_1/2}{w} = \frac{2{,}0/2}{2{,}2} = 0{,}45 \text{ then } I_{\sigma 1} = 0{,}78 \tag{E.5}$$

Second layer:

$$X_2 = \frac{H_1 + (\;_2 / \;)}{w} = \left[\frac{\; + (\; / \;)}{\;} \right] = 1{,}52 \text{ then } I_{\sigma 2} = 0{,}38 \tag{E.6}$$

Third layer:

$$X_3 = \frac{H_1 + \;_2 + (H_3/2)}{w} = \left[\frac{\; + \; + (\; / \;)}{\;} \right] = 2{,}89 \text{ then } I_{\sigma 3} = 0{,}22 \tag{E.7}$$



Key

X depth ratio, X_i

Y influence value, I_σ

Figure E.2 — Relationship between the influence value and the depth ration

E.5.6 Increased load, ΔP_i

This is calculated using Equations (E.8) to (E.10):

$$\Delta P_1 = I_{\sigma 1} \cdot \Delta W = 0{,}78 \times 9{,}6 = 7{,}5 \text{ kN/m}^2 \quad \text{(E.8)}$$

$$\Delta P_2 = I_{\sigma 2} \cdot \Delta W = 0{,}38 \times 9{,}6 = 3{,}6 \text{ kN/m}^2 \quad \text{(E.9)}$$

$$\Delta P_3 = I_{\sigma 3} \cdot \Delta W = 0{,}22 \times 9{,}6 = 2{,}1 \text{ kN/m}^2 \quad \text{(E.10)}$$

where

ΔP_1 is the increased load at the first layer, in newtons per square metre (N/m^2);

ΔP_2 is the increased load at the second layer, in newtons per square metre(N/m^2);

ΔP_3 is the increased load at the third layer, in newtons per square metre(N/m^2);

$I_{\sigma 1}$ is the influence value by depth at the first layer = 0,78 [Equation (E.5)];

$I_{\sigma 2}$ is the influence value by depth at the second layer = 0,38 [Equation (E.6)];

$I_{\sigma 3}$ is the influence value by depth at third layer = 0,22 [Equation (E.7)];

ΔW is the increased load at face A = 9,6 kN/m^2 [Equation (E.4)].

E.5.7 Ground subsidence, δ_i, of each layer

This is calculated using Equations (E.11) to (E.13):

$$\delta_1 = \cdot \Delta \cdot = \times \times \times = 0{,}054 \text{ m} \tag{E.11}$$

$$\delta_1 = \cdot \Delta \cdot = \times \times \times = 0{,}020\ 4 \text{ m} \tag{E.12}$$

$$\delta_3 = \cdot \Delta \cdot = \times \times \times = 0{,}000\ 7 \text{ m} \tag{E.13}$$

where

δ_1 is the subsidence at the first layer;

δ_2 is the subsidence at second layer;

δ_3 is the subsidence at third layer;

mv_1 is the volume change ratio at the first layer = 3,6 × 10^{-3} m^2/kN (see Table E.1);

mv_2 is the volume change ratio at the second layer = 2,1 × 10^{-3} m^2/kN (see Table E.1);

mv_3 is the volume change ratio at the third layer = 1,0 × 10^{-4} m^2/kN (see Table E.1);

ΔP_1 is the increased load at the first layer = 7,5 kN/m^2 [Equation (E.8);

ΔP_2 is the increased load at the second layer = 3,6 kN/m^2 [Equation (E.9)];

ΔP_3 is the increased load at the third layer = 2,1 kN/m^2 [Equation (E.10).

E.5.8 Total amount of subsidence, δ

This is calculated using Equation (E.14):

$$\delta = \delta_1 + \delta_2 + \delta_3 = + + = 0{,}075\ 1 \text{ m} \tag{E.14}$$

where

δ_1 is the subsidence at first layer = 0,054 [Equation (E.11)];

δ_2 is the subsidence at second layer = 0,020 4 [Equation (E.12);

δ_3 is the subsidence at third layer = 0,000 7 [Equation (E.13)].

Consequently, subsidence δ is calculated to be 0,075 1 m at this point.

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