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Earthquake-resistant and subsidence-resistant design of ductile iron pipelines

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Earthquake-resistant and subsidence-resistant design of ductile iron pipelines

Conception de canalisations en fonte ductile résistant aux tremblements de terre et aux phénomènes de subsidence

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Foreword

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This document was prepared by Technical Committee ISO/TC 5, *Ferrous metal pipes and metallic fittings*, Subcommittee SC 2, *Cast iron pipes, fittings and their joints*.

This second edition cancels and replaces the first edition (ISO 16134:2006), which has been technically revised.

The main changes compared to the previous edition are as follows:

— the classification of pipelines components in Table 3 is modified;

— the relationship between seismic intensity and ground surface acceleration in Table B.1 is modified;

— the calculation method of checking the safety of pipeline against ground deformation is added in 5.3.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

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-resistant and subsidence-resistant design of ductile iron pipelines

1 Scope

This document specifies the design of earthquake-resistant 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 gives example calculations. It is applicable to ductile iron pipes and fittings with joints as specified in ISO 2531, ISO 7186 and ISO 16631 that have expansion/contraction and deflection capabilities, used in pipelines buried underground.

NOTE   Subsidence is not the effects of an earthquake or a sinkhole.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 2531, *Ductile iron pipes, fittings, accessories and their joints for water applications*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 2531 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
burying
placing of pipes underground in a condition where they touch the soil directly

3.2
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

3.3
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

3.4
earthquake-resistant joint
joint having slip out resistance as well as expansion/contraction and deflection capabilities

3.5
flexible joint
joint having expansion and deflection capabilities

4   Earthquake-resistant design

4.1   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 the 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.

4.2   Qualitative design considerations

4.2.1   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.

4.2.2   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)   liquefiable ground, and/or

h)   near an active fault.

4.3   Design procedure

To make 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 resistance 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.

4.4   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 formulae only for earthquake resistance calculation are given in 4.5. 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

```
┌─────────────┐
│    START    │
└─────────────┘
       │
       ▼
┌─────────────────────┐
│ Set earthquake motion │
└─────────────────────┘
       │
       ▼
┌──────────────────────────────────┐
│ Predominant period of subsurface layer │
└──────────────────────────────────┘
       │
       ▼
┌─────────────┐
│ Wave length │
└─────────────┘
       │
       ▼
┌──────────────────────────────────────────┐
│ Horizontal displacement amplitude of ground │
└──────────────────────────────────────────┘
       │
       ▼
┌───────────────┐
│ Pipeline data │
└───────────────┘
       │
       ▼
┌──────────────────────────────────────────┐
│            Pipe body stress               │
│ Amount of expansion/contraction of joint  │
│        Deflection angle of joint          │
└──────────────────────────────────────────┘
       │
       ▼
     Allowable value
      satisfied?   ──── NO
       │
       │ YES
       ▼
     Determine
   possibility of  ──── NOT POSSIBLE ──► END
   liquefaction
       │
       │ POSSIBLE
       ▼
┌──────────────────────────┐
│ Check for ground deformation │
└──────────────────────────┘
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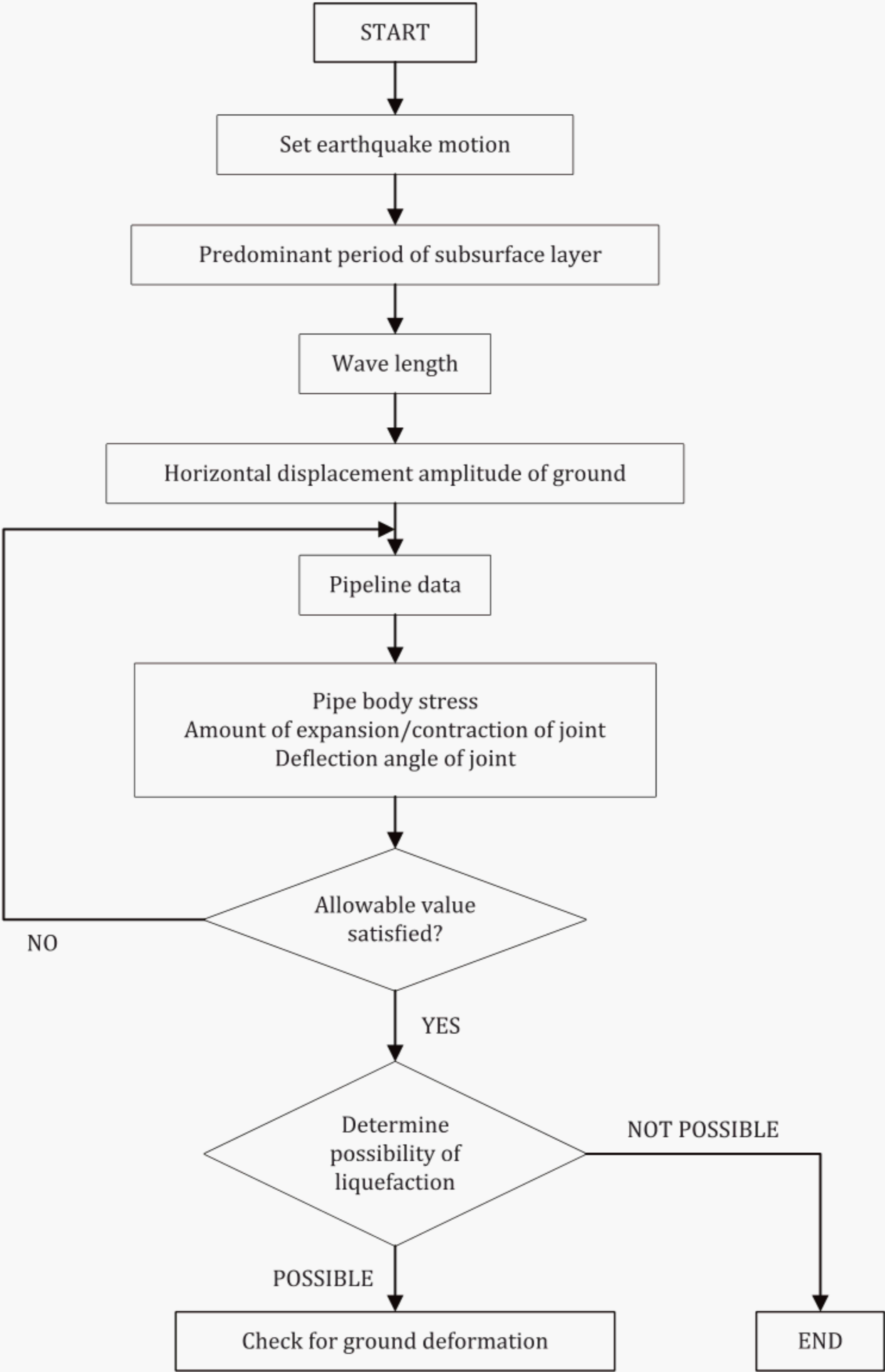
Figure 1 — Flowchart for calculation of earthquake resistance of buried pipelines

4.5   Calculation of earthquake resistance — Response displacement method

4.5.1   General

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

4.5.2 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.

4.5.3 Horizontal displacement amplitude of ground

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

$$U_h(x) = \left[\frac{T_G}{2\pi}\right]^2 \cdot a \cdot \gamma \cdot \cos\frac{\pi \cdot x}{2H} \tag{1}$$

where

$U_h(x)$	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);
γ	is the ground inhomogeneous coefficient (see Table 2)
H	is the thickness of the subsurface layer, in metres (m).

Table 2 — Ground inhomogeneous coefficient

Geotechnical condition	Ground inhomogeneous coefficient γ
Homogeneous	1,0
Inhomogeneous	1,4
Extremely inhomogeneous	2,0

4.5.4 Pipe body stress

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

Axial stress:

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

Bending stress:

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

Combined stress:

$$\sigma_x = \sqrt{3,12 \cdot \sigma_L^2 + \sigma_B^2} \tag{4}$$

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).

4.5.5 Expansion/contraction of joint in pipe axis direction

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

$$u = \pm \varepsilon_G \cdot l \tag{5}$$

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 $= \dfrac{\pi \cdot U_h}{L}$;
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).

4.5.6 Joint deflection angle

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

$$\theta = \pm \frac{4 \cdot \pi^2 \cdot l \cdot U_h}{L^2} \tag{6}$$

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).

5 Design for ground deformation by earthquake

5.1 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.

5.2 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 ≤25 m from the ground surface;

b) average grain diameter, D_{50}, ≤10 mm;

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

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

$$F_L = R/L \tag{7}$$

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 $F_L < 1,0$, the layer is considered to be liquefied.

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

5.3 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.

For ground deformation in pipe axis direction, the safety of the pipeline shall be checked by Formula (8). 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.

$$E_l > \delta_a \tag{8}$$

where

$$E_l = \beta . n . l / 100$$

$$\delta_a = f . \varepsilon_G . n . l / 100$$

E_l is total amount of expansion/contraction of joint, in metres (m);

δ_a is ground displacement in pipe axis direction, in metres (m);

β is the amount of expansion/contraction of the joint, in per cent (%) of the pipe length;

n is the number of joints;

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

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, in per cent (%).

When E_l does not exceed $\delta_a\left(E_l \leq \delta_a\right)$, all joints expand to the joint's capacity, then the safety of the joint's slip-out resistance against friction force between pipe and soil shall be checked by Formula (9).

$$F_P > \pi \cdot D \cdot \alpha \cdot \tau \cdot n \cdot l \tag{9}$$

where

F_P is the joint's slip-out resistance, in kilonewtons (kN);

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

α is reduction factor of friction force;

τ is friction force per unit area between pipe and soil, in kilopascals (kPa).

The examples of safety checking including the case of pipe perpendicular direction are given in Annex D.

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

6.1   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 Formulae (10), (11) and (12):

$$\delta_c = \frac{e_0 - e}{1 + e_0} \cdot H_c \tag{10}$$

$$\delta_c = m_v \cdot \Delta P \cdot H_c \tag{11}$$

$$\delta_c = \frac{C_c}{1 + e_0} \cdot H_c \cdot \log \frac{P + \Delta P}{p} \tag{12}$$

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

$$\Delta P = I_\sigma \cdot \Delta W \tag{13}$$

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

6.2 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.

7 Pipeline system design

7.1 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 3.

Table 3 — 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

Key

L the component length, in millimetres (mm)

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

θ_a the joint deflection angle as shown in Table 4, in degrees (°)

Table 3 *(continued)*

Parameter	Class	Component performance
Slip-out resistance	A	3 d kN or more
	B	1,5 d kN to less than 3 d kN
	C	0,75 d kN to less than 1,5 d kN
	D	Less than 0,75 d kN
Joint deflection angle	M-1	θ_a or more
	M-2	$\theta_a/2$ to less than θ_a
	M-3	Less than $\theta_a/2$
Key			
L the component length, in millimetres (mm)			
d the nominal diameter of pipe, in millimetres (mm)			
θ_a the joint deflection angle as shown in Table 4, in degrees (°)			

Table 4 — Joint deflection angle

Nominal diameter d	80 to 400	450 to 1 000	1 100 to 1 500	1 600 to 2 200	2 400 to 2 600
Joint deflection angle θ_a	8°	7°	5°30′	4°	3°30′
(Ref) Pipe length[a]	6 m	6 m	6 m	5 m	4 m
[a] Ductile iron pipe is available in shorter lengths and, where needed, can be cut during installation to achieve greater pipeline deflection over shorter pipeline lengths.					

7.2   Countermeasures for large ground deformation such as liquefaction

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.
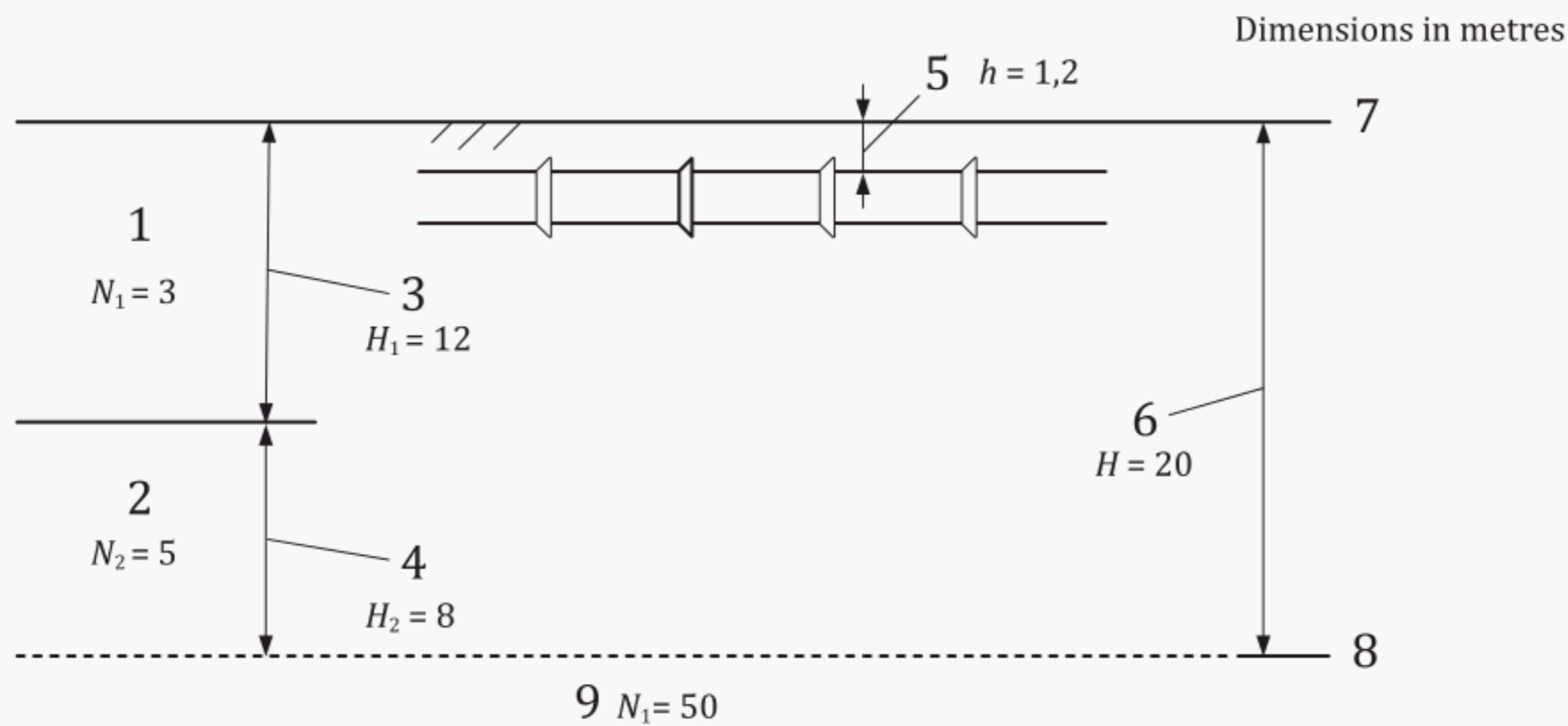
A.2 Specifications and conditions

The example pipeline and conditions are the following.

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

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

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

d) Calculated thickness of the pipe: $t_1 = 0,007\ 2$ m $(= t - 0,001\ 8)$
(= minimum thickness of the pipe)

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 the ductile cast iron: $E = 1,6 \times 10^8$ kN/m^2

i) Design acceleration on the ground surface: $a = 1,80$ m/s^2 (corresponding to Modified Mercalli scale intensity of VI).

j) Ground inhomogeneous coefficient: $\gamma = 2,0$ (corresponding to extremely inhomogeneous geotechnical condition)

A.3 Ground model

See Figure A.1.

Dimensions in metres

Key

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

NOTE N_1 and N_2 are the equivalent N values, which are derived from the standard penetration test defined in JIS A 1219, ASTM D1586 and BS 1377 test 19, etc. See Table A.1.

Figure A.1 — Ground model

A.4 Various values of pipe profiles

A.4.1 Cross-sectional area, A_r

This is calculated using Formula (A.1):

$$A_r = \frac{\pi}{4} \cdot \left[D^2 - (D - 2 \cdot t_1)^2 \right] = \frac{\pi}{4} \times \left[0{,}532^2 - (0{,}532 - 2 \times 0{,}007\,2)^2 \right] = 1{,}187 \times 10^{-2}\,\text{m}^2 \tag{A.1}$$

where

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

   t_1 is the calculated thickness of the pipe = 0,007 2 m.

A.4.2 Moment of inertia of area, I

This is calculated using Formula (A.2):

$$I = \frac{\pi}{64} \cdot \left[D^4 - (D - 2 \cdot t_1)^4 \right] = \frac{\pi}{64} \times \left[0{,}532^4 - (0{,}532 - 2 \times 0{,}007\,2)^4 \right] = 4{,}087 \times 10^{-4}\,\text{m}^4 \tag{A.2}$$

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 Formula (A.3):

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

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 $(= N_1)$	$61,8\,N^{0,211} = 61,8 \times 3^{0,211}$ $= 77,92\,(V_{s1})$	0,154 0 $(= H_1/V_{s1})$
Second	8 $(= H_2)$	Alluvium sandy soil	5 $(= N_2)$	$61,8\,N^{0,211} = 61,8 \times 5^{0,211}$ $= 86,79\,(V_{s2})$	0,092 2 $(= H_2/V_{s2})$
Bedrock	—	Diluvium sandy soil	50	$205\,N^{0,125} = 205 \times 50^{0,125}$ $= 334,29\,(V_{BS})$	—
[a] N_1 and N_2 are the equivalent N values, which are derived from the standard penetration test defined in JIS A 1219, ASTM D1586 and BS 1377 test 19, etc.					
[b] See Reference [8].					

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 The classification is based on the composition ratio of sand and clay type soils.				
NOTE 3 For the surface ground, the shearing strain of 10^{-3} level is used, and 10^{-6} for the bed rock.				
NOTE 4 Table taken from Reference [8].				

A.5.1.3 Predominant period of subsurface layer, T_G

This is calculated using Formula (A.4):

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

A.5.1.4 Wavelength, L

This is calculated using Formula (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 the subsurface layer = 81,23 m/s [Formula (A.3)];

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

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

A.5.1.5 Apparent wavelength, L'

This is calculated using Formula (A.6):

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

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

A.5.2 Calculation

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

This is calculated using Formula (A.7):

$$U_h(x) = \left(\frac{T_G}{2\pi}\right)^2 \cdot a \cdot \gamma \cdot \cos\frac{\pi x}{2H} = \left(\frac{0{,}98}{2\pi}\right)^2 \times 1{,}80 \times 2{,}0 \times \cos\frac{\pi \times 1{,}47}{2 \times 20} = 8{,}70 \times 10^{-2}\,\text{m} \tag{A.7}$$

where

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

a is the design acceleration on the ground surface = 1,80 m/s² (corresponding to a Modified Mercalli scale intensity of VI);

γ is the ground inhomogeneous coefficient = 2,0 (corresponding to extremely inhomogeneous geotechnical condition);

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

x is the depth of the pipe centre $= h + D/2 = 1{,}20 + 0{,}532/2 = 1{,}47\,\text{m}$.

A.5.2.2 Ground strain in pipe axis direction, ε_G

This is calculated using Formula (A.8):

$$\varepsilon_G = \frac{\pi \cdot U_h(x)}{L} = \frac{\pi \times 8,70 \times 10^{-2}}{128,09} = 0,002\ 13 \tag{A.8}$$

where

$U_h(x)$ is the horizontal displacement amplitude of the ground = $8,70 \times 10^{-2}$ m [Formula (A.7)];

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

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

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

$$K_{g1} = C_{g1} \cdot \frac{\gamma_t}{g} \cdot V_{s1}^2 = 1,5 \times \frac{17}{9,8} \times 77,92^2 = 1,58 \times 10^4 \text{ kN/m}^2 \tag{A.9}$$

$$K_{g2} = C_{g2} \cdot \frac{\gamma_t}{g} \cdot V_{s1}^2 = 3 \times \frac{17}{9,8} \times 77,92^2 = 3,16 \times 10^4 \text{ kN/m}^2 \tag{A.10}$$

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 the subsurface layer (first layer) in the 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 Formulae (A.11) and (A.12):

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

$$\alpha_2 = \frac{1}{1 + \dfrac{E \cdot I}{K_{g2}} \left(\dfrac{2\pi}{L} \right)^4} = \frac{1}{1 + \dfrac{1,6 \times 10^8 \times 4,087 \times 10^{-4}}{3,16 \times 10^4} \left(\dfrac{2\pi}{128,09} \right)^4} = 1,000 \tag{A.12}$$

where

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

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

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

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

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

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

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

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

This is calculated using Formulae (A.13) and (A.14):

$$\xi_1 = \sqrt{\varphi_1^2 + \varphi_2^2} \,/\left[\exp(v' \cdot \lambda_1 \cdot L') - \exp(-v' \cdot \lambda_1 \cdot L')\right] \tag{A.13}$$

$$\xi_2 = \sqrt{\varphi_3^2 + \varphi_4^2} \tag{A.14}$$

where

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

$$v = \ell/L = 6/128,09 = 0,047$$

$$v' = \ell/L' = 6/181,15 = 0,03$$

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

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

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

$$C_1 = \sin(v \cdot \beta \cdot L) \cdot \sinh(v \cdot \beta \cdot L) = -6,952$$

$$C_2 = \sin(v \cdot \beta \cdot L) \cdot \cosh(v \cdot \beta \cdot L) = -6,963$$

$$C_3 = \cos(v \cdot \beta \cdot L) \cdot \sinh(v \cdot \beta \cdot L) = -15,979$$

$$C_4 = \cos(v \cdot \beta \cdot L) \cdot \cosh(v \cdot \beta \cdot L) = -16,006$$

$$e_1 = \sin(\mu \cdot \beta \cdot L) \cdot \sinh(\mu \cdot \beta \cdot L) = 2,717$$

$$e_2 = \sin(\mu \cdot \beta \cdot L) \cdot \cosh(\mu \cdot \beta \cdot L) = 2,89$$

$$e_3 = \cos(\mu \cdot \beta \cdot L) \cdot \sinh(\mu \cdot \beta \cdot L) = -0,459$$

$$e_4 = \cos(\mu \cdot \beta \cdot L) \cdot \cosh(\mu \cdot \beta \cdot L) = -0,488$$

$$\Delta = (C_3 + C_2) \cdot (C_3 - C_2) + 2C_1^2 = 303{,}506$$

$$f_1 = \frac{1}{\Delta}\left\{\left[C_1 \cdot (C_4 - C_1) - C_3 \cdot (C_3 + C_2) - C_1 \cdot \cos(2 \cdot \pi \cdot v)\right]\frac{2 \cdot \pi}{\beta \cdot L} + (C_3 + C_2) \cdot \sin(2 \cdot \pi \cdot v)\right\} = -0{,}103\,36$$

$$f_2 = \frac{1}{\Delta}\left[C_1 \cdot (C_3 - C_2) - C_4 \cdot (C_3 + C_2) + (C_3 + C_2) \cdot \cos(2 \cdot \pi \cdot v) + C_1 \cdot \frac{2 \cdot \pi}{\beta \cdot L} \cdot \sin(2 \cdot \pi \cdot v)\right] = -1{,}076\,25$$

$$f_3 = \frac{1}{\Delta}\left\{\left[C_1 \cdot (C_4 + C_1) - C_2 \cdot (C_3 + C_2) - C_1 \cdot \cos(2 \cdot \pi \cdot v)\right]\frac{2 \cdot \pi}{\beta \cdot L} + (C_3 + C_2) \cdot \sin(2 \cdot \pi \cdot v)\right\} = -0{,}020\,22$$

$$f_4 = \frac{1}{\Delta}\left\{\left[C_3 \cdot (C_4 + C_1) - C_2 \cdot (C_4 - C_1) + (C_2 - C_3) \cdot \cos(2 \cdot \pi \cdot v)\right]\frac{2 \cdot \pi}{\beta \cdot L} - 2 \cdot C_1 \cdot \sin(2 \cdot \pi \cdot v)\right\} = 0{,}098\,92$$

$$f_5 = \frac{1}{\Delta}\left[(C_3 - C_2)^2 + 2 \cdot C_1 \cdot C_4 - 2 \cdot C_1 \cdot \cos(2 \cdot \pi \cdot v) - (C_2 - C_3) \cdot \frac{2 \cdot \pi}{\beta \cdot L} \cdot \sin(2 \cdot \pi \cdot v)\right] = 1{,}044\,2$$

$$\varphi_1 = \left[\exp(-v' \cdot \lambda_1 \cdot L') - \cos(2 \cdot \pi \cdot v')\right] \cdot \exp(\mu' \cdot \lambda_1 \cdot L') - \left[\exp(v' \cdot \lambda_1 \cdot L') - \cos(2 \cdot \pi \cdot v')\right] \cdot \exp(-\mu' \cdot \lambda_1 \cdot L')$$

$$+ 2 \cdot \sinh(v' \cdot \lambda_1 \cdot L') \cdot \cos(2 \cdot \pi \cdot \mu') = 0{,}046\,61$$

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

$$\varphi_3 = f_3 \cdot e_3 - f_1 \cdot e_2 - f_4 \cdot e_1 - \sin(2 \cdot \pi \cdot \mu) = -0{,}104\,79$$

$$\varphi_4 = e_4 + f_2 \cdot e_3 - f_2 \cdot e_2 - f_5 \cdot e_1 - \cos(2 \cdot \pi \cdot \mu) = -0{,}710\,31$$

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

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

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

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

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

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

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

A_r is the cross-sectional area of the pipe = $1{,}187 \times 10^{-2}$ m^2 [Formula (A.1)].

Consequently,

$$\xi_1 = 0{,}041\,02$$

$$\xi_2 = 0{,}718$$

A.5.2.6   Pipe body stress, $\sigma_{\mathrm{L}}, \sigma_{\mathrm{B}}, \sigma_x$

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

Axial stress:

$$\sigma_{\mathrm{L}} = \xi_1 \cdot \alpha_1 \cdot \frac{\pi \cdot U_{\mathrm{h}}(x)}{L} \cdot E = 0,041\,02 \times 0,873 \times \frac{\pi \times 0,087\,0}{128,09} \times 1,6 \times 10^8 \ \mathrm{kN/m^2} \tag{A.15}$$

$$= 12,23 \times 10^3 \ \mathrm{kN/m^2} = 12,23 \ \mathrm{MPa}$$

Bending stress

$$\sigma_{\mathrm{B}} = \xi_2 \cdot \alpha_2 \cdot \frac{2 \cdot \pi^2 \cdot D \cdot U_{\mathrm{h}}(x)}{L^2} \cdot E = 0,718 \times 1,000 \times \frac{2 \times \pi^2 \times 0,532 \times 0,087\,0}{128,09^2} \times 1,6 \times 10^8 \ \mathrm{kN/m^2} \tag{A.16}$$

$$= 6,40 \times 10^3 \ \mathrm{kN/m^2} = 6,40 \ \mathrm{MPa}$$

Combined stress

$$\sigma_x = \sqrt{3,12 \cdot \sigma_{\mathrm{L}}^2 + \sigma_{\mathrm{B}}^2} = \sqrt{3,12 \times 12,23^2 + 6,40^2} = 22,53 \ \mathrm{MPa} \tag{A.17}$$

where

α_1 is the transfer coefficient of ground displacement in the pipe axis direction = 0,873 [Formula (A.11)];

α_2 is the transfer coefficient of ground displacement in the pipe perpendicular direction = 1,000 [Formula (A.12)];

$U_{\mathrm{h}}(x)$ is the horizontal displacement amplitude of the ground = $8,70 \times 10^{-2}$ m [Formula (A.7)];

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

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

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

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

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

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

This is calculated using Formula (A.18):

$$u = \pm \varepsilon_{\mathrm{G}} \cdot l = \pm 0,002\,13 \times 6 = \pm 0,012\,78 \ \mathrm{m} \tag{A.18}$$

where

ε_{G} is the ground strain in the pipe axis direction = 0,002 13 [Formula (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 Formula (A.19):

$$\theta = \pm \frac{4 \cdot \pi^2 \cdot l \cdot U_\text{h}(x)}{L^2} = \pm \frac{4 \times \pi^2 \times 6 \times 0,087\,0}{128,09^2} = \pm 0,001\,256 \, \text{rad} = \pm 0°4'19'' \tag{A.19}$$

where

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

$U_\text{h}(x)$ is the horizontal displacement amplitude of ground = $8{,}70 \times 10^{-2}$ m [Formula (A.7)];

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

A.6 Summary of calculation results

Table A.3 shows the calculation results.

Table A.3 — Calculation results

Pipe body stress (MPa)	22,53
Amount of expansion/contraction of joint (mm)	±12,78
Deflection angle of joint	±0° 4′ 19″

Annex B
(informative)

Relationship between seismic intensity scales and ground surface acceleration

The relationship between seismic intensity scales such as the Modified Mercalli, JMA, MSK and China Seismic Intensity scales and ground surface acceleration are reported as shown in Table B.1.

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

Modified Mercalli Scale

Intensity	I	II to III	IV	V	VI	VII	VIII	IX	≥X
Acceleration (cm/s^2)	<1,7	1,7 to 14	14 to 38	38 to 90	90 to 180	180 to 330	330 to 630	630 to 1 200	>1 200

JMA scale (Japan Meteorological Agency Seismic Intensity Scale)

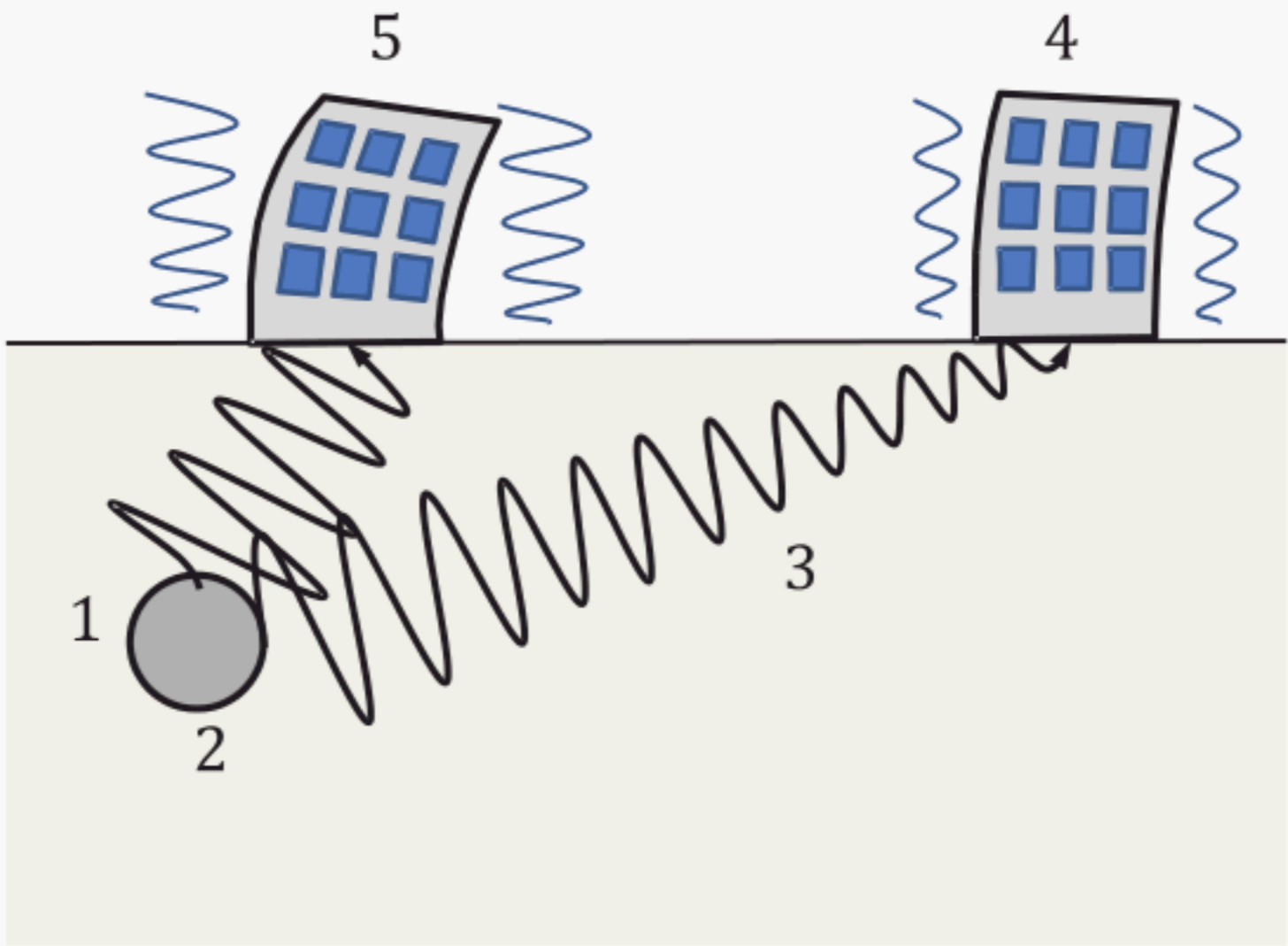| Intensity	0	1	2	3	4	5-lower	5-upper	6-lower	6-upper	7
Acceleration (cm/s^2)	<0,8	0,8 to 2,5	2,5 to 8,0	8,0 to 25	25 to 80	80 to 140	140 to 250	250 to 450	450 to 800	>800

MSK scale (Medvedev–Sponheuer–Karnik scale)

Intensity	I to IV	V	VI	VII	VIII	IV	X	XI to XII
Acceleration (cm/s^2)	<12	12 to 25	25 to 50	50 to 100	100 to 200	200 to 400	400 to 800	>800

China Seismic Intensity Scale

Intensity	I to IV	V	VI	VII	VIII	IV	X	XI to XII
Acceleration (cm/s^2)	—	22 to 44	45 to 89	90 to 177	178 to 353	354 to 707	708 to 1 414	—

NOTE   "Seismic intensity" represents the strength of shaking at one place when a certain earthquake occurs. On the other hand, "magnitude" such as the Richter scale means the amount of energy of an earthquake itself at the epicenter. Other Seismic intensity scale can be referred as per respective country code.

Seismic intensity depends on not only the magnitude but also the distance from the epicenter or soil properties. For example, if the earthquake with small magnitude is close to the epicenter, the ground will shake a lot and the seismic intensity will be higher, and vice versa. See Figure B.1.

Key

1	epicenter	4	strong shake (high seismic intensity)
2	magnitude	5	small shake (low seismic intensity)
3	seismic wave		

Figure B.1 — Difference between magnitude and seismic intensity scale

Annex C
(informative)

Example of calculation of liquefaction resistance coefficient value
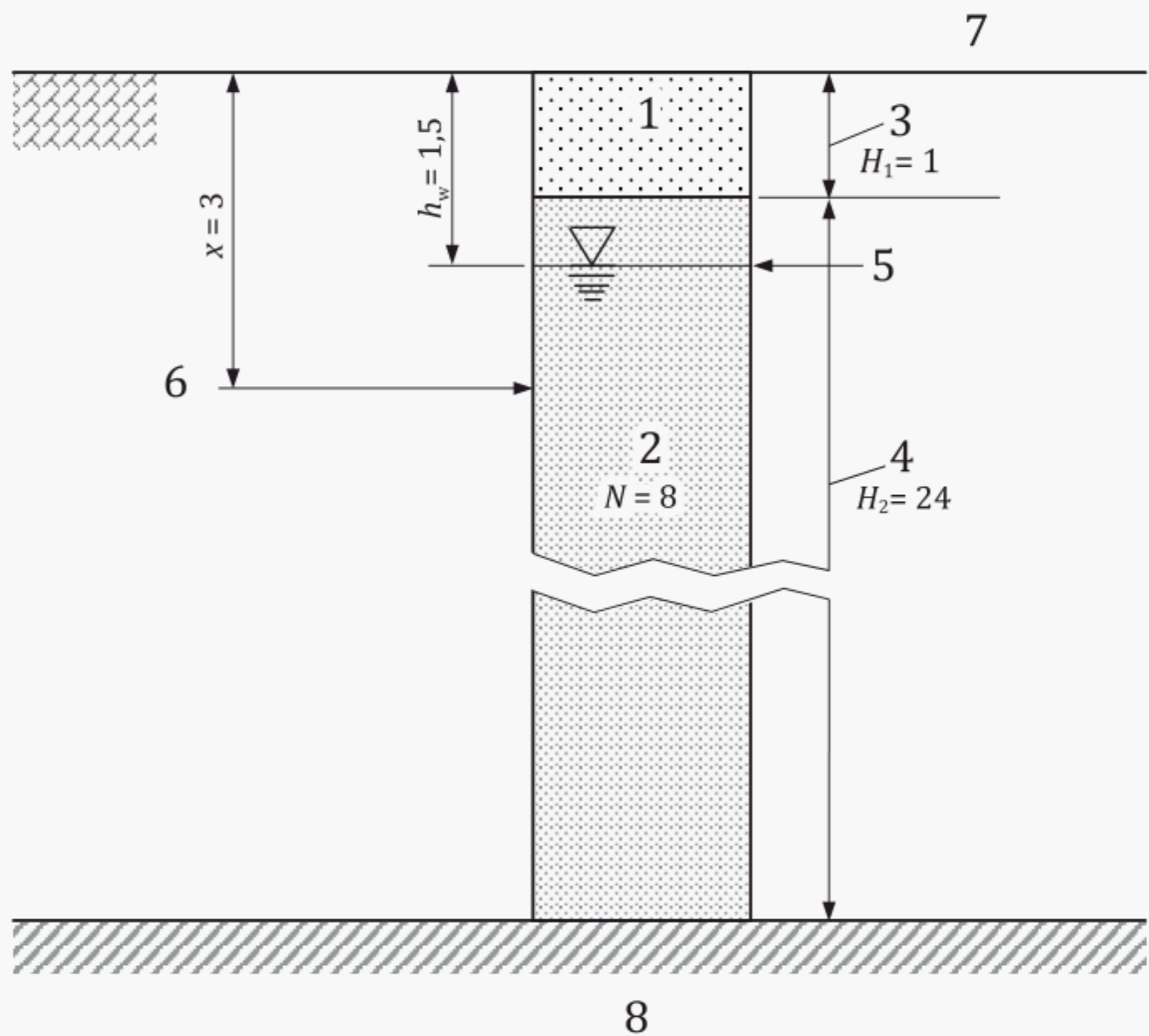
C.1   General

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

NOTE   *N* is the equivalent *N* value, which is derived from the standard penetration test defined in JIS A 1219, ASTM D1586 and BS 1377 test 19, etc.

Figure C.1 — Soil layers model

C.2.2   Ground acceleration for design

The maximum ground surface acceleration: a = 3,30 m/s^2 (corresponding to a Modified Mercalli scale intensity of VII).

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 Formula (C.1):

$$\gamma_d = 1,0 - 0,015 \cdot x = 1,0 - 0,015 \times 3 = 0,955 \tag{C.1}$$

where

γ_d is the reduction coefficient of the 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 Formula (C.2):

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

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 Formula (C.3):

$$\sigma_x = \gamma_{11} \cdot h_w + \gamma_{12} \cdot (x - h_w) = \gamma_{11c} \cdot H_1 + \gamma_{11s} \cdot (h_w - H_1) + \gamma_{12s} \cdot (x - h_w)$$

$$= 13,73 \times 1,0 + 17,65 \times (1,5-1,0) + 19,61 \times (3,0-1,5) = 51,97 \text{ kN/m}^2 \tag{C.3}$$

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 Formula (C.4):

$$\sigma'_x = \gamma_{11} \cdot h_w + \gamma'_{12} \cdot (x - h_w) = \gamma_{11c} \cdot H_1 + \gamma_{11s} \cdot (h_w - H_1) + \gamma'_{12s} \cdot (x - h_w)$$

$$= 13,73 \times 1,0 + 17,65 \times (1,5-1,0) + 9,80 \times (3-1,5) = 37,26 \text{ kN/m}^2 \tag{C.4}$$

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 $= \gamma_{12} - \gamma_w$, 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;

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

γ_{12s} 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 [Formula (C.5)]:

$$L = \frac{a}{g} \cdot \gamma_d \cdot \gamma_n \cdot \frac{\sigma_x}{\sigma'_x} = \frac{3,30}{9,81} \times 0,955 \times 0,6 \times \frac{51,97}{37,26} = 0,269 \qquad (C.5)$$

where

L is the ground shear stress ratio during earthquakes;

a is the maximum ground surface acceleration = 3,30 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 [Formula (C.1)];

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

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

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

C.4   Calculation of dynamic shear strength ratio, R

C.4.1   Equivalent N value, N_1

This is calculated using Formula (C.6):

$$N_1 = C_N \cdot N = 1{,}62 \times 8 = 13{,}0 \tag{C.6}$$
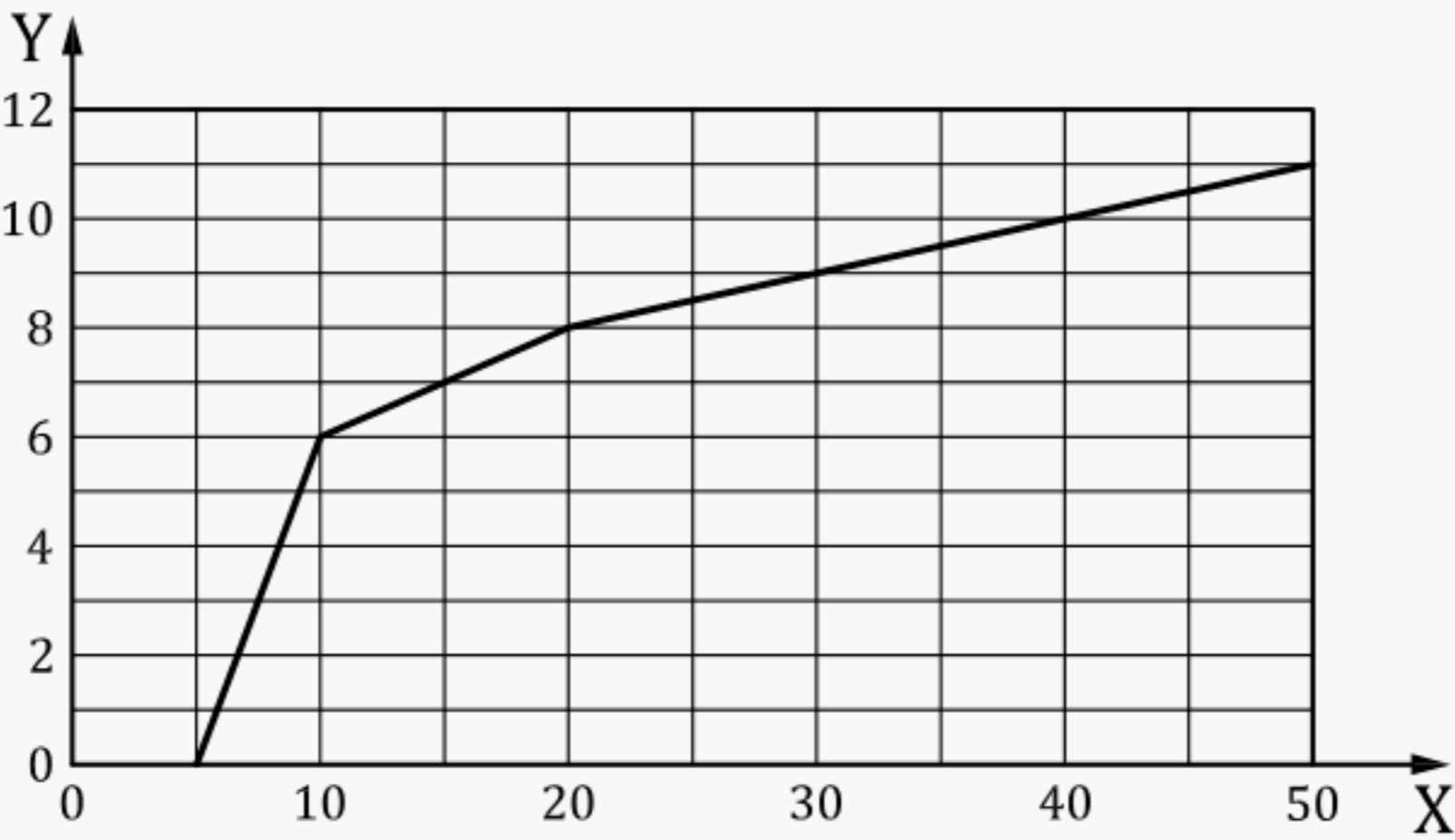
where

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 [Formula (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 Formula (C.7):

$$N_a = N_1 + \Delta N_F = 13{,}0 + 0 = 13{,}0 \tag{C.7}$$
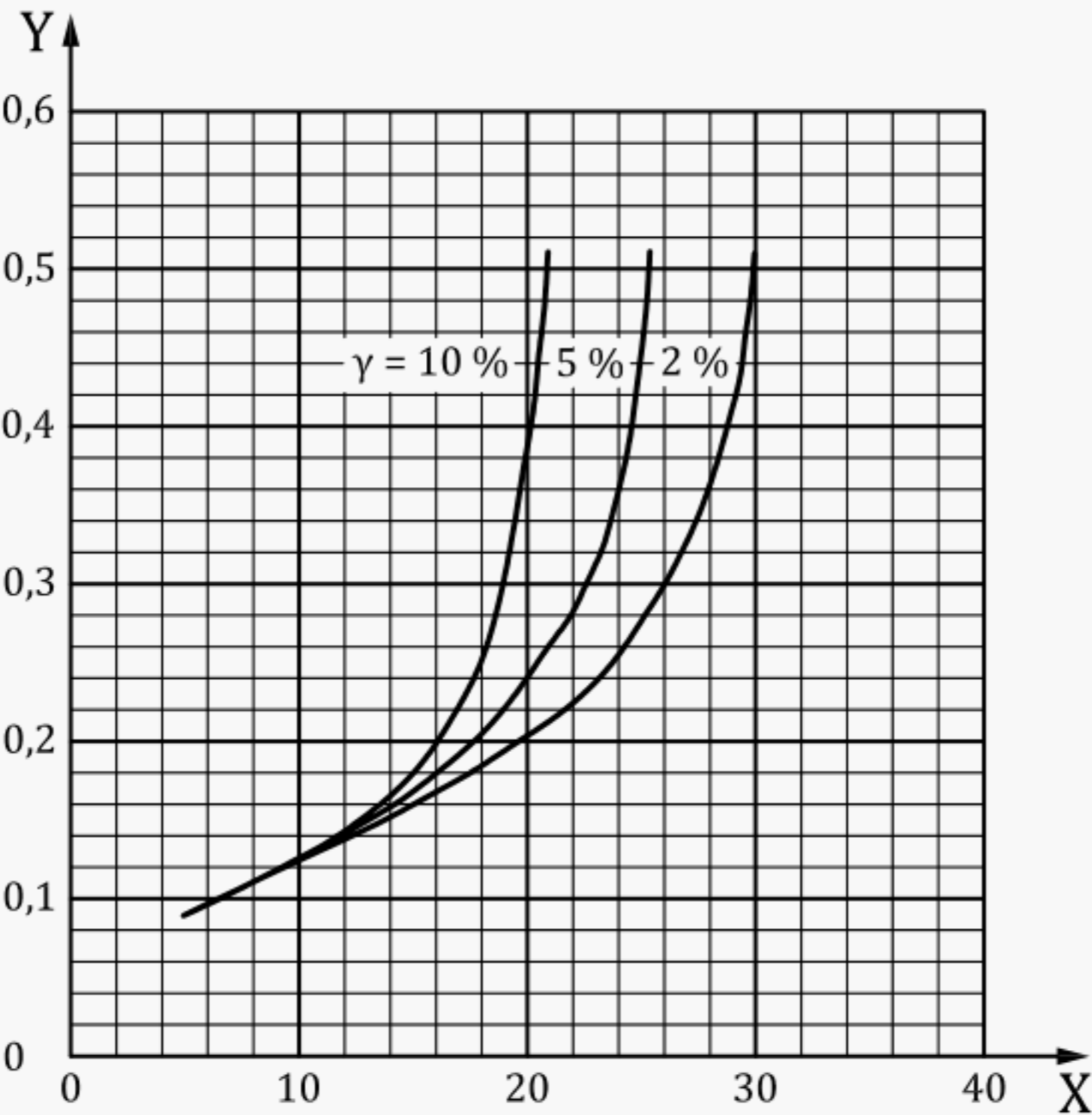
where

N_a is the modified N value;

N_1 is the equivalent N value = 13,0 [Formula (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 Formula (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 Formula (C.9):

$$F_L = R/L = 0,15/0,269 = 0,56 \tag{C.9}$$

where

F_L is the liquefaction resistance coefficient;

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

L is the ground shear stress ratio during the earthquake = 0,269 [Formula (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 earthquakes.

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 the pipe axis direction: $\varepsilon_G = 0,5\%$

f) Reduction ratio of the 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 Formula (D.1):

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

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 Formula (D.2):

$$\delta_a = f \cdot \varepsilon_G \cdot n \cdot l / 100 = 0,5 \times 0,5 \times 20 \times 6 / 100 = 0,3 \text{ m} \tag{D.2}$$

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 the 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: $\theta = 7°$

c) Number of joints: $n = 12$

d) Pipe length: $l = 6$ m

e) Assumed ground displacement in the 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 Formula (D.3) and illustrated in Figure D.1:

$$H_{max} = l \times (\tan\theta + \tan 2\theta + \tan 3\theta + \tan 2\theta + \tan\theta) = 6,0 \times (\tan 7° + \tan 14° + \tan 21° + \tan 14° + \tan 7°)$$
$$= 7,0\,\text{m} \tag{D.3}$$

where

    l is the pipe length = 6,0 m;

    θ is the maximum deflection angle at joint = 7°

Dimensions in metres
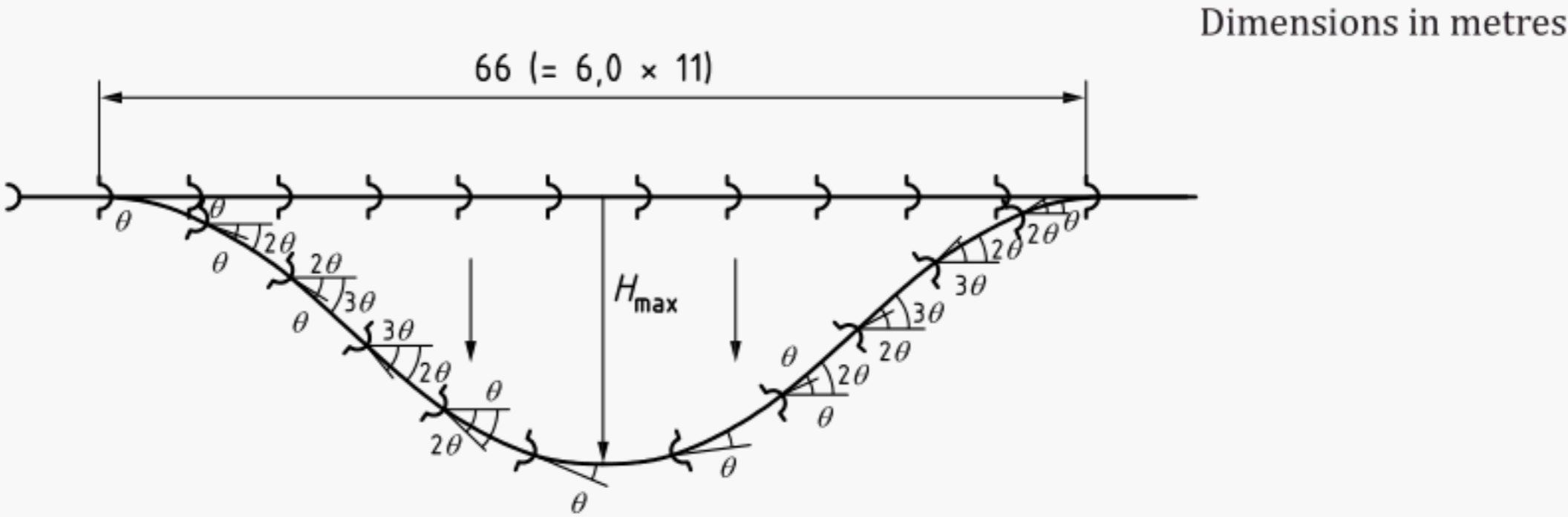
66 (= 6,0 × 11)

H_{max}

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 Formula (11). 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.
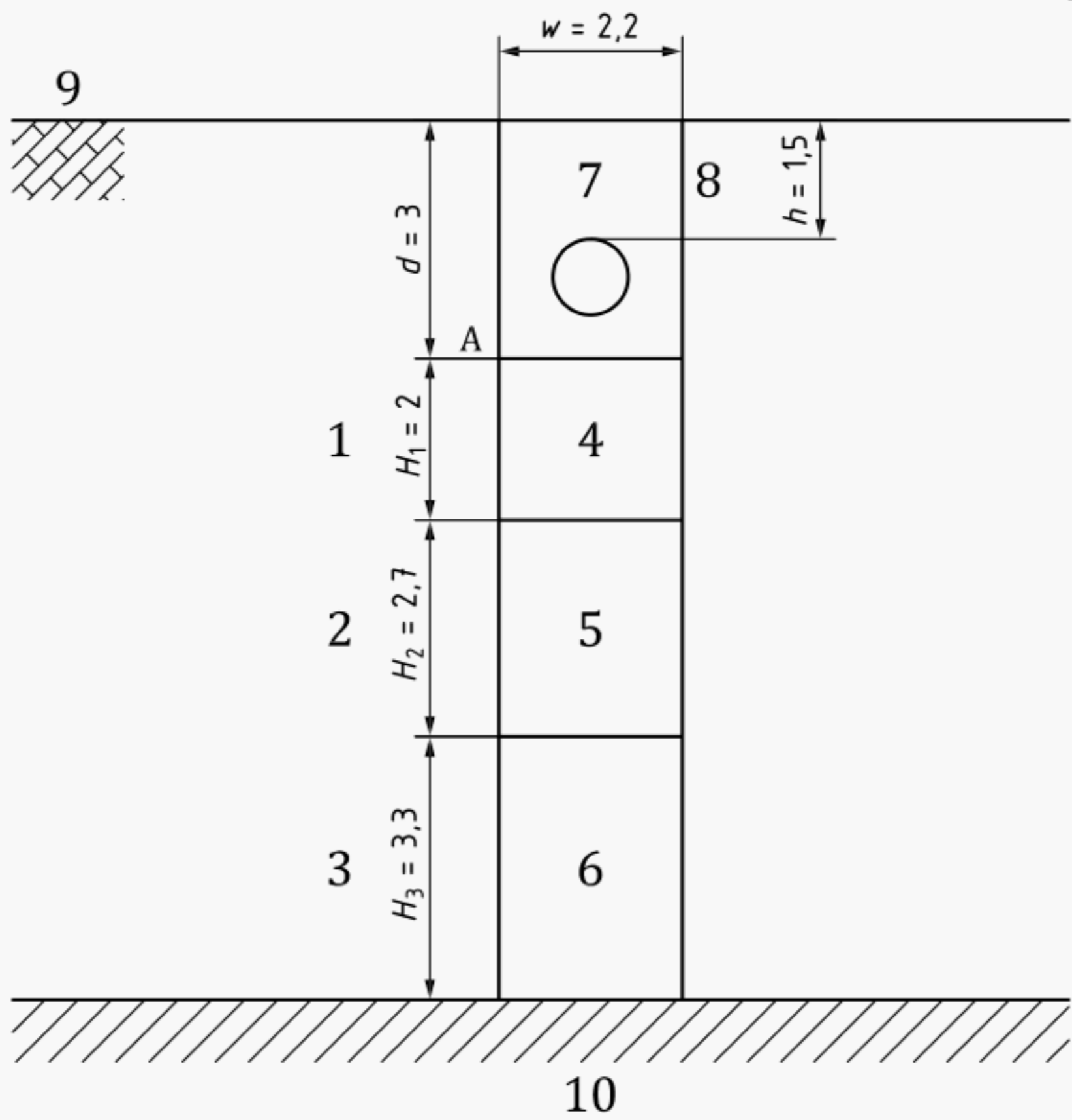
E.2 Specifications and conditions

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

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

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

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

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

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

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

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

i)   Unit weight of the 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	6	third layer (sand)
2	thickness of second layer	7	replace with sand
3	thickness of third layer	8	soil covering
4	first layer (clay)	9	ground surface
5	second layer (clay)	10	bedrock
A	face A		

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 [Formula (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 the excavated ground = γ_1 = 16 kN/m^3.

E.5.2   Weight of back-filling sand, W_3

This is calculated using [Formula (E.2)]:

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

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 the back-fill sand = 20 kN/m^3

E.5.3   Weight of the water in pipes, W_4

This is calculated using [Formula (E.3)]:

$$W_4 = \frac{\pi \cdot D_1^2 \cdot \gamma_w}{4} = \frac{3,14 \times 1,021^2 \times 9,81}{4} = 8,0 \tag{E.3}$$

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 [Formula (E.4)]:

$$\Delta W = (W_1 + W_3 + W_4 - W_2)/w = (4,0 + 114,8 + 8,0 - 105,6)/2,2 = 9,6 \, \text{kN/m}^2 \tag{E.4}$$

where

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

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

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

W_4 is the weight of water in the pipes = 8,0 kN/m [Formula (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 Formulae (E.5) to (E.7).
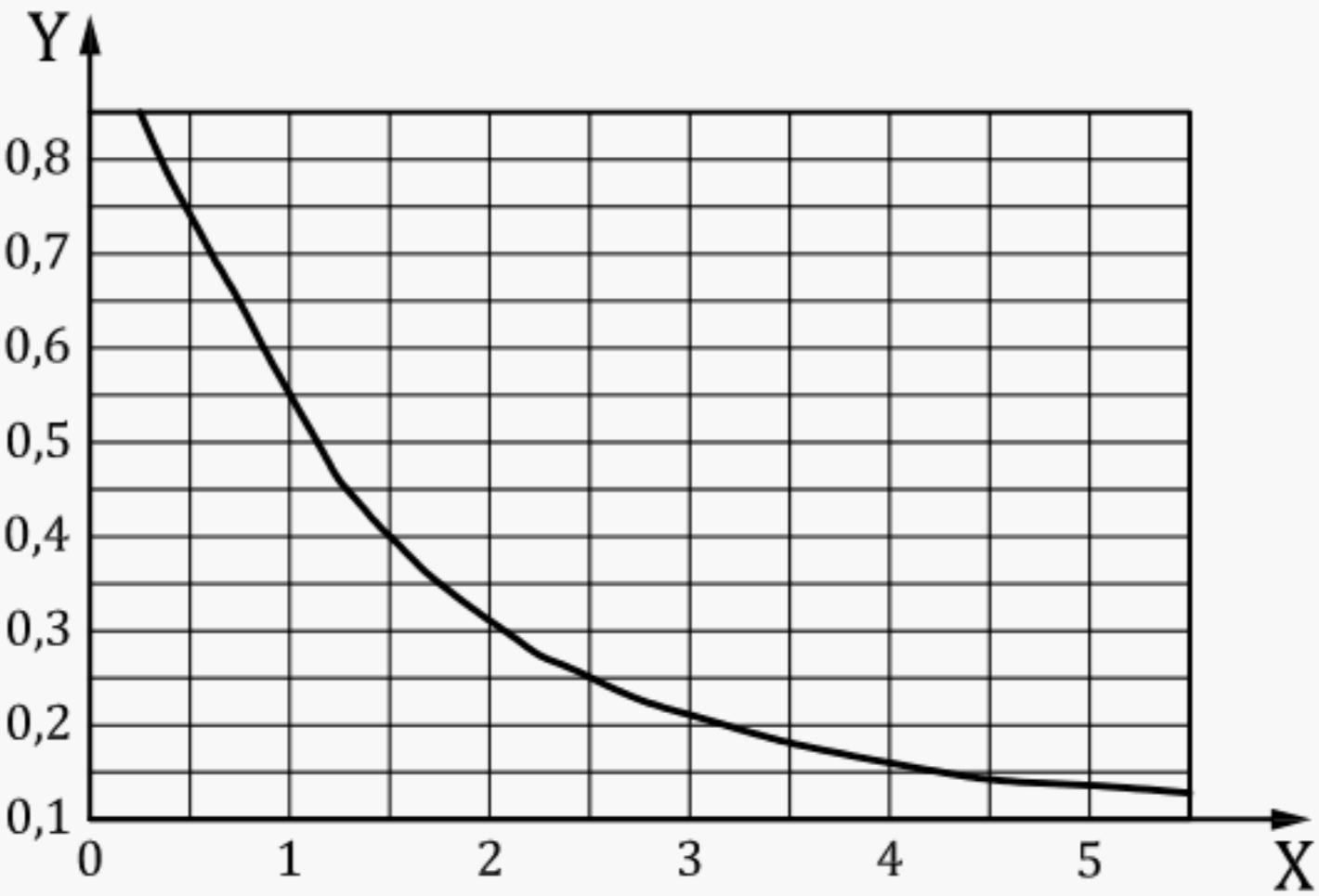
First layer:

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

Second layer:

$$X_2 = \frac{H_1 + (H_2/2)}{w} = \left[\frac{2,0 + (2,7/2)}{2,2}\right] = 1,52 \text{ then } I_{\sigma 2} = 0,38 \tag{E.6}$$

Third layer:

$$X_3 = \frac{H_1 + H_2 + (H_3/2)}{w} = \left[\frac{2,0 + 2,7 + (3,3/2)}{2,2}\right] = 2,89 \text{ then } I_{\sigma 3} = 0,22 \tag{E.7}$$

Key
X   depth ratio, X_i
Y   influence value, I_σ

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

E.5.6 Increased load, ΔP_i

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

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

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

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

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 [Formula (E.5)];
$I_{\sigma 2}$	is the influence value by depth at the second layer = 0,38 [Formula (E.6)];
$I_{\sigma 3}$	is the influence value by depth at third layer = 0,22 [Formula (E.7)];
ΔW	is the increased load at face A = 9,6 kN/m^2 [Formula (E.4)]

E.5.7 Ground subsidence, δ_i, of each layer

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

$$\delta_1 = m_{v1} \cdot \Delta P_1 \cdot H_1 = 3{,}6 \times 10^{-3} \times 7{,}5 \times 2{,}0 = 0{,}054 \, \text{m} \tag{E.11}$$

$$\delta_2 = m_{v2} \cdot \Delta P_2 \cdot H_2 = 2{,}1 \times 10^{-3} \times 3{,}6 \times 2{,}7 = 0{,}020\,4 \, \text{m} \tag{E.12}$$

$$\delta_3 = m_{v3} \cdot \Delta P_3 \cdot H_3 = 1{,}0 \times 10^{-4} \times 2{,}1 \times 3{,}3 = 0{,}000\,7 \, \text{m} \tag{E.13}$$

where

δ_1	is the subsidence at the first layer;
δ_2	is the subsidence at the second layer;
δ_3	is the subsidence at the third layer;
m_{v1}	is the volume change ratio at the first layer = 3,6 × 10^{-3} m^2/kN (see Table E.1);
m_{v2}	is the volume change ratio at the second layer = 2,1 × 10^{-3} m^2/kN (see Table E.1);
m_{v3}	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 [Formula (E.8);

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

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

E.5.8   Total amount of subsidence, δ

This is calculated using Formula (E.14):

$$\delta = \delta_1 + \delta_2 + \delta_3 = 0,054 + 0,020\,4 + 0,000\,7 = 0,075\,1 \text{ m} \tag{E.14}$$

where

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

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

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

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

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