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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

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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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.

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):

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

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);

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

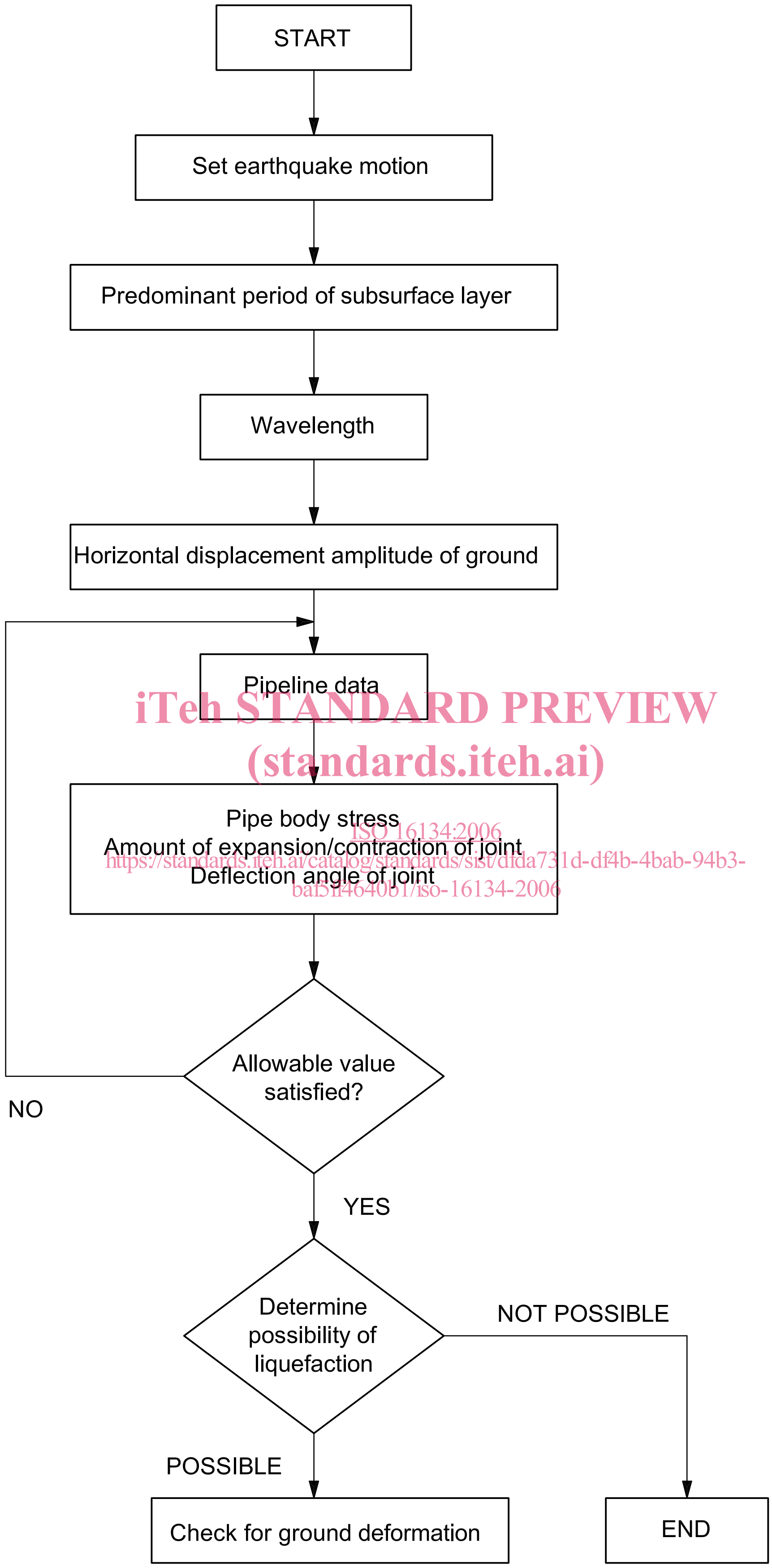

Figure 1 — Flowchart for calculation of earthquake resistance of buried pipelines

3.5.4 Pipe body stress

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

Axial stress:

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

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).

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):

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

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).

3.5.6 Joint deflection angle

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

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

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):

$$F_L = R/L \quad (7)$$

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 $F_L < 1{,}0$, 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):

$$\delta_c = \frac{e_0 - e}{1 + e_0} \cdot H_c \qquad (8)$$

$$\delta_c = m_v \cdot \Delta P \cdot H_c \qquad (9)$$

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

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

$$\Delta P = I_\sigma \cdot \Delta W \qquad (11)$$

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.