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Full document details: 23/30479680 DC

Introduction

This draft standard is based on national and international discussions. Your comments on this draft are invited and will assist in the preparation of the consequent standard.

For international standards, comments will be reviewed by the relevant UK national committee before sending the consensus UK vote and comments to the international committee, which will then decide appropriate action. If the international standard is approved, it is usual for the text to be published as a British Standard.

For national standards, comments will be reviewed by the relevant UK national committee and the resulting standards published as a British Standard.

UK Vote

Please indicate whether you consider the UK should submit a negative (with supporting technical reasons) or positive vote on this draft. Please indicate if you are aware of any reason why this draft standard should not be published as a British Standard.

Submission of Comments

- **Annotated drafts are not acceptable and will be rejected.**
- All comments should be submitted online at <https://standardsdevelopment.bsigroup.com/>. You will need to register in order to comment.

Template for comments and secretariat observations

Date: xx/xx/20xx	Document: ISO/DIS xxxx
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1	2	(3)	4	5	(6)	7
MB	Clause No./ Subclause No./Annex (e.g. 3.1)	Paragraph/ Figure/Table/Note	Type of comment	Comment (justification for change) by the MB	Proposed change by the MB	Secretariat observations on each comment submitted
	3.1	Definition 1	ed	Definition is ambiguous and needs clarifying.	Amend to read '...so that the mains connector to which no connection...'	
	6.4	Paragraph 2	te	The use of the UV photometer as an alternative cannot be supported as serious problems have been encountered in its use in the UK.	Delete reference to UV photometer.	

English Version

**Eurocode 8 - Design of structures for earthquake
resistance - Part 4: Silos, tanks, pipelines, towers, masts
and chimneys**

Eurocode 8 - Calcul des structures pour leur résistance
au séisme - Part 4: Silos, réservoirs, canalisations,
tours, mâts et cheminées

Eurocode 8 - Auslegung von Bauwerken gegen
Erdbeben - Teil 4: Silos, Tankbauwerke und
Rohrleitungen, Türme, Maste und Schornsteine

This draft European Standard is submitted to CEN members for enquiry. It has been drawn up by the Technical Committee CEN/TC 250.

If this draft becomes a European Standard, CEN members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration.

This draft European Standard was established by CEN in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CEN member into its own language and notified to the CEN-CENELEC Management Centre has the same status as the official versions.

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Recipients of this draft are invited to submit, with their comments, notification of any relevant patent rights of which they are aware and to provide supporting documentation.

Warning : This document is not a European Standard. It is distributed for review and comments. It is subject to change without notice and shall not be referred to as a European Standard.



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COMITÉ EUROPÉEN DE NORMALISATION
EUROPÄISCHES KOMITEE FÜR NORMUNG

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European foreword

This document (prEN 1998-4:2023) has been prepared by Technical Committee CEN/TC 250 “Structural Eurocodes”, the secretariat of which is held by BSI. CEN/TC 250 is responsible for all Structural Eurocodes and has been assigned responsibility for structural and geotechnical design matters by CEN.

This document is currently submitted to the CEN Enquiry.

This document will supersede EN 1998-4:2007 and EN 1998-6:2005.

The first generation of EN Eurocodes was published between 2002 and 2007. This document forms part of the second generation of the Eurocodes, which have been prepared under Mandate M/515 issued to CEN by the European Commission and the European Free Trade Association.

The Eurocodes have been drafted to be used in conjunction with relevant execution, material, product and test standards, and to identify requirements for execution, materials, products and testing that are relied upon by the Eurocodes.

The Eurocodes recognise the responsibility of each Member State and have safeguarded their right to determine values related to regulatory safety matters at national level through the use of National Annexes.

0 Introduction

0.1 Introduction to the Eurocodes

The Structural Eurocodes comprise the following standards generally consisting of a number of parts:

- EN 1990 Eurocode: Basis of structural and geotechnical design
- EN 1991 Eurocode 1: Actions on structures
- EN 1992 Eurocode 2: Design of concrete structures
- EN 1993 Eurocode 3: Design of steel structures
- EN 1994 Eurocode 4: Design of composite steel and concrete structures
- EN 1995 Eurocode 5: Design of timber structures
- EN 1996 Eurocode 6: Design of masonry structures
- EN 1997 Eurocode 7: Geotechnical design
- EN 1998 Eurocode 8: Design of structures for earthquake resistance
- EN 1999 Eurocode 9: Design of aluminium structures
- New parts are under development, e.g. Eurocode for design of structural glass

The Eurocodes are intended for use by designers, clients, manufacturers, constructors, relevant authorities (in exercising their duties in accordance with national or international regulations), educators, software developers, and committees drafting standards for related product, testing and execution standards.

NOTE Some aspects of design are most appropriately specified by relevant authorities or, where not specified, can be agreed on a project-specific basis between relevant parties such as designers and clients. The Eurocodes identify such aspects making explicit reference to relevant authorities and relevant parties.

0.2 Introduction to EN 1998 (all parts)

EN 1998 (all parts) defines the rules for the seismic design of new buildings and engineering works and the assessment and retrofit of existing ones, including geotechnical aspects, as well as temporary structures.

NOTE This standard also covers the verification of structures in the seismic situation during construction, when required.

Attention should be paid to the fact that, for the design of structures in seismic regions, the provisions of EN 1998 should be applied in addition to the relevant provisions of EN 1990 to EN 1997 (all parts) and EN 1999 (all parts). In particular, EN 1998 should be applied to structures of consequence classes CC1, CC2 and CC3, as defined in EN 1990:2023, 4.3. Structures of consequence class CC4 are not fully covered by the Eurocodes but may be required to follow EN 1998, or parts of it, by the relevant Authorities.

By nature, perfect protection (a null seismic risk) against earthquakes is not feasible in practice, namely because the knowledge of the hazard itself is characterized by a significant uncertainty. Therefore, in Eurocode 8, the seismic action is represented in a conventional form, proportional in amplitude to earthquakes likely to occur at a given location and representative of their frequency content. This representation is not the prediction of a particular seismic movement, and such a movement could give rise to more severe effects than those of the seismic action considered, inflicting damage greater than the one described by the Limit States contemplated in this standard.

Not only the seismic action cannot be predicted, but in addition, it should be recognised that engineering methods are not perfectly predictive when considering the effects of this specific action, under which structures are assumed to respond in the non-linear regime. Such uncertainties are taken into account according to the general framework of EN 1990, with a residual risk of underestimation of their effects.

EN 1998 is subdivided in various parts

EN 1998-1-1, *Eurocode 8 — Design of structures for earthquake resistance – Part 1-1: General rules and seismic action*;

EN 1998-1-2, *Eurocode 8 — Design of structures for earthquake resistance – Part 1-2: Buildings*;

EN 1998-2, *Eurocode 8 — Design of structures for earthquake resistance – Part 2: Bridges*;

EN 1998-3, *Eurocode 8 — Design of structures for earthquake resistance – Part 3: Assessment and retrofitting of buildings and bridges*;

EN 1998-4, *Eurocode 8 — Design of structures for earthquake resistance – Part 4 Silos, tanks, pipelines, towers, masts and chimneys*;

EN 1998-5, *Eurocode 8 — Design of structures for earthquake resistance – Part 5: Geotechnical aspects, foundations, retaining and underground structures*.

0.3 Introduction to prEN 1998-4

prEN 1998-4 provides specific requirements for earthquake resistant design of new on-ground and elevated silos, on-ground, elevated and underground tanks, above-ground and buried pipeline systems, towers, masts and chimneys and ancillary elements attached to the aforementioned structures or in industrial facilities, which are additional to the ones in other Eurocodes.

prEN 1998-4 is subdivided in ten clauses and includes seven annexes, where Annex A is normative and Annexes B, C, D, E, F, G are informative.

0.4 Verbal forms used in the Eurocodes

The verb “shall” expresses a requirement strictly to be followed and from which no deviation is permitted in order to comply with the Eurocodes.

The verb “should” expresses a highly recommended choice or course of action. Subject to national regulation and/or any relevant contractual provisions, alternative approaches could be used/adopted where technically justified.

The verb “may” expresses a course of action permissible within the limits of the Eurocodes.

The verb “can” expresses possibility and capability; it is used for statements of fact and clarification of concepts.

0.5 National annex for prEN 1998-4

National choice is allowed in this standard where explicitly stated within notes. National choice includes the selection of values for Nationally Determined Parameters (NDPs).

The national standard implementing prEN 1998-4 can have a National Annex containing all national choices to be used for the design of buildings to be constructed in the relevant country.

When no national choice is given, the default choice given in this standard is to be used.

When no national choice is made and no default is given in this document, the choice can be specified by a relevant authority or, where not specified, agreed for a specific project by the relevant parties.

National choice is allowed in prEN 1998-4 through notes to the following clauses:

4.2(2)

4.2(3)

4.3(6)

4.3(7)

National choice is also allowed in prEN 1998-4 on the application of the following informative annexes:

Annex B

Annex C

Annex D

Annex E

Annex F

Annex G

The National Annex can contain, directly or by reference, non-contradictory complementary information for ease of implementation, provided it does not alter any provisions of the Eurocodes.

1 Scope

1.1 Scope of prEN 1998-4

(1) This document is applicable to the seismic design of on-ground and elevated silos, on-ground, elevated and underground tanks, above-ground and buried pipeline systems, towers, masts and chimneys and ancillary elements attached to the aforementioned structures or in industrial facilities.

(2) Unless specifically stated, EN 1998-1-1:—², and EN 1998-5:—⁴ apply.

(3) prEN 1998-4 is applicable in complement to the other relevant Eurocodes.

NOTE This document contains only those provisions that, in addition to the provisions of the other relevant Eurocodes, are used for the design of new structures, as listed in (1), in seismic regions. prEN 1998-4 complements in this respect the other Eurocodes.

1.2 Assumptions

(1) The assumptions of EN 1998-1-1:—², 1.2, are assumed to be applied.

(2) It is assumed that the changes in a) and b) will not take place during the construction phase or during the subsequent life span for all structures covered by prEN 1998-4, unless proper justification and verification is provided:

- a) substantial changes in the structural systems, supporting structures or attached ancillary elements listed in 1.1 (1);
- b) substantial changes of masses or mass distribution. This includes, in particular, changes in production, such as specific changes of filling loads, filling states and ancillary elements.

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.

NOTE See the Bibliography for a list of other documents cited that are not normative references, including those referenced as recommendations (i.e. in 'should' clauses), permissions ('may' clauses), possibilities ('can' clauses), and in notes.

EN 1990:2023, *Eurocode — Basis of structural and geotechnical design*

EN 1991-1-4:—¹, *Eurocode 1 – Actions on structures – Part 1-4: Wind Actions*

EN 1998-1-1:—², *Eurocode 8 – Design of structures for earthquake resistance – Part 1-1: General rules and seismic action*

EN 1998-1-2:—³, *Eurocode 8 – Design of structures for earthquake resistance – Part 1-2: Buildings*

EN 1998-5:—⁴, *Eurocode 8 – Design of structures for earthquake resistance – Part 5: Geotechnical aspects, foundations, retaining and underground structures*

EN ISO 80000 (all parts), *Quantities and units*

¹ Under development.

² Under preparation. Stage at the time of publication: prEN 1998-1-1:2022.

³ Under preparation. Stage at the time of publication: prEN 1998-1-2:2023.

⁴ Under preparation. Stage at the time of publication: prEN 1998-5:2022.

3 Terms, definitions and symbols

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in EN 1990, EN 1991-1-4:—¹, EN 1998-1-1:—², EN 1998-5:—⁴, and the following, apply.

3.1.1

ancillary element

architectural, mechanical or electrical element, system and technical plant component such as container, pipeline, pump, conveyor and many other plant-specific components connected to or supported by the structures of 1.2 (1). An ancillary element is not considered in seismic design as load-carrying element but required for the safe operation of the facility and may be the cause of risk to persons or to the structure in case of earthquake

3.1.2

floating roof

height adjustable roof of tanks. The roof rises and falls with the liquid level in the tank

3.1.3

freeboard

space kept between the top of liquid level and the bottom of the roof slab of the tank or the depth between the overflow pipe and the base of the roof slab

3.1.4

lattice structure

structure in which the joints are not designed to resist the plastic moment of the connected members

3.1.5

masonry chimney

industrial chimney constructed of masonry units and mortar

3.1.6

silo battery

group of silos with individual cells connected to each other or stand-alone and permitting different types of similar solids to be stored separately

3.1.7

tangent tower

transmission tower used where the cable line is straight or has an angle not exceeding 3° in plan. It supports vertical loads, a transverse load from the angular pull of the wires, a longitudinal load due to unequal spans, and forces resulting from the wire-stringing operation, or a broken wire

3.1.8

telescope joint

joint between tubular elements without a flange, the internal diameter of one being equal to the external diameter of the other

3.1.9

transmission tower

tower used to support low or high voltage electrical transmission cables

3.2 Symbols and abbreviations

For the purposes of this document, the symbols and abbreviations given in EN 1990, EN 1998-1-1:—², EN 1998-1-2:—³, EN 1998-5:—⁴ apply.

For the symbols related to materials, as well as for symbols not specifically related to the seismic design situation, the provisions of the relevant Eurocodes apply.

In addition, further symbols and abbreviations, used in connection with the seismic design situation, are defined in the present standard where they occur, for ease of use. However, the most frequently occurring symbols used in this document are listed and defined in 3.2.1 and additional abbreviations are given in 3.2.2.

3.2.1 Symbols

3.2.1.1 Symbols used in Clause 5

Upper case Latin symbols

E	Young's modulus
F_b	total base shear
F_{bv}	vertical reaction force at the silo bottom
H_f	maximum design filling level of the silo content
M_b	overturning moment
R	radius of circular silo, silo compartment or tank

Lower case Latin symbols

b	horizontal dimension of a rectangular silo parallel to the horizontal seismic action
d_c	inner dimension of a silo parallel to the horizontal seismic action
m_s	total mass of the silo and its content
p_0	hydrostatic normal pressure
x_s	vertical coordinate of a point on a silo wall from a flat silo bottom or the apex of a conical or pyramidal hopper
x, y, z	coordinates

Upper case Greek symbols

$\Delta_{ph,s}$	additional normal pressure on the silo wall
$\Delta_{ph,so}$	reference normal pressure on silo walls
$\Delta_{ph,s,inc}$	increased additional normal pressure on compression-loaded silo wall

Lower case Greek symbols

α	ratio of the response acceleration of a silo at the level of interest, z , to the acceleration of gravity
----------	---

β	angle of inclination of the hopper wall in a silo, measured from the vertical, or the steepest angle of inclination to the vertical of the wall in a pyramidal hopper
β_{sc}	scaling factor for pressures on vertical silo walls, silo hoppers and silo bottoms
θ	angle ($0^\circ \leq \theta < 360^\circ$) for the geometrical description of circular silos and tanks
ρ_u	upper characteristic value of the bulk density of the particulate solid

3.2.1.2 Symbols used in Clause 6

Upper case Latin symbols

B	half width of rectangular tanks
D	diameter of circular tanks
$F_{b,c}$	maximum convective base shear
$F_{b,inf,h}$	horizontal base shear due to mass inertia effects of flexible tanks
$F_{b,inf,v}$	vertical reaction force due to mass inertia effects of flexible tanks
$F_{b,inr,h}$	horizontal base shear due to mass inertia effects of rigid tanks
$F_{b,inr,v}$	vertical reaction force due to mass inertia effects of rigid tanks
$F_{b,if,h}$	impulsive flexible horizontal base shear
$F_{b,if,v}$	impulsive flexible vertical reaction force
$F_{b,ir,h}$	impulsive rigid horizontal base shear
$F_{b,ir,v}$	impulsive rigid vertical reaction force
$F_{bv,res}$	resulting vertical reaction force
$F_{bh,res}$	resulting horizontal reaction force
$F_{b,c,1}$	convective base shear for elevated tanks for the 1 st eigenmode
$F_{b,c,2}$	convective base shear for elevated tanks for the 2 nd eigenmode
$F_{b,ir,1}$	impulsive rigid base shear for elevated tanks for the 1 st eigenmode
$F_{b,ir,2}$	impulsive rigid base shear for elevated tanks for the 2 nd eigenmode
F_h	correction factor for the impulsive flexible time period in horizontal direction
F_v	correction factor for the impulsive flexible time period in vertical direction
H	filling height of tanks
H_T	total height of a vertical cylindrical tank
$I_{if,h}$	increase factor to consider mass inertia effects of flexible tanks in horizontal direction
$I_{if,v}$	increase factor to consider mass inertia effects of flexible tanks in vertical direction
L	half-length of rectangular tank
$M_{G,c}$	total convective moment at the base with base pressure
$M_{G,if,h}$	impulsive flexible moment below the base plate
$M_{G,ir,h}$	rigid impulsive moment below the base plate
$M_{G,res}$	resulting overturning moment below the base plate

M_R	overturning moment for unanchored tanks
$M_{W,c}$	convective moment just above the base plate
$M_{W,if,h}$	the flexible impulsive moment just above the base plate
$M_{W,ir,h}$	impulsive rigid moment just above the base plate
$M_{W,res}$	resulting overturning moment above the base plate
S_{ev}	velocity response spectrum
T_{con}	first natural period of the convective mode
$T_{if,h}$	impulsive flexible period in horizontal direction
$T_{if,v}$	impulsive flexible vertical period in vertical direction
$T_{ir,h}$	first natural period of the impulsive response in horizontal direction
$T_{ir,v}$	first natural period of the impulsive response in vertical direction

Lower case Latin symbols

d_t	wall deflection of rectangular tanks
d_{max}	absolute maximum value of the vertical wave height
h_{ir}	impulsive rigid lever arms without bottom pressure
h_{if}	impulsive flexible lever arms without bottom pressure
h_c	convective lever arms without bottom pressure
h'_{ir}	impulsive rigid lever arms without bottom pressure
h'_{if}	impulsive flexible lever arms without bottom pressure
h'_c	convective lever arms without bottom pressure
k_c	convective spring stiffness
k_s	spring stiffness for substructures of elevated tanks
k_{θ}^*	coefficient for unanchored tanks
k_{sp}	stiffness of substructures of spherical tanks
l_{up}	uplift length of a rectangular tank
m_l	total liquid mass
m_{ir}	equivalent impulsive mass
m_c	equivalent convective mass
m_{if}	flexible impulsive mass
m_r	roof mass
m_w	wall mass
p_b	hydrostatic normal pressure on the uplifted length for unanchored tanks
p_c	convective pressure component
$p_{if,h}$	impulsive flexible pressure function for horizontal seismic actions
$p_{if,v}$	impulsive flexible pressure function for vertical seismic actions

$p_{ir,v}$	impulsive rigid pressure function for vertical seismic actions
$p_{ir,h}$	impulsive rigid pressure function on the tank wall for horizontal seismic actions
p_w	uniform pressure on the tank wall corresponding to inertia forces
p_{wif}	uniformly distributed load for impulsive flexible vibration mode of rectangular tanks
$p_{v,res}$	resulting vertical pressure component
$p_{h,res}$	resulting horizontal pressure component
q_{ir}	dimensionless impulsive rigid pressure function
q_c	dimensionless convective pressure function
s_w	uniform thickness of the tank wall or the average in case of stepwise wall thickness
s_p	thickness of the base plate for tanks
$\bar{y}_{c,1}$	maximum displacement of the convective mass for the 1 st eigenmode for elevated silos
$\bar{y}_{c,2}$	maximum displacement of the convective mass for the 2 nd eigenmode for elevated silos
$\bar{y}_{ir,1}$	maximum displacement of the impulsive rigid mass for the 1 st eigenmode for elevated silos
$\bar{y}_{ir,2}$	maximum displacement of the impulsive rigid mass for the 2 nd eigenmode for elevated silos

Upper case Greek symbols

$\Gamma_{ir,h}$	participation factor of the impulsive rigid pressure component
$\Gamma_{ir,v}$	participation factor of the impulsive rigid pressure in vertical direction
Δm	self-weight of the substructures of elevated tanks
Δm_{ss}	contributing mass of the substructure for spherical tanks
Ψ_1, Ψ_2	constants for the calculation of displacements for elevated tanks

Lower case Greek symbols

η	specified liquid weight
ζ	dimensionless height for vertical cylindrical tanks
ν	Poisson's ratio of the tank material
θ^*	angle for unanchored tanks
μ	dimensionless parameter for unanchored tanks
ξ_T	dimensionless radius for vertical cylindrical tanks
ρ_L	liquid density
ρ_{sw}	density of the tank wall
σ_{pu}	additional membrane stresses in the base plate of unanchored tanks
φ_n	n-mode shape of an elevated tank
$\varphi_{1,an}$	fundamental mode shape value at the height of attachment of the ancillary element to the supporting structure
ω_{ir}	circular frequency of the impulsive rigid mode for spherical tanks

3.2.1.3 Symbols used in Clause 7

Lower case Latin symbols

r_p	pipeline radius
t_p	wall thickness of pipelines

3.2.1.4 Symbols used in Clause 8

Upper case Latin symbols

$D_{\max}$	greatest outer diameter of the pipeline after its ovaling
$D_{\min}$	smallest outer diameter of the pipeline after its ovaling
D_{mean}	mean outer diameter of the pipeline before ovaling
D_p	medium diameter of the pipeline
D_{op}	outer diameter of the pipeline
L_A	effective unanchored length between the fault trace and the anchor point
L_{em}	embedment length of the pipeline
L_{PGD}	length of the permanent ground motion zone
O_v	ovaling value of the pipeline
V_{app}	apparent shear wave celerity of the wave along a pipeline
V_{BU}	buoyant force per unit length of the pipeline
W_{PGD}	width of the permanent ground motion zone

Lower case Latin symbols

d_w	wave amplitude
m_{an}	mass of ancillary element
u	soil motion
x'	direction of wave propagation

Upper case Greek symbols

Δn	fault movement along the fault plane in normal direction
Δs	fault movement along the fault plane in normal direction
Δx	fault movement in axial pipeline direction
Δy	fault movement in transverse direction to the pipeline
Δz	fault movement in vertical direction to the pipeline
χ^p	maximum curvature of the pipeline

Lower case Greek symbols

α_{fv}	fault dip angle
β_{fh}	fault-pipeline crossing angle in the horizontal plane
$\varepsilon_{a,\text{max}}^p$	maximum axial strain in the pipeline due to wave propagation
ε_a^f	average axial strain in the pipeline due to fault movement

ε_b^p	minimum/maximum bending strain in the pipeline
ε_p	plastic tensile strain of the pipeline
ε_y	yield strain of the pipeline
γ_c	unit weight of the pipeline content
γ_p	unit weight of the pipeline material
γ_s	total unit weight of soil
δ_{PGD}^t	maximum amplitude of the permanent ground motion in transverse direction to the pipeline
δ_{PGD}^a	maximum amplitude of the permanent ground motion in axial direction to the pipeline
λ_a	apparent wave length of the predominant seismic wave at the ground surface where a pipeline is buried
θ_w	angle between the direction of wave propagation and the pipeline axis

3.2.1.5 Symbols used in Clause 9

Upper case Latin symbols

AMP	amplification factor for ancillary element acceleration
F_{an}	horizontal seismic force acting on ancillary element
S_{an}	horizontal floor acceleration spectrum value of ancillary element
$S_{ep,1}$	elastic response spectra acceleration at the fundamental mode of the ancillary element supporting structure
T_{p1}	fundamental mode period of the ancillary element supporting structure

Lower case Latin symbols

q'_{an}	behaviour factor of ancillary element
q'_D	period and ductility dependent behaviour factor of the ancillary element supporting structure

Lower case Greek symbols

γ_{an}	ancillary element performance factor
μ_D	ductility capacity of the ancillary element anchorage system
ξ_a	damping ratio for ancillary elements
$\xi_{p,1}$	fundamental mode damping of the ancillary element supporting structure

3.2.1.6 Symbols used in Clause 10

Upper case Latin symbols

E_{cbl}	Modulus of elasticity of the cable material
E_{eq}	Equivalent modulus of elasticity
M_o	first-order overturning moment at the base level
P	normal force
PFA	peak floor acceleration

Lower case Latin symbols

d_r	relative deflection between different points of support of the liner
e_L	horizontal eccentricity
k_r	modification factor of the behaviour factor q to account for irregularities
$l_{cbl,h}$	horizontal projected cable length

Upper case Greek symbols

Γ_1	participation factor of the fundamental mode in the direction under consideration
Δ	is the displacement corresponding to the moment
ΔH	vertical distance of adjacent platforms supporting the liner

Lower case Greek symbols

β_w	wrapping angle of the single chord
γ_{cbl}	unit weight of the cable, including the weight of ice load on the cable
δM	additional overturning moment at the base level due to second-order ($P-\Delta$) effect
λ_s	slenderness of structural members
σ_{cbl}	tensile stress in the cable

3.2.1.7 Symbols used in Annex A*Upper case Latin symbols*

C_c	dimensionless convective pressure function
$C_{F,c}$	convective base shear coefficient
$C_{F,if,h}$	dimensionless impulsive flexible base shear coefficient
$C_{F,ir,h}$	impulsive rigid base shear coefficient
$C_{if,h}$	dimensionless impulsive flexible pressure function
$C_{ir,h}$	dimensionless impulsive rigid pressure function
$C_{if,v}$	dimensionless impulsive flexible pressure function
$C_{M,c}$	convective overturning moment coefficient
$C_{M,if,h}$	impulsive flexible overturning moment coefficient
$C_{M,ir,h}$	impulsive rigid overturning moment coefficient
$C_{MW,c}$	convective overturning moment coefficient
$C_{MW,if,h}$	impulsive flexible overturning moment coefficient
$C_{MW,ir,h}$	impulsive rigid overturning moment coefficient
P_h	dimensionless period coefficient in horizontal direction
P_v	dimensionless period coefficient in vertical direction

Upper case Greek symbols

Γ_c	participation factor of the convective pressure component
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$\Gamma_{if,h}$ participation factor of the impulsive flexible horizontal mode

$\Gamma_{if,v}$ participation factor of the impulsive flexible vertical mode

Lower case Greek symbols

β_c correction factor for taking account of the clamping effect

γ ratio of filling height to tank radius

3.2.1.8 Symbols used in Annex B

Upper case Latin symbols

G_s shear modulus of the soil

K_{if} flexible tank stiffness associated to the impulsive flexible mode

K_x horizontal stiffness of the foundation

K_θ rotational stiffness of the foundation

K_v vertical stiffness of the foundation

R_b radius of the foundation

$T_{if,h}^*$ impulsive flexible period of vibration in horizontal direction with soil-structure interaction

$T_{if,v}^*$ impulsive flexible period of vibration in vertical direction with soil-structure interaction

$T_{ir,h}^*$ impulsive rigid period of vibration in horizontal direction with soil-structure interaction

$T_{ir,v}^*$ impulsive rigid period of vibration in vertical direction with soil-structure interaction

Lower case Latin symbols

m_b mass of the base plate

a, a_2, a_3 numerical coefficients for rotational dynamic stiffness modifier

b_1, b_2, b_3 numerical coefficients for vertical dynamic stiffness modifier

Lower case Greek symbols

α_v dimensionless coefficient for the rotational stiffness of rigid circular footings

α_x dimensionless stiffness modifier for the horizontal stiffness

α_θ dimensionless stiffness modifier for the rotational stiffness

ν_s is the Poisson's ratio of the soil

ν_s is the soil mass density

3.2.1.9 Symbols used in Annex D

Upper case Latin symbols

F_{pipeline} force applied to the pipeline by the spring

F_{ult} ultimate force applied to the pipeline

H_p depth from the soil surface to the centreline of the pipeline

K_0 coefficient of earth pressure at rest

N_{ch} dimensionless horizontal bearing capacity factor for fine-grained soil

N_{qh}	dimensionless horizontal bearing capacity factor for coarse-grained soil
N_{cv}	dimensionless vertical uplift factor for fine-grained soil
N_{qv}	dimensionless vertical uplift factor for coarse-grained soils
N_c	dimensionless vertical bearing capacity factor for cohesive soil
N_q	dimensionless bearing capacity factor for passive earth pressure due to the self-weight of the soil
N_γ	dimensionless bearing capacity factor for passive earth pressure due to the downward movement of the pipeline
P_u	ultimate transverse force per unit length for the pipeline soil interaction model
Q_u	ultimate transverse (vertical uplift) force per unit length
Q_d	ultimate transverse (vertical downward) force per unit length
T_u	is the ultimate force per unit length at the soil-pipeline interface
V_s	shear wave velocity of the soil

Lower case Latin symbols

c'	soil cohesion
d_{ult}	ultimate displacement
f_p	pipe-coating dependent factor
$x_{s,disp}$	displacement applied to the soil spring

Upper case Greek symbols

ΔT_u	axial ultimate relative displacement for pipe-soil interaction model
ΔP_u	transverse ultimate relative displacement for pipe-soil interaction model
ΔQ_u	transverse (vertical uplift) ultimate relative displacement for pipe-soil interaction model
ΔQ_d	transverse (vertical downward) ultimate relative displacement for pipe-soil interaction model

Lower case Greek symbols

α^{sp}	soil/pipeline adhesion factor
γ'	effective soil unit weight
γ_w	water unit weight
δ_{pf}	friction angle between the soil and the pipe
φ	internal friction angle of the soil in degrees (°)

3.2.1.10 Symbols used in Annex E

Upper case Latin symbols

C_F	confidence factor for the fault recurrence rate
L_F	fault length
X_L	ratio of the distance of the pipeline-fault crossing point to the closest fault end over the fault length

Lower case Latin symbols

$a_0, \dots, a_8$	coefficients that depend on Δ_F and the recurrence rate
f_L	recurrence-rate-independent function of the fault and fault-crossing characteristics
p_1 to p_7	coefficients for recurrence rate

Upper case Greek symbols

Δ_F	fault differential displacement
Δ_{Fcap}	a deterministic cap on the fault differential displacement

Lower case Greek symbols

a_{CF}	recurrence rate approximate estimation
v_F	fault recurrence rate

3.2.2 Abbreviations

GFRP	Glass fibre-reinforced plastic
HDPE	High density polyethylene
NDP	National determined parameter
PE	Polyethylene
G	Centre of mass
C	Centre of stiffness
RL	Rigid link

3.3 S.I. Units

S.I. Units in accordance with EN ISO 80000 (all parts) shall be used.

For calculations, the following units should be used when applicable:

– forces and loads:	kN, kN/m, kN/m ²
– length, displacement:	m, mm
– unit mass:	kg/m ³ , t/m ³
– mass:	kg, t
– weight density:	kN/m ³
– stresses and strengths:	Pa (= N/m ²), kPa (= kN/m ²), MPa (= MN/m ²)
– moments (bending, etc.):	kNm
– acceleration:	m/s ²

4 Basis of design

4.1 Performance requirements

(1) Structures addressed by this standard shall be designed to meet the objectives given in a) to f) with an appropriate degree of reliability:

- a) protection of human lives and personal injury;
- b) lifeline systems important for civil protection to remain operational;
- c) protection of environment;
- d) prevention of induced damage to connected plant components, nearby buildings and adjacent facilities to avoid cascading effects;
- e) limitation of damage to preserve the full or limited functionality;
- f) minimisation of economic and social consequences.

(2) To meet the performance requirements in (1), it should be verified that structures are designed in such a way that the specified limit states for structures listed in 1.1(1) are not exceeded under prescribed seismic actions, determined with respect to the consequence class of the considered structure.

4.2 Consequence classes

(1) The consequence classes CC1, CC2 and CC3 should be applied as defined in EN 1990:2023, 4.3. The choice of the consequence class should depend on the consequences of collapse or damage, on their importance for public safety and civil protection in the immediate post-earthquake period, and on the economic, social and environmental consequences. The specific definitions of the consequence classes given in EN 1990:2023, Annex A, should be considered.

(2) Consequence class CC3 should be divided into the two subclasses CC3-a and CC3-b, according to EN 1998-1-1:—², 4.2(3). Class 3-b should be chosen if the integrity of the structure, including ancillary elements, is of vital importance for the public safety and environment or can induce damage to connected plant components, nearby buildings or adjacent facilities. Furthermore, class CC3-b should be selected for all structures and systems which could jeopardise the operational civil protection services in the immediate post-earthquake period. In all other cases, structures of class CC3 may be assigned to subclass CC3-a.

NOTE 1 The definition of the classes CC3-a and CC3-b given in (2) is applied, unless the National Annex or relevant authorities give different definitions.

NOTE 2 Examples for important operational civil protection services in CC3-b are: energy and water supply systems, emergency routes, hospitals, fire stations, telecommunication, safety systems.

NOTE 3 The consequence class CC4 for large risk structures and their ancillary elements and systems is not covered by the present document. The categories of structures of consequence class CC4 where this document or parts of it apply in a country can be found in EN 1990:2023, Annex A.4, the National Annex or can be provided by the relevant authorities. The principles of calculation and design given in this document can also be applied for structures with consequence class CC4 (e.g. LNG tanks).

(3) For the application of EN 1998-1-1:—², 4.1(4), δ values should be determined.

NOTE The values of δ applicable to the structures addressed in this document and to the associated geotechnical systems are those given in Table 4.1 (NDP), unless the relevant authorities or the National Annex give different values.

Table 4.1 (NDP) — δ values of structures addressed in this standard as listed in 1.1(1)

	Consequence class (CC)			
	CC1	CC2	CC3-a	CC3-b
δ	0,60	1,0	1,4	1,8

4.3 Limit states and associated seismic actions

(1) The performance requirements shall refer to the state of damage in the structures, herein described through the Limit States (LS) according to the definition in EN 1998-1-1:—², 4.3(1).

(2) The seismic performance of the structures addressed by in this standard shall correspond to the Significant Damage (SD) limit state, in which the structure and its ancillary elements are significantly damaged, but both retain their structural integrity with controlled leakage of contents.

(3) Depending on the characteristics and the function of the structure considered, the LS of Damage Limitation (DL) or Fully Operational LS (OP) may be checked additionally.

(4) LS of DL should be defined as the one in which the extent and amount of damage of the considered system, including some of its ancillary elements, is limited, so that after the operations for damage checking and control are carried out, the capacity of the system can be restored up to a predefined level of operation. Liquid-filled systems should remain leak-proof.

(5) LS of OP should be defined as the one in which the considered system, including a specified set of ancillary elements integrated with it, remains fully serviceable under the relevant seismic action. Liquid-filled systems should remain leak-proof.

(6) Unless (7) is applied, the seismic action should be specified in terms of its return period. The attainment of the performance requirements should be achieved by selecting appropriate return periods, $T_{LS,CC}$, depending on the specified limit states and consequence class of the structure and its ancillary elements under consideration.

NOTE 1 The values of $T_{LS,CC}$ according to EN 1998-1-1:—², 4.3(3), for NC, SD and DL limit states, are those given in Table 4.2 (NDP), unless relevant authorities or the National Annex give different values.

NOTE 2 The values of $T_{LS,CC}$ at OP limit state applied to specified structures and its ancillary elements can be provided by the relevant authorities or can be found in the National Annex.

NOTE 3 Values are given for NC for completeness in (6) and (7), although this limit state is not covered in the present document. They can be used for existing structures.

NOTE 4 Values of $T_{LS,CC}$ for consequence class CC4 are not covered by the present document. They can be found in other European standards (e.g. prEN 14620 for LNG tanks), in the National Annex.

Table 4.2 — (NDP) Return periods $T_{LS,CC}$ of seismic action in years

Limit state	Consequence class			
	CC1	CC2	CC3-a	CC3-b
NC	800	1600	2500	5000
SD	250	475	1300	2500
DL	50	60	150	250

(7) Alternatively to (6), performance factors, $\gamma_{LS,CC}$, may be used alternatively to return periods.

NOTE 1 The values of $\gamma_{LS,CC}$ according to EN 1998-1-1:—², 4.3(4), for NC, SD and DL limit states, are those given in Table 4.3 (NDP), unless the National Annex or relevant authorities give different values.

NOTE 2 Values of $\gamma_{LS,CC}$ for consequence class CC4 are not covered by the present standard. They can be found in other European standards, in the National Annex or can be provided by the relevant authorities.

Table 4.3 — (NDP) Performance factors $\gamma_{LS,CC}$

Limit state	Consequence class			
	CC1	CC2	CC3-a	CC3-b
NC	1,2	1,5	1,8	2,2
SD	0,8	1,0	1,4	1,8
DL	0,4	0,5	0,7	0,8

NOTE 3 The values of $\gamma_{LS,CC}$ at OP limit state applied to specified structures and its ancillary elements can be provided by the relevant authorities or can be found in the National Annex.

(8) The site conditions and seismic action on the ground surface at the location of the structure shall be determined according to EN 1998-1-1:—², Clause 5.

(9) The seismic action for geotechnical systems and geotechnical structures shall be determined according to EN 1998-5:—⁴, 5.2.

4.4 Modelling and methods of analysis

(1) Unless otherwise specified for particular types of structures in the relevant clauses of this standard, the structural modelling and types of analysis (force-based approach, non-linear static analysis and response-history analysis) should be applied according to EN 1998-1-1:—², 6, and EN 1998-1-2:—³, 5.

(2) The value of β introduced in EN 1998-1-1:—², 6.4.1(5), is equal to 0,08 for structures addressed in this standard as given in 1.1(1).

(3) The combination coefficients ψ_{Ei} as defined in EN 1998-1-1:—², 6.2.1(3), for the masses associated to variable actions should be calculated with the minimum values ϕ according to EN 1998-1-2:—³, 5.1.2(1), and the combination factors $\psi_{2,i}$ as given in EN 1990:2023, Annex A, unless otherwise defined in Clause 5 to 10.

(4) Soil-structure interaction effects should be considered using models provided in EN 1998-5:—⁴, 8, whenever they may have an adverse influence on the response of the structural system and its ancillary elements. Beneficial soil-structure interaction effects should be modelled in a conservative manner.

(5) The specific behaviour factors for structures addressed in this standard as given in 1.1(1) should be applied according 5 to 10.

4.5 Combination of the effects of the components of the seismic action

(1) If the force-based approach is used, the structural response of the three components of the seismic action should be evaluated separately and combined. If the structure is not perfectly axisymmetric in plan, combination should be performed according to EN 1998-1-1:—², 6.4.4.

(2) For axisymmetric structures in plan (e.g. on-ground vertical cylindrical silos and tanks, tubular towers), only the vertical and one horizontal component of seismic action should be evaluated, where the latter should be multiplied by a factor of 1,12. The action effect due to the combination of the vertical and horizontal component should be calculated using Formulas (4.1) and (4.2):

$$1,12 E_{Edx} + 0,30 E_{Edz} \quad (4.1)$$

$$0,34 E_{Edx} + 1,00 E_{Edz} \quad (4.2)$$

NOTE The factor 0,34 is the result of $0,30 \times 1,12$ using the combination according to EN 1998-1-1:—², 6.4.4.

(3) If non-linear response-history analysis is applied, the seismic action should be applied simultaneously in three directions. The input motions for response history analysis and the spatial model of the seismic action should be defined in accordance to EN 1998-1-1:—², 5.2.3 unless otherwise defined in Clause 5 to 10.

(4) If non-linear static analysis is applied, the lateral seismic forces should be applied in the most unfavourable direction with both positive and negative signs. The maximum seismic action effects resulting from both cases should be used. Seismic action effects due to the combination of the horizontal components of the seismic action, the effects of higher modes, torsion and minimum eccentricity should be evaluated according to EN 1998-1-2:—³, 5.3.5.

4.6 Material requirements

4.6.1 Design to DC1, DC2 and DC3

(1) Unless otherwise specified for particular types of structures in the relevant clauses of this document, the material specific rules according to EN 1998-1-2:—³, 10 to 15, should be applied.

4.6.2 Safety verifications

(1) For Significant Damage (SD) limit state verification, partial factors according to EN 1998-1-2:—³, 8 to 15, not lower than 1, should be used, unless otherwise specified for particular types of structures in the relevant clauses of this document.

4.7 Verification to limit states

4.7.1 General

(1) The seismic performance of the structures shall be verified according to EN 1998-1-1:—², 4.4.

(2) In the seismic design situation, it should be verified that the action effects defined in EN 1990:2023, 8.3.4.4, do not exceed the corresponding resistance of structural elements according to EN 1990:2023, 8.3.5, for the specified limit states.

(3) The verifications in 4.7.1(2) may be considered as satisfied if the total base shear over the entire specific structures of this part at the base level of the structure (foundation or top of a rigid basement for structures, points of attachment to the structure for ancillary elements) in the seismic design situation is less than the corresponding base shear in other design situations. The total base shear should be calculated with the force-based approach with a behaviour factor of $q = 1,0$ using the elastic design spectrum given in EN 1998-1-1:—².

NOTE 1 For example, this can be the case in regions where the wind action can be higher than the seismic action.

NOTE 2 The definition and verification of the NC limit state is not covered in this document. EN 1998-3:—⁵ provides rules for the verification of the NC limit state for existing buildings and structures.

NOTE 3 Due to resonance phenomena in ancillary elements, when clause (3) applies at the level of the supporting structure, it does not necessarily imply that it also applies for the ancillary elements themselves, which can still need to be checked under the seismic design situation.

NOTE 4 The comparison of seismic base shear with that due to other actions can be insufficient for structural members where higher modes of vibration contribute more than the fundamental mode.

⁵ Under preparation. Stage at the time of publication: prEN 1998-3:2023.

4.7.2 Verification of Significant Damage (SD) limit state

(1) The non-exceedance of the SD limit state for the specific structures given in 1.1(1) should be verified according to Clause 5 to 10.

4.7.3 Verification of Damage Limitation (DL) limit state

(1) When appropriate, the DL limit state for the specific structures given in 1.1(1) should be verified according to Clause 5 to 10.

4.7.4 Verification of Fully Operational (OP) limit state

(1) When appropriate, the OP limit state for the specific structures given in 1.1(1) should be verified according to Clause 5 to 10.

5 Rules for silos

5.1 Scope

(1) Clause 5 gives rules for the structural analysis and design of steel, reinforced concrete and prestressed precast reinforced concrete silos subjected to seismic actions.

NOTE A distinction is made between:

- on-ground;
- elevated silos, supported on a skirt extending to the ground or by substructures.

5.2 Basis of design

5.2.1 Design concept

(1) The effects of horizontal and vertical components of the seismic action considered on silos should be seismic induced stresses and deformations in the silo wall and seismic forces and moments applied to substructures and foundations.

(2) The principles of the seismic analysis procedures may also be applicable for silos made of other materials (e.g. glass fibre-reinforced plastic/polymer (GFRP), high density polyethylene (HDPE) or polyethylene (PE)).

NOTE The definitions of limit states and safety verifications for materials other than those in (2) are not covered by this document.

(3) Silos should be designed in DC1.

(4) Substructures of elevated silos may be designed according to ductility classes DC1, DC2 or DC3.

(5) If seismic protection is provided through base isolation or energy dissipation systems, the design provisions in EN 1998-1-1:—², 6.8, and in EN 1998-1-2:—³, Clauses 8 and 9, should be applied.

5.2.2 Safety verification

(1) Partial factors $\gamma_{M,i}$ should comply with EN 1998-1-2:—³.

(2) Partial factors $\gamma_{M,i}$ given by EN 1993-4-1:—⁶, 2.9.2.2, should be used for the limit state verifications of the shell and hopper of steel silos.

(3) Overstrength effects that may occur in the substructure of silos designed in DC2 or DC3 should be considered in verifications.

5.3 Modelling and structural analysis

5.3.1 Modelling

(1) The dynamic calculation model of the silo should reproduce accurately the strength, the damping, the geometrical properties and the stiffness and mass distribution of the silo, containment structures, external ancillary elements, connecting pipes, extensions rigidly connected to the silo and the substructure.

(2) The dynamic effects of the silo content should be considered by additional structural masses assuming that the particulate content moves together with the silo shell. The distribution of the masses should reproduce the dynamic effects of the silo content. The effects of the content should be considered

⁶ In development.

up to the part of the wall that is in contact with the stored contents, corresponding to the part on which static pressures are exerted according to EN 1991-1-4:—¹, 1.2.

(3) The silos may be idealised by simple beam models with distributed masses. Elevated silos should be modelled with their substructures. In case the silo and the substructure are modelled separately, their frequencies should differ by more than 20 %. In case of squat or retaining silos according to EN 1991-1-4:—¹, 7.1, shell models for the silo wall and rigidly connected volume elements for the content may be used to account for the load transfer by friction and shear at the silo bottom.

(4) Steel silos with or without substructures may be analysed assuming linear elastic behaviour according to EN 1993-1-6:—⁷, 2.2. If the silo shell is modelled, the modelling rules according to EN 1993-1-6:—⁷, 5.2, should be applied.

(5) Reinforced concrete and prestressed precast reinforced concrete silos with or without substructures may be analysed assuming linear elastic behaviour according to EN 1992-1-1:—⁸.

(6) Soil-structure interaction effects should be taken into account in accordance with EN 1998-5:—⁴, Clause 8, with respect to the type of foundation.

(7) The mass of the content should be determined in accordance with EN 1991-1-4:—¹, Annex C, using the upper characteristic value of the bulk unit weight γ_u of the particulate solid. If the specific bulk material is not given in EN 1991-1-4:—¹, Annex C, the characteristic value of the bulk unit weight may be determined by material tests.

NOTE The owner or other parties to the project can provide the value of the bulk unit weight.

(8) The dynamic effects should be calculated for the maximum filling level determined based on operating conditions. Intermediate filling levels may be taken into account, if the corresponding structural periods for the empty or full silo straddle the upper corner period T_c of the applied response spectrum, as defined in EN 1998-1-1:—², 5.2.2.2 (1).

(9) In batteries of silos, different likely distributions of full, intermediate filled and empty silos should be considered according to the operation rules of the facility. In each of the silos, only symmetrical filling loads should be considered.

(10) In silos internally subdivided in several cells, the most unfavourable distribution of full, intermediate filled and empty cells should be considered to account for unsymmetrically loading conditions under seismic actions.

5.3.2 Structural analysis

(1) Except when (2) or (3) are applied, on-ground or elevated silos should be calculated with the force-based approach using calculation models specified in 5.3.1(3).

(2) Silos with or without substructures may be analysed with non-linear approaches according to EN 1993-1-6:—⁷, 2.2, using non-linear response-history analysis and application rules given in EN 1998-1-1:—², 6.6.

NOTE Non-linear static analysis of silos with or without substructures are not covered by this document.

(3) The substructures of elevated silos may be analysed using non-linear static or non-linear response-history analysis according to EN 1998-1-1:—², 6.5 and 6.6.

(4) If non-linear response-history analysis is performed, damping ratios of 2 % for bolted and welded steel, 5 % for reinforced concrete and 2 % for prestressed precast reinforced concrete silo structures should be used.

⁷ Under preparation. Stage at the time of publication: prEN 1993-1-6:2023.

⁸ Under preparation. Stage at the time of publication: FprEN 1992-1-1:2023.

5.3.3 Behaviour factors

5.3.3.1 Behaviour factor for the horizontal components of the seismic action

5.3.3.1.1 Silos

(1) The behaviour factor components for silos in DC1 should be applied as given in a) and b):

- a) bolted and welded steel silos: $q_R = 1,0$, $q_D = 1,0$, $q_S = 1,2$;
- b) reinforced concrete or prestressed precast reinforced concrete tanks: $q_R = 1,0$, $q_D = 1,0$, $q_S = 1,5$.

5.3.3.1.2 Substructures of elevated silos

(1) The behaviour factors for substructures of elevated silos in DC1, DC2 and DC3 should be applied as given in the relevant parts of EN 1998-1-2:—³.

5.3.3.2 Behaviour factor for the vertical component of the seismic action

(1) The behaviour factor q_v for the silo and any substructure should be applied as $\min(q; 1,5)$, where q is the behaviour factor for the horizontal component of the seismic action applied to the silo per 5.3.3.1.1.

5.4 Seismic loads according to the force-based approach

5.4.1 Total base shear, overturning moment and vertical reaction force at the silo bottom

(1) The total base shear F_b , overturning moment M_b and vertical reaction force F_{bv} at the silo bottom with or without substructures should be calculated with a response spectrum analysis according to EN 1998-1-1:—², 6.4.2, by using the calculation models specified in 5.3.1(3) and the combination of the effects of the seismic action as given in 4.5.

(2) The lateral forces method of analysis according to EN 1998-1-2:—³, 5.3.3, may be applied for on-ground silos. In this case the base shear, the vertical reaction force and the overturning moment in each horizontal direction may be calculated as given in Formulas (5.1) to (5.3).

$$F_b = S_r(T_{1h}) m_S \lambda \quad (5.1)$$

$$F_{bv} = S_{rv}(T_{1v}) m_S \quad (5.2)$$

$$M_b = S_r(T_{1h}) m_S \lambda \frac{H_f}{2} \quad (5.3)$$

where

T_{1h}	is the fundamental period of vibration of the silo structure in the horizontal direction under consideration;
T_{1v}	is the fundamental period of vibration in the vertical direction;
$S_r(T_{1h})$	is the ordinate of the reduced spectrum in horizontal direction at period T_{1h} as defined in EN 1998-1-1:— ² , 6.4.1(5);
$S_{rv}(T_{1v})$	is the ordinate of the reduced spectrum in vertical direction at period T_{1v} ; the maximum spectral acceleration in the constant acceleration range may be applied, if the period T_{1v} is not explicitly calculated;
m_S	is the total mass of the silo and its content, calculated with the upper characteristic value of the bulk unit weight γ_u as defined in 5.3.1(7);

λ is the reduction factor used in lateral force method taken between $\lambda = 0,8$ to $1,0$;

H_f is the height of the maximum design filling level of the silo content.

(3) The base shear F_b and overturning moment M_b in each horizontal direction may be calculated for cylindrical on-ground silos with radius R without taking into account grain-wall friction effects, as given by Formulas (5.4) and (5.5).

NOTE These Formulas are more accurate than Formulas (5.2) and (5.3) in this particular case.

$$F_b = S_r(T_{1h}) \rho_u \pi R^2 H_f \left(1 - \frac{R}{6H_f}\right) \quad (5.4)$$

$$M_b = S_r(T_{1h}) \rho_u \pi \frac{R^2}{2} \left(H_f^2 - \frac{R^2}{27}\right) \quad (5.5)$$

where ρ_u is the density calculated with the upper characteristic value of the bulk unit weight γ_u as defined in 5.3.1(7).

5.4.2 Seismic pressures on silo walls and hoppers due to the horizontal seismic actions

5.4.2.1 Reference normal pressure

(1) The seismic loads on silo walls should be calculated using an acceleration profile over the silo height, which is described in terms of the function $\alpha(z)$ corresponding to the ratio of the response acceleration at a depth z from the equivalent surface of the stored content over the acceleration of gravity.

(2) The function of the response acceleration $\alpha(z)$ should be calculated with a response spectrum analysis according to EN 1998-1-1:—2, 6.4.3, by using the calculation models specified in 5.3.1(3) and the combination of the effects of the seismic action as described in 4.5. Alternatively, $\alpha(z)$ may be approximated by linear a linear response acceleration profile between the response accelerations at the silo bottom and the level of the equivalent surface. In case of stiff silos, a constant response acceleration, calculated as the average of the response accelerations at the silo bottom and the level of the equivalent surface of the stored content, may be applied.

(3) The effect on the shell of the response of the particulate content to the horizontal components of the seismic action may be represented through an additional normal pressure on the wall, $\Delta_{ph,s}$. At points on the silo vertical wall at a vertical distance x from a flat bottom or the apex of a conical or pyramidal hopper, the reference pressure normal to the wall $\Delta_{ph,so}$ may be calculated using Formula (5.6).

$$\Delta_{ph,so} = \alpha(z) \gamma_u \min(h_b; d_c/2; 3x) \quad (5.6)$$

where

$\alpha(z)$ is the ratio of the response acceleration at a depth z from the equivalent surface of the stored content, to the acceleration of gravity;

γ_u is the upper characteristic value of the bulk unit weight of the particulate solid as defined in 5.3.1(7);

h_b is the overall height of the silo, from a flat bottom or the hopper outlet to the equivalent surface of the stored content as defined in EN 1991-1-4:—1, 1.2;

d_c is the inner dimension of the silo parallel to the horizontal component of the seismic action (inside diameter, d_c in circular silos or silo compartments, inside horizontal dimension b parallel to the horizontal component of the seismic action in rectangular ones) as defined in EN 1991-1-4:—1, 1.2.

(4) Within the height of a hopper, the reference normal pressure $\Delta_{ph,so}$ may be taken as given by Formula (5.7).

$$\Delta_{ph,so} = \alpha(z) \gamma_u \min(h_b; d_c/2; 3x) \cos \beta \quad (5.7)$$

where β is the angle of inclination of the conical hopper wall, measured from the vertical, or the steepest angle of inclination to the vertical of the wall in a pyramidal hopper and x is the vertical coordinate of a point on a silo wall from a flat silo bottom or the apex of a conical or pyramidal hopper as given in EN 1991-1-4:—1, 8.

5.4.2.2 Loads on walls in circular silos

(1) The additional normal pressure (Figure 5.1a) on the wall of circular silos (or silo compartments) may be taken at any level as equal to $\Delta_{ph,s}$ given by Formula (5.8).

$$\Delta_{ph,s} = \Delta_{ph,so} \cos \theta \quad (5.8)$$

where θ is the angle ($0^\circ \leq \theta < 360^\circ$) between the radial line to the point of interest on the wall and the direction of the horizontal component of the seismic action.

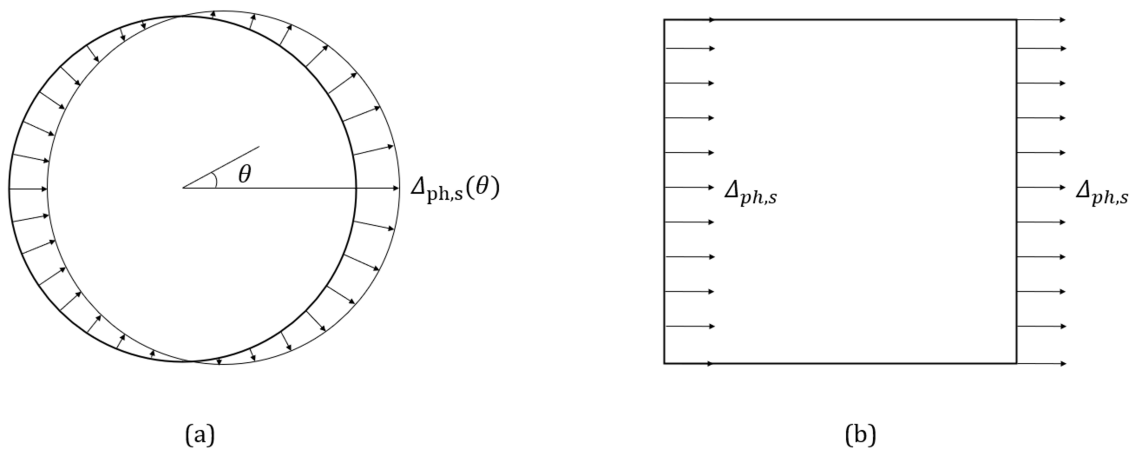


Figure 5.1 — Additional normal pressure in: (a) circular silos and (b) rectangular silos

5.4.2.3 Loads on walls in rectangular silos or silo compartments

(1) The additional normal pressure (Figure 5.1b) on the wall due to a horizontal component of the seismic action parallel or normal to the silo walls may be taken equal to one of the values given in a) to c):

- a) on the 'leeward' wall which is normal to the horizontal component of the seismic action, by Formula (5.9).

$$\Delta_{ph,s} = \Delta_{ph,so} \quad (5.9)$$

- b) on the 'windward' wall which is normal to the horizontal component of the seismic action, by Formula (5.10).

$$\Delta_{ph,s} = -\Delta_{ph,so} \quad (5.10)$$

c) on the walls parallel to the horizontal component of the seismic action, by Formula (5.11).

$$\Delta_{ph,s} = 0 \quad (5.11)$$

5.4.2.4 Loads on silo walls and hoppers due to vertical components of seismic actions

(1) The seismic action due to the vertical component should be considered by a scaling factor β_{sc} given in Formula (5.12), applied to the frictional pressures p_{wf} , the vertical pressures p_{vf} and the horizontal pressures p_{hf} for vertical silo walls, silo hoppers and silo bottoms, calculated according to EN 1991-1-4:-1, Clauses 7, 8 and 9.

$$\beta_{sc} = 1 + \frac{S_{rv}(T_{1v})}{g} \quad (5.12)$$

where S_{rv} is the ordinate of the reduced spectrum at period T_{1v} as defined in EN 1998-1-1:—2, 6.4.1(6).

5.4.2.5 Superposition with hydrostatic pressure

(1) The resulting pressure at any point on the silo wall should be the sum of the hydrostatic normal pressure p_0 of the particulate material on the wall and the normal pressure of the seismic action effect, $\Delta_{ph,s}$. If at any position on the silo wall the sum is negative (implying net suction on the wall), the resulting pressure should be set to zero and the negative pressure should be added to the opposite compression-loaded side of the silo wall. If $p_0 < \Delta_{ph,s}(\theta)$, the increased additional normal pressure $\Delta_{ph,s,inc}(\theta)$ on the compression-loaded side may be calculated as given by Formula (5.13).

$$\Delta_{ph,s,inc}(\theta) = \Delta_{ph,s}(\theta) + |p_0 - \Delta_{ph,s}(\theta)| \quad (5.13)$$

5.5 Verification to limit states

5.5.1 General

(1) It should be verified that the action effects in the design seismic situation do not exceed the corresponding resistances of the silo, the substructure and the foundation, including connections, relevant ancillary elements and connecting pipes for the specified limit states. The verification of structural members should comply with EN 1998-1-2:—3, Clause 6.

5.5.2 Verification of Significant Damage (SD) limit state

(1) In application of EN 1998-1-1:—2, 6.2, the SD limit state may be considered as verified if the conditions in 5.5.2.1 to 5.5.2.5 in the seismic design situation are met.

5.5.2.1 Global stability

(1) Silos with or without substructures should be verified for overturning and sliding for the total base shear, overturning moment and vertical reaction force calculated according to 5.4.1. Limited sliding of the silo may be accepted, if it is demonstrated that the implications of sliding for the connections between the various parts of the structure and between the structure and any piping are taken into account in the analysis and the verifications.

(2) Uplift of on-ground silos should be avoided by sufficient anchorage according to 5.5.2.5.

5.5.2.2 Foundations

(1) Silo foundation systems should be verified in accordance with EN 1998-5:—4, Clause 9 for the supporting loads according to 5.4.1.

5.5.2.3 Silo shell and hopper

- (1) The seismic action effects in the silo shell and hopper (membrane forces and bending moments, circumferential or meridional, and membrane shear) should be calculated in the seismic design situation.
- (2) Steel silos should be verified in the seismic design situation according to EN 1993-4-1:—⁶, Clauses 5 to 9.
- (3) Reinforced concrete and prestressed precast reinforced shells should be verified according to EN 1992-3 and EN 1992-1-1:—⁸.

5.5.2.4 Substructures of elevated silos

- (1) Substructures of elevated silos should be verified in the seismic design situation according to the relevant clauses of EN 1998-1-2:—³.

5.5.2.5 Anchorage systems

- (1) Anchorage systems of silo structures to their foundation should be designed to remain elastic in the seismic design situation. The anchorage systems should be designed by applying the capacity design principle taking into account all relevant overstrength effects of the silo and its substructure. For DC2 and DC3 the overstrength factors should be applied according to the relevant clauses of EN 1998-1-2:—³. For all ductility classes, a minimum overstrength factor of 1,25 should be used.
- (2) The anchorage systems of silo structures to their foundation should be provided with sufficient ductility to avoid brittle failures in case the seismic loads are exceeded. Therefore, the strength associated to the steel anchorage plastic mechanism should be smaller than the resistance associated to brittle failure of concrete, also accounting for overstrength of the former. The design principles in accordance with EN 1998-1-1:—², Annex G, should be applied.
- (3) Installed anchors should sustain the seismic action effects in tension, shear and combined tension and shear to which they are subjected in the design seismic situation while providing adequate resistance to failure (ultimate limit state) according to EN 1998-1-1:—², Annex G.

NOTE Fasteners of category C1 provides capacities only in term of resistances at ultimate limit state, while fasteners of category C2 provides capacities in terms of both resistances at ultimate and displacements at damage limitation state and ultimate state. The requirements for category C2 are more stringent compared to those for category C1. The performance category valid for a fastener is given in the corresponding European Technical Product Specification.

- (4) Pre-installed anchors should be designed to resist the effects of the seismic design loads according to EN 1993-1-8:—¹⁰. They should provide design resistance to tension due to uplift forces and bending moments where appropriate. One of the methods in a) to d) should be used to secure anchor bolts into the foundation:

- a) a hook;
- b) a washer plate;
- c) some other appropriate load distributing member embedded in the concrete;
- d) some other fixing which has been adequately tested and approved.

- (5) Structural connections between the silo structure and ancillary elements or connecting pipes should be designed to remain elastic in the seismic design situation. The connections should be capacity designed, taking into account all relevant overstrength effects of the components and connecting pipes.

5.5.2.6 Inlets, outlets, pipes and ancillary elements

(1) Inlets, outlets and further pipes should be verified to accommodate stresses and distortions due to relative displacements between silos, between silos and adjacent structures and between silos and the foundation (EN 1998-1-1:—², 5.2.2.4), without their functions being impaired.

(2) If connected pipes induce too high local stresses in the thin walls of steel tanks, flexible connections may be provided by the use of armoured hoses, compensators, swing arm joints or arrangement of flexible bend configurations.

(3) In case of silos with base isolation, the deformation compatibility of the structure and the ancillary elements connecting the silo to the ground or to adjacent structures should be verified.

(4) Anchorages of ancillary elements (e.g. conveyors, screw feeders) should be verified in the design seismic situation for the SD limit state according to 9.

NOTE The seismic verification of the ancillary elements burdens the producer and is not covered in this document.

5.5.3 Verification of Damage Limitation (DL) limit state

5.5.3.1 Silo shell and hopper

(1) The DL limit state may be considered as verified when the silo shell, the hopper, the substructure, the anchorage, connecting pipes and connections of ancillary elements resist the seismic actions in the elastic range.

NOTE Additional verifications at DL limit state applied to silos can be specified by a relevant authority or can be found in the National Annex or can be elsewhere be provided by the relevant Authorities.

5.5.4 Verification of Fully Operational (OP) limit state

(1) It should be verified that strains (or generalised deformations such as drifts) resulting from the corresponding seismic design situation do not exceed values that are acceptable to maintain the function of the silo and associated equipment.

(2) Criteria applicable to the silo and associated equipment, in addition to EN 1998-1-1:—², 6.7.3(7), should be derived from the analysis of the components the operability of which is required, as well as from the analysis of their supporting systems.

NOTE For a specific project, the relevant parties can specify all components of interest in the verification, together with a description of relevant damage states for each component and the associated requirements.

6 Rules for tanks

6.1 Scope

(1) Clause 6 gives rules for the structural analysis and design of steel, reinforced concrete and prestressed precast reinforced concrete liquid storage tanks with circular and rectangular cross sections subjected to seismic actions.

(2) This clause gives rules for anchored and unanchored tanks with fixed or floating roofs.

NOTE A distinction is made between:

- above-ground;
- underground;
- elevated tanks, supported by substructures.

6.2 Basis of design

6.2.1 Design concept

(1) The effects of horizontal and vertical components of the seismic action considered on tanks should be seismic induced stresses and deformations in the tank wall and seismic forces and moments applied to substructures and foundations.

(2) The principles of the seismic analysis procedures may also be applicable for tanks made of other materials (e.g. glass fibre-reinforced plastic/polymer (GFRP), high density polyethylene (HDPE) or polyethylene (PE)).

NOTE The definitions of limit states and safety verifications for materials other than those in (2) are not covered by this document.

(3) Tanks should be designed in DC1.

(4) Substructures of elevated tanks may be designed according to ductility classes DC1, DC2 or DC3.

(5) If seismic protection is provided through base isolation or energy dissipation systems, the design provisions in EN 1998-1-1:—², 6.8, and in EN 1998-1-2:—³, 8 and 9 should be applied.

6.2.2 Safety verification

(1) Partial factors $\gamma_{M,i}$ should comply with EN 1998-1-2:—³.

(2) Partial factors $\gamma_{M,i}$ given by EN 1993-4-2:—²¹, 2.9.2.2, should be used for the limit state verifications of the shell and of steel tanks.

(3) Overstrength effects that may occur in the substructure of tanks designed in DC2 or DC3 should be considered in verifications.

6.3 Modelling and structural analysis

6.3.1 Modelling

(1) Dynamic calculation models of the tank should reproduce accurately the stiffness, the strength, the damping, the mass and the geometrical properties of the tank structure and should account for the hydrodynamic response of the contained liquid.

(2) Dynamic calculation models should properly consider effects in a) to e), where relevant:

- a) sloshing of the liquid at the free surface (convective component);
- b) horizontal and vertical movement of the liquid together with the rigid tank (impulsive component);
- c) fluid-structure vibrations of the tank and the liquid in case of flexible tanks (impulsive flexible component);
- d) soil-structure-interaction;
- e) sliding and uplift in case of unanchored tanks.

(3) For the purpose of evaluating the dynamic response under seismic actions, the liquid may be assumed as incompressible.

(4) Steel tanks with or without substructures may be analysed assuming linear elastic behaviour according to EN 1993-1-6:—⁷, 2.2. If the tank shell is modelled, the modelling rules according to EN 1993-1-6:—⁷, 5.2, should be applied.

(5) Reinforced concrete and prestressed precast reinforced concrete tanks with or without substructures may be analysed assuming linear elastic behaviour according to EN 1992-1-1:—⁸.

(6) Soil-structure interaction effects should be taken into account in accordance with EN 1998-5:—⁴, Clause 8 with respect to the type of foundation.

(7) The mass of the liquid should be determined in accordance with EN 1991-1-1:—²⁰, Annex A, using the specified liquid weights γ . If the specific liquid is not given in EN 1991-1-1:—²⁰, Annex A, the liquid weight should be taken from reliable sources, or may be determined by material tests.

NOTE The owner or other parties to the project can provide the value of the liquid weight.

(8) The dynamic effects should be calculated for the maximum filling level determined based on operating conditions. Intermediate filling levels may be taken into account, if the corresponding vibration periods for the empty or full tank straddle the upper corner period T_c of the applied response spectrum, as defined in EN 1998-1-1:—², 5.2.2.2 (1).

(9) Tank structures may be analysed with three-dimensional fluid-structure interaction simulation models, which are able to represent the hydrodynamic pressures on the tank shell and bottom under seismic excitation, soil-structure interaction effects as well as sliding and uplift in case of unanchored tanks.

(10) The convective, impulsive and impulsive flexible seismic action effects due to horizontal and seismic actions may be calculated separately with dynamic calculation models, in which the hydrodynamic effects of the liquid are considered by additional structural masses on the tank wall.

(11) The calculation model for tanks under horizontal seismic actions may be represented by spring-mass models which describe the hydrodynamic response by impulsive rigid, impulsive flexible and convective masses with corresponding lever arms (Figure 6.1).

(12) The calculation model for tanks under vertical seismic actions should represent the impulsive rigid response by the total liquid mass rigidly connected to the tank bottom and the impulsive flexible response with the total liquid mass connected by a spring to the tank bottom.

(13) Rigid tanks may be analysed without consideration of the flexible impulsive vibration modes in horizontal and vertical directions.

(14) Mass inertia effects of the tank wall, roof and ancillary elements should be considered for rigid and flexible tanks.

(15) Sliding and uplift of unanchored tanks may be considered in the calculation models by contact formulations or nonlinear springs.

NOTE The seismic loads are defined with the notations and key given in Figure 6.1.

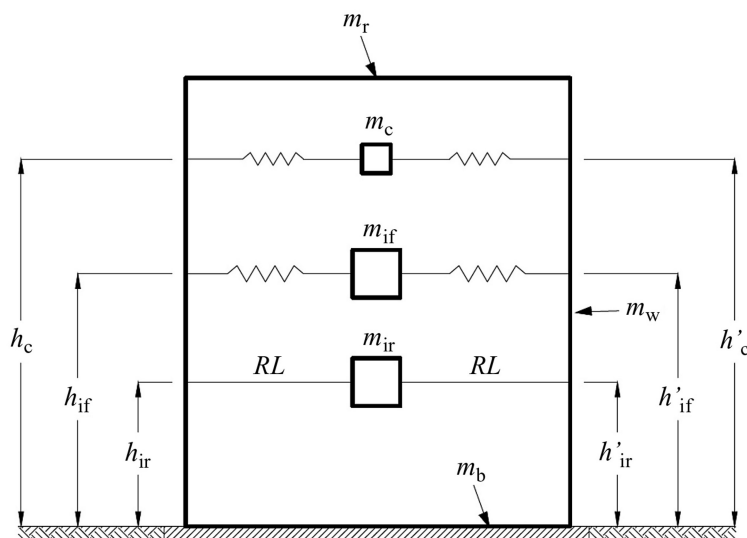


Figure 6.1 — Spring mass model and notations for tanks under horizontal seismic actions

Key

RL	rigid link
m_l	total liquid mass
m_w, m_b, m_r	masses of the tank wall, tank bottom and tank roof
m_{ir}, m_{if}, m_c	equivalent impulsive rigid, impulsive flexible and convective masses as defined in 6.4.1.4 for vertical cylindrical tanks and in 6.5.1.4 for vertical rectangular tanks
h_{ir}, h_{if}, h_c	equivalent lever arms without consideration of the bottom pressure as defined in 6.4.1.4 for vertical cylindrical tanks and in 6.5.1.4 for vertical rectangular tanks
h'_{ir}, h'_{if}, h'_c	equivalent lever arms with consideration of the bottom pressure as defined in 6.4.1.4 for vertical cylindrical tanks and in 6.5.1.4 for vertical rectangular tanks
$T_{ir,h}, T_{if,h}, T_{con}$	first natural periods of the impulsive rigid, impulsive flexible and convective vibration modes as defined in 6.4.1.3 for vertical cylindrical tanks and in 6.5.1.3 for vertical rectangular tanks
$T_{ir,v}, T_{if,v}$	first natural periods of the impulsive rigid and impulsive flexible vibration modes in vertical direction as defined in 6.4.1.3 for vertical cylindrical tanks and in 6.5.1.3 for vertical rectangular tanks
$S_r(T_{ir,h})$	ordinate of the reduced spectrum in horizontal direction at period $T_{ir,h}$ as defined in EN 1998-1-1:— ² , 6.4.1(5) using the behaviour factor given in 6.3.3
$S_{rv}(T_{ir,v})$	ordinate of the reduced spectrum in vertical direction at period $T_{ir,v}$ as defined in EN 1998-1-1:— ² , 6.4.1(6) using the behaviour factor given in 6.3.3
$S_e(T_{con})$	spectral acceleration obtained from a horizontal elastic response spectrum as defined in EN 1998-1-1:— ² , 5.2.2.2(1), corresponding to the convective period T_{con} and to the damping ratio of the liquid of 0,5% (6.3.2(5)); for convective periods longer than 4,0 s, EN 1998-1-1:— ² , 5.2.2.2(13), should be used
$S_r(T_{if,h})$	ordinate of the reduced spectrum in horizontal direction at period $T_{if,h}$ as defined in EN 1998-1-1:— ² , 6.4.1(5) using the behaviour factor given in 6.3.3
$S_{rv}(T_{if,v})$	ordinate of the reduced spectrum in vertical direction at period $T_{if,v}$ as defined in EN 1998-1-1:— ² , 6.4.1(6) using the behaviour factor as indicated in 6.3.3

NOTE Only the first fundamental periods are considered within the proposed force-based approach in this document.