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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.

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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.	



DRAFT International Standard

ISO/DIS 18407

Simplified design of prestressed concrete tanks for potable water

*Conception simplifiée du réservoir pour l'eau potable en béton
pré-armé*

ICS: 91.080.40

ISO/TC 71/SC 5

Secretariat: **KATS**

Voting begins on:
2025-08-19

Voting terminates on:
2025-11-11

This document is circulated as received from the committee secretariat.

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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.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation on the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 71, *Concrete, reinforced concrete and prestressed concrete*, Subcommittee SC 5, *Simplified design standard for concrete structures*.

This second edition cancels and replaces the first edition (ISO 18407:2018), which has been technically revised.

The main changes are as follows:

— xxxxxxxxxxxxxxxxxxxxxxxxx

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

The aim of this document is to provide rules for the design and construction of prestressed concrete water tanks to be built in less-developed areas of the world. The design rules are based on simplified worldwide-accepted strength models. This document is self-contained; therefore actions (loads) and simplified analysis procedures are included, as well as minimum acceptable construction practice guidelines.

A great effort was made to include self-explanatory tables, graphics and design aids to simplify the use of this document and provide procedures. Notwithstanding, the economic implications of the conservatism inherent in approximate procedures as a substitution to sound and experienced engineering should be a matter of concern to the designer who employs this document and to the owner who hires him.

A prestressed concrete tank for potable water generally comprises the roof, wall and base slab. The roof is made to entirely cover the top of the cylindrical wall so as to protect the water from contamination with rainwater, etc. In many cases, it is made in the form of a dome shaped like a convex disc cut off from a sphere. The wall is a vertical cylinder that forms a container for water in combination with the flat disc base slab. Normally, only the wall of a prestressed concrete water tank is made with prestressed concrete, while the roof and base slab are made with reinforced concrete. Prestress is generally applied to the wall using prestressing steel in the vertical and circumferential directions, but in some cases, prestress is applied only to the circumferential direction. For this reason, this document defines a prestressed concrete cylindrical tank as a structure having prestressing steel at least in the circumferential direction of the wall to apply prestress, so as to cover both types. Therefore, the roof, base slab and wall in the vertical direction may not necessarily be of prestressed concrete construction but may be of reinforced concrete construction.

A prestressed concrete water tank construction is generally adopted to preserve a water storage facility with the aim of preventing severe secondary disasters and allowing the standing water to be used as an emergency water supply. For this reason, it is required to be designed as a rule as a high degree of importance.

The minimum dimensional provisions contained in this document are intended to account for undesirable side effects that will require more sophisticated analysis and design procedures. Material and construction provisions are aimed at site-mixed concrete, as well as ready-mixed concrete and steel of the minimum available strength grades.

The earthquake-resistance provisions are included to account for the fact that numerous developing regions of the world occur in earthquake-prone areas. The earthquake resistance is based upon the employment of structural concrete walls (shear walls) that limit the lateral deformations of the structure and provide for its lateral strength.

This document contains provisions that can be modified by the National Standards Body due to local design and construction requirements and practices. The specifications that can be modified are indicated using ["boxed values"]. The National Standards Body is expected to review the "boxed values" and may substitute alternative definitive values for these elements for use in the national application of this document.

Simplified design of prestressed concrete tanks for potable water

1 Scope

This document provides guidelines for the planning, design and construction of a cylindrical tank constructed on the ground with prestressed concrete (PC) for use with potable water tank.

This document is applicable to PC tanks for potable water with a capacity of 30 000 m³ or less and the diameter-to-height ratio (D/H) from 1,0 to 3,0.

NOTE When designing and constructing a tank not covered by this document (reinforced concrete tanks, underground tanks, elevated tanks, etc.), a designer can refer to this document for common elements where possible.

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 1920-3, *Testing of concrete — Part 3: Making and curing test specimens*

ISO 1920-4, *Testing of concrete — Part 4: Strength of hardened concrete*

ISO 6934-1, *Steel for the prestressing of concrete — Part 1: General requirements*

ISO 6934-2, *Steel for the prestressing of concrete — Part 2: Cold-drawn wire*

ISO 6934-3, *Steel for the prestressing of concrete — Part 3: Quenched and tempered wire*

ISO 6934-4, *Steel for the prestressing of concrete — Part 4: Strand*

ISO 6934-5, *Steel for the prestressing of concrete — Part 5: Hot-rolled steel bars with or without subsequent processing*

ISO 6935-1, *Steel for the reinforcement of concrete — Part 1: Plain bars*

ISO 6935-2, *Steel for the reinforcement of concrete — Part 2: Ribbed bars*

ISO 6935-3, *Steel for the reinforcement of concrete — Part 3: Welded fabric*

ISO 12439, *Mixing water for concrete*

ISO 14654, *Epoxy-coated steel for the reinforcement of concrete*

ISO 14824-3, *Grout for prestressing tendons — Part 3: Test methods*

3 Terms and definitions

For the purposes of this document, the following terms and definitions 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 <https://www.electropedia.org/>

3.1

bending analysis

method for determining the membrane force and bending moment in consideration of the boundary conditions at the base of the dome

3.2

clearance

distance between the designed high-water level and the upper edge of the tank wall

3.3

convective pressure

hydrodynamic pressures on the tank during an earthquake due to the upper (sloshing) portion of contained water

3.4

cylindrical prestressed concrete tank

concrete tank comprising the roof, cylindrical wall and base slab, for which prestressing steel is provided at least in the circumferential direction to apply prestress

3.5

disc part

part other than the ring plate of the base slab that resists bending moments

3.6

dome ring

circular beam provided along the base of the roof of a spherical or other shape of the dome to control radial displacement at the base of the roof

3.7

dynamic water pressure

water pressure due to the effect of an earthquake

3.8

embedded system

system of applying prestress, whereby circumferential prestressing steel is provided within concrete members

3.9

fixed support

wall-bottom connection whereby the rotation or horizontal displacement of the wall with respect to the bottom is not allowed

3.10

foundation slab

reinforced concrete or prestressed concrete slab provided in contact with the bottom surface of the base slab

3.11

freely sliding support

wall-bottom connection, whereby the rotation and horizontal displacement of the wall with respect to the bottom are allowed

3.12

hinged support

wall-bottom connection, whereby the rotation of the wall with respect to the bottom is allowed

3.13

hoop tension

circumferential axial tensile force generated by such loads as water pressure

3.14

horizontal thrust

horizontal component of the axial force in the meridian direction of the dome at the base of the dome

3.15

Housner method

conventional approximate analysis method for liquid vibration proposed by G. W. Housner

3.16

imposed load

load of portions not directly included in the design calculation as structural members and load applied to the roof for such purposes as inspection

3.17

impulsive pressure

dynamic water pressure (3.7) in response to short-period components of an earthquake and water pressure associated with inertia force produced by accelerations of the tank wall and directly proportional to these accelerations

3.18

inertia force

force given by the product of the mass of the structure and the structural response acceleration due to ground motion by earthquake

3.19

in-plane shear force

shear force that acts parallel to the shell surface

3.20

membrane floor

part other than the ring plate of the base slab that does not resist bending moments

3.21

membrane force

in-plane axial force of a shell structure

3.22

out-of-plane shear force

shear force that acts at a right angle to the shell surface

3.23

particular load

special load that acts depending on the natural conditions of the tank construction site

Note 1 to entry: Particular load is judged as a *primary load* (3.25) or a *subsidiary load* (3.31) on a case-by-case basis.

3.24

pilaster

rectangular projections from the tank wall along its generatrix lines for anchoring circumferential prestressing steel

3.25

primary load

load that constantly acts

3.26

ring plate

peripheral part of the base slab for transmitting forces primarily from the tank wall to the ground

3.27

sloshing

vibration of a solid oscillating surface generated in response to relatively long-period components of an earthquake

3.28

spherical dome

curved shell in the form of a part of a sphere cut off by a plane

3.29

subsidiary load

load that rarely acts

3.30

tank empty condition

state in which no water is present in the tank

3.31

tank full condition

state in which the water level in the tank reaches the design high water level

3.32

velocity potential method

method for a theoretical solution to irrotational vibration of a non-compressive and non-viscous fluid

3.33

waterstop

plate inserted in joints between concrete lifts and the wall-bottom joints for waterstopping

4 Symbols

A	projection area
A_{ep}	area subjected to the effect of anchorage set
A_b	area of concrete subjected to bearing load
A_c	cross-sectional area of member
A_c	cross-sectional area of concrete
A_c	total area of concrete surface
A_d	surface area of dome
A_i	cross-sectional area of element i
A_p	cross-sectional area of prestressing steel
A_s	cross-sectional area of tensile reinforcement
b	member width
C	wind force coefficient
C_e	earth pressure coefficient
C_s	structure characteristic coefficient
C_z	correction factor by region
c	concrete cover depth
D	diameter of tank
D_{he}	correction factor dependent on damping constant

D_i	flexural stiffness of node i
D_η	response reduction ratio due to plastic deformability
E	elastic modulus
E_c	elastic modulus of concrete
E_p	elastic modulus of prestressing steel
E_s	elastic modulus of steel reinforcement
F_d	prestressing force applied to dome ring
f'_{cd}	design compressive strength of concrete
f'_{ck}	characteristic compressive strength of concrete
f_{pu}	tensile strength of prestressing steel
f_{py}	yield strength of prestressing steel
f_{sy}	yield strength of steel reinforcement
f_t	tensile strength of concrete
f_{ud}	design tensile strength of prestressing steel
f_{yd}	design yield strength of steel reinforcement and structural steel
g	gravitational acceleration
g_0	uniform pressure
H	height of tank
H	total water depth of tank
H_G	distance from the lower edge of tank wall to the point of action of the dome inertia force or other partial weight inertia force
H_h	length of thickened zone of tank wall (haunch height)
H_s	total height of earth pressure action
H_t	horizontal thrust
h	height from the ground surface
h_d	rise of dome
h_{rE}	height above the base of the wall to the centre of gravity of the impulsive lateral force excluding base pressure
h_{rI}	distance from tank bottom to solid mass point when dynamic water pressure acting on base slab is considered
h_{sE}	height above the base of the wall to the centre of gravity of the convective lateral force excluding base pressure
h_{sI}	distance from tank bottom to solid oscillating mass point when dynamic water pressure acting on base slab is considered

h_{th}	virtual thickness of member
I_i	second moment of area of element i
J_1	vessel function
K	flexural stiffness
K_h	design horizontal seismic coefficient
K_{h01}	standard horizontal seismic coefficient for Level 1 ground motion
K_{h02}	standard horizontal seismic coefficient for Level 2 ground motion
K_{h1}	design horizontal seismic coefficient for Level 1 ground motion
K_{h2}	design horizontal seismic coefficient for Level 2 ground motion
K_s	horizontal subgrade reaction modulus
K_v	vertical subgrade reaction modulus
K_{vi}	vertical spring constants of node i
K_{v1}	design vertical seismic coefficient for Level 1 ground motion
K_{v2}	design vertical seismic coefficient for Level 2 ground motion
$K_{\theta i}$	rotational spring constants of node i
k	spring constant of bearing
k_α	coefficient considering the characteristics of foundations
k_β	coefficient considering the rigidity of base slab
L_{rp}	ring plate length
L_w	water depth
l	length from the tension end of prestressing steel to the design cross-section
l_d	basic development length
l_{max}	maximum spacing of prestressing steel
l_p	length of prestressing steel
l_1	distance from the upper edge of tank wall to the starting point of the action of distributed load
l_2	distance from the upper edge of tank wall to the end point of the action of distributed load
M_a	corrected vertical bending moment
M_d	vertical bending moment of member
M_e	vertical bending moment at the bottom of tank wall generated by changes in the curvature radius of tank wall
M_{ri}	bending moment per unit length in the radial directions at node i
M_{ud}	design flexural fracture capacity

M_x	vertical bending moment
M_{xi}	bending moment at node i determined by planar frame analysis
$M_{x\phi}$	torsional moment
M_{x0}	vertical bending moment
M_0	restraining moment at the bottom of tank wall
M_{0c}	vertical bending moment at the bottom of tank wall with a constant thickness
M_{0e}	vertical bending moment at the bottom of tank wall generated by curvature changes when wall thickness is constant at t
M_{0f}	vertical bending moment at the bottom of tank wall
M_{0h}	vertical bending moment at the bottom of tank wall considering an increase in wall bottom thickness
$M_{0T}(x)$	moment at distance, x from the lower edge of tank wall
M_{0v}	vertical bending moment at the bottom of tank wall generated by the effect of Poisson's ratio due to vertical prestress when wall thickness is constant
$\overline{M_x}$	vertical bending moment obtained from axisymmetric analysis under equivalent load
M_ϕ	circumferential bending moment
$M_{\phi x}$	torsional moment
$M_{\theta i}$	bending moment per unit length in the circumferential directions at node i
M_ξ	vertical bending moment at ξ from the top of the wall
N_x	axial force in the vertical direction
$N_{xo}(x)$	vertical axial force at distance, x from the lower edge of tank wall
$N_{x\phi}$	in-plane shear force
N_ϕ	membrane force in the meridian direction
$N_{\phi d}$	membrane force per unit length of dome in the meridian direction
$N_{\phi x}$	in-plane shear force
$N_{\phi 0}$	circumferential axial force due to non-axisymmetric loads
N_θ	membrane force in the parallel direction
$N_{\theta d}$	membrane force per unit length of dome in the parallel direction
n	elastic modulus ratio ($=E_p/E_c$)
P	prestressing force in the vertical direction
P_{Fi}	concentrated load acting on node i
$P_{br}(r)$	maximum impulsive pressure acting on base slab
$P_{bs}(r)$	maximum convective pressure acting on base slab

P_i	tensile force of prestressing steel at the jack position
P_l	dynamic water pressure at the lower edge
P_r	horizontal impulsive force acting on the centre of gravity
P_s	horizontal convective force acting on the centre of gravity
P_{sh}	total earth pressure
P_{si}	concentrated load per unit length acting on node i
P_t	tensile force of prestressing steel at jack position after considering the set length
P_u	dynamic water pressure at the upper edge
P_w	wind load
$P_{wr}(\xi)$	maximum impulsive pressure acting on tank wall
$P_{ws}(\xi)$	maximum convective pressure acting on tank wall
P_x	tensile force of prestressing steel at design cross-section
P_{0l}	impulsive pressure at the lower edge
P_{1l}	convective pressure at the lower edge
P_{1u}	convective pressure at the upper edge
p	pressure at the bottom of tank wall
p_{sh}	earth pressure
$p_o(x)$	radial component of load
Q_a	load at the deformation limit
Q_a	design circumferential tensile capacity of member
Q_{cr}	cracking load of member
Q_e	elastic response axial tensile force
Q_{he}	circumferential axial tensile force of member by elastic analysis under an earthquake load calculated from design horizontal seismic coefficient
Q_{py}	load at yielding of prestressing steel
Q_{sy}	load at yielding of steel reinforcement
Q_x	out-of-plane shear force
Q_y	yield load of member
Q_y	virtual yield load of member
Q_0	restrained shear force at the bottom of tank wall
Q_ϕ	out-of-plane shear force
q	wind pressure

q_d	deadweight per unit area
q_l	imposed load per unit area
$q_o(x)$	circumferential component of load
q_0	unit weight of liquid
q_1	unit weight of tank wall
R	radius of tank wall
r	horizontal distance from the centre of tank
r	inside radius bent of steel reinforcement
r	radius of dome
r_h	ratio of secondary stiffness after yielding to yield stiffness
r_i	radius of node i
S_v	span of dome
S_v	velocity response spectrum
T	temperature difference
T	natural period of tank in a tank full condition
T_c	resultant force of tensile stress generated in concrete
t	tank wall thickness
t_b	base slab thickness
t_e	effective age of concrete when the creep factor is calculated
t_h	thickness of the bottom of tank wall
t_i	thickness of base slab at node i
$t_{\min}$	minimum thickness of tank wall
t_{rp}	thickness of ring plate
t_0	effective age of concrete when concrete is loaded
u	perimeter of member in contact with ambient air
V	tank volume capacity
V_d	vertical load per unit length in the circumferential direction at dome margin
W	total weight of contained water
W	dome weight or other partial weights
W_r	equivalent weight of the impulsive component of water
W_s	equivalent weight of the convective component of water

w_s	unit weight of soil
w_x	radial displacement of tank wall
w_{xo}	radial displacement of tank wall at the point of maximum dynamic water pressure
w_1	strength of uniformly distributed load
w_2	strength of triangularly distributed load
X	external force in x direction
x	distance from the lower edge of tank wall
x_t	distance from the tension edge of member to neutral axis
Y	external force in y direction
y_s	height of the point of action of earth pressure
Z	section modulus for the distance from the neutral axis to the compression edge when tank is assumed to be a thin-wall ring
Z	external force in z direction
α	angular change of prestressing steel
α	coefficient for the hardening rate of concrete
α_d	half angle of dome
α_e	linear expansion coefficient of concrete
α_p	correction factor for vertical bending moment at the bottom of tank wall due to change in the curvature radius of tank wall
α_r	response acceleration of the impulsive component of water
α_s	response acceleration of the convective component of water
α_0	correction factor
α_1	pressure gradient
β	characteristic value of tank wall
$\beta_d(t_e - t_0)$	function related to effective number of days after loading, $(t_e - t_0)$
$\beta_f(t_e)$	function related to effective age of concrete, t_e , and virtual thickness of member, h_{th}
$\beta_f(t_0)$	function related to effective age of concrete, t_0 , and virtual thickness of member, h_{th}
β_1	pressure at the lower edge of tank wall
γ	relaxation ratio of prestressing steel
γ_b	member factor
γ_i	structure factor
γ_m	material factor

γ_0	inner diameter-water depth ratio ($=D/H$)
ε	strain in general
ε_{cr}	cracking strain of member
ε_{py}	yield strain of prestressing steel
ε_r	circumferential response strain
ε_{ra}	circumferential strain limit determined from securing of watertightness
ε_{sy}	yield strain of steel reinforcement
ε_y	virtual yield strain of member
ε'_c	creep strain of concrete
ε'_s	drying shrinkage of concrete
η	effectiveness coefficient
η	mean cumulative plastic magnification
η_r	mean magnification of cumulative plastic deformation
θ	angle of seismic action to the horizontal plane
λ	friction coefficient per unit length of prestressing steel
λ_e	environmental factor
δ_y	yield deformation
δ_0	cumulative plastic deformation
μ	friction coefficient per radian of angle change
ν	Poisson's ratio
ξ	vertical distance from the water surface
ξ	vertical distance from the upper edge of tank wall
ρ	unit weight of water
ρ_c	unit weight of concrete
σ	stress in general
σ_c	tensile stress of concrete
σ_c	stress of concrete
σ_{pe}	effective tensile stress of prestressing steel
σ_{pt}	tensile stress of prestressing steel immediately after prestressing
σ_{sa}	tensile stress limit of reinforcement
σ'_{ba}	bearing stress limit of concrete

σ'_c	compressive stress of concrete
σ'_{ca}	compressive stress limit of concrete
σ'_{cp}	stress of concrete under sustained load at the position of prestressing steel
σ'_{cpg}	concrete stress at the centroid of prestressing steel due to prestressing
σ'_{cpt}	prestress immediately after prestressing at the position of prestressing steel
Δl	set length
ΔP	tensile force loss of prestressing steel due to setting of prestressing steel
Δt	number of days when the temperature is T
π	circular constant
$\Delta\sigma_p$	tensile stress loss of prestressing steel due to elastic deformation of concrete
$\Delta\sigma_{py}$	tensile stress loss of prestressing steel due to relaxation of prestressing steel
$\Delta\sigma_{p\varphi}$	tensile stress loss of prestressing steel due to creep, drying shrinkage and autogenous shrinkage of concrete
ϕ_d	angle from the rotation axis at an arbitrary point of dome
ϕ_i	deflection angle at node i determined by planar frame analysis
ϕ_s	internal friction angle of soil
φ	creep factor for concrete
φ_{d0}	basic creep factor for delayed elastic strain
φ_{f0}	basic creep factor for flow strain
ω_s	s -th natural circular frequency

5 Design principles

To design the PC water tank safe under loads application, its construction site shall be carefully selected through investigation on topography, geology and past disaster records. It is necessary to conduct ground surveys at the stage of structural planning according to the state of the site and the type and size of the water PC tank.

The elastic method should be adopted with regard to safety and serviceability of members of the PC water tank; that is, the serviceability and ultimate limit states, respectively. Safety of members in an ordinary state shall be investigated by confirming that the stresses of concrete, prestressing steel and steel reinforcement under loads are equal to or less than the stress limits specified in [Clause 8](#) that are determined based on the corresponding limit state. The primary purpose of the design of a PC water tank is to secure its watertightness in service and the PC water tank designed in this manner is generally known to have sufficient bearing capacity against failure (ultimate limit state). For the simplified design of the PC water tank in an ordinary state, the tensile stress limit of concrete to be prestressed should be kept low so as not to cause cracking even under the action of subsidiary loads, while adequate tensile reinforcement should be arranged where tensile stress is generated to increase the deformability of the cross-section. Safety of members shall be investigated with respect to the most severe unfavourable combination of loads. Safety of members during an earthquake shall be investigated, as necessary, by confirming that the PC water tank can ensure the performance requirements during an earthquake. They shall be verified in relation to the combinations of ground motion levels used for seismic design and the importance degrees of the PC tank. Details are described in [Clause 9](#).

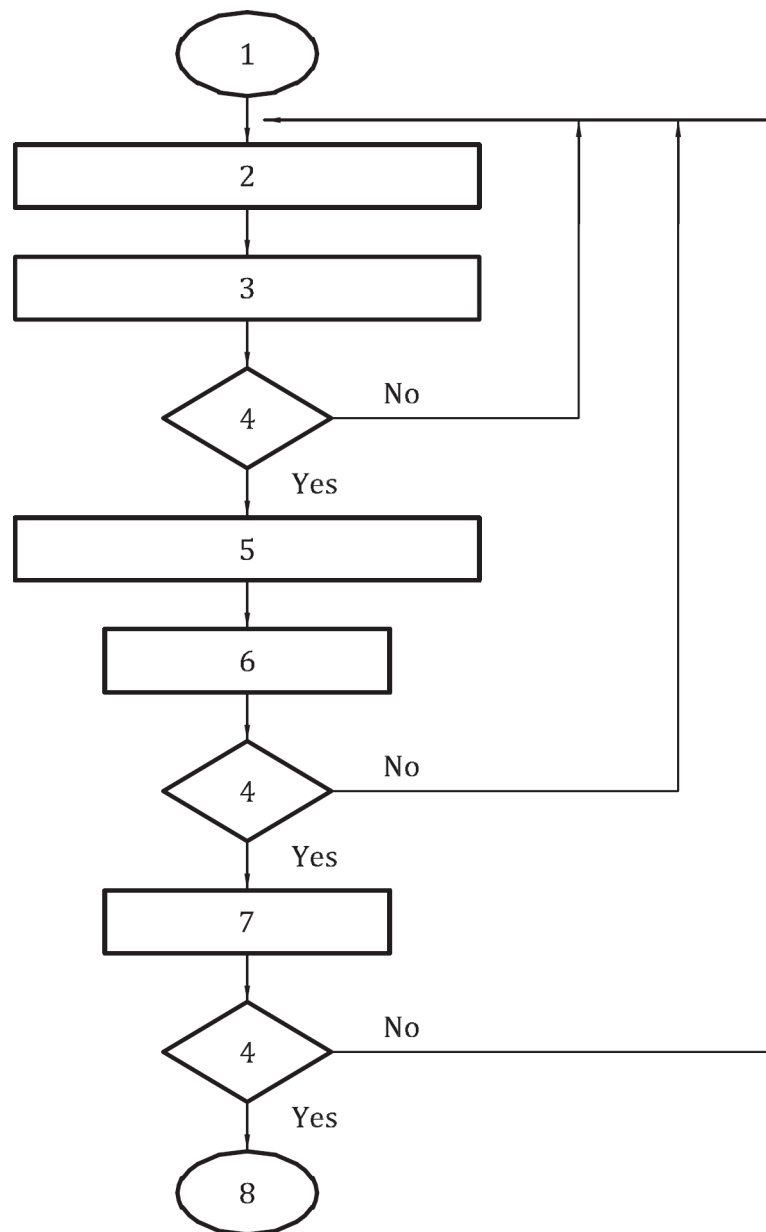
The member force to be used for the design of members shall be calculated based on the elastic theory on the assumption that the entire cross-section of concrete is effective even with partial cracking, partly because the stress limit is specified so that the crack width would be smaller than in general concrete members in consideration of the characteristics of the PC tank. In this case, the member force may be calculated by assuming the entire cross-section of concrete to be effective while ignoring reinforcement.

Although the provisions contained in this document were established to produce, when properly employed, a prestressed concrete structure with an appropriate margin of safety, this document is not a substitute for sound and experienced engineering. In order for the resulting structure designed in accordance with these provisions to attain the intended margin of safety, this document shall be used as a whole, and alternative procedures should be employed only when explicitly permitted by the provisions. In most cases, the minimum dimensional provisions in this document should be considered to be equivalent to those in national design codes. Yet, the simplicity of the procedures presented in this document can have a positive economic impact on the construction of prestressed concrete structures.

The professional performing the structural design in accordance with this document should have appropriate training and a minimum of knowledge of structural mechanics, statics, strength of materials, structural analysis and prestressed concrete design and construction.

Simplified design of the PC water tank should be made according to the design flow presented in [Figure 1](#). Additional explanation with reference sections is given in [Table 1](#). An example of the arrangement of prestressing steel (bars and strands) is given in [Figure 2](#).

NOTE An example of design calculation in accordance with this document is given in [Annex A](#).



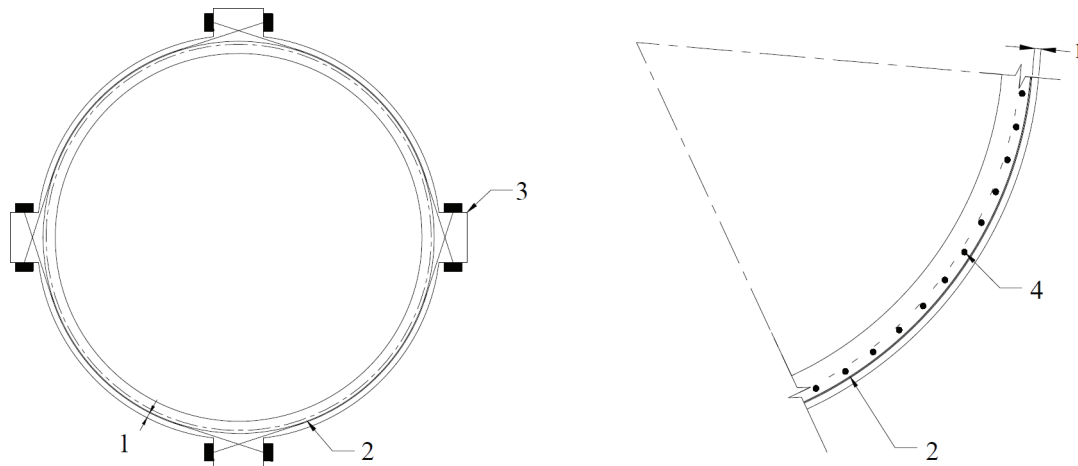
Key

- 1 start
- 2 confirmation of design conditions
- 3 calculation in ordinary condition
- 4 check
- 5 verification of earthquake conditions
- 6 Level 1 earthquake
- 7 Level 2 earthquake
- 8 end

Figure 1 — Design flow

Table 1 — Explanation of design flow

No	Design item		Design investigation			Reference clause in this document	
	Matter	Detail	Confirming states	Remark positions	Check conditions		
1	Confirmation of design condition	Kinds of structures	—	—	—	5	11
		Shapes				11	
		Materials				7	12
		Analysis methods				7	11
		Loads				6	
		Seismic conditions				9	
		Soil and foundation				11	
		Others				11	
2	Design calculation in ordinary conditions	Primary load	Watertightness	All	Stress limits	6	
		Subsidiary load				8	
		Particular load				11	
3	Verification of earthquakes conditions	Level 1 (conventional earthquakes)	No damage	All	Stress limits	8	
		Level 2 (very strong earthquakes)	Retainable function safety	Circumference wall	Bearing capacity and response strain	9	9.3.4
				Vertical wall	Bearing capacity		
		Foundation	Stability and safety	Spread foundation	Stability (Level 1)	9	9.4
				Pile foundation	Limit state (Levels 1 and 2)		
4	Confirmation of general structural details	—	—	—	—	10	
5	Reference of appurtenances	—	—	—	—	13	

**Key**

- 1 concrete cover
- 2 circumferential prestressing tendons
- 3 pilaster
- 4 vertical prestressing bars

Figure 2 — Example of the arrangement of prestressing steel**6 Load****6.1 General**

When designing the PC water tank, consideration shall be given to the deadweight, imposed load, hydrostatic pressure, prestressing force, effects of creep and drying shrinkage of concrete, temperature change, seismic action, wind load, snow load, earth pressure, uplift pressure, etc., as necessary. The loads to be used for design shall be selected after thoroughly surveying and checking the natural conditions of the construction site of the tank. The loads given in the above requirement are classified into three categories, primary loads, subsidiary loads and particular loads, as given in [Table 2](#).

Table 2 — Load classification

Primary load	a) Deadweight
	b) Imposed load
	c) Hydrostatic pressure
	d) Prestressing force
	e) Effects of creep and drying shrinkage of concrete
Subsidiary load	a) Temperature change
	b) Seismic action
	c) Wind load
Particular load	a) Snow load
	b) Earth pressure
	c) Uplift pressure
	d) Other

NOTE Among the particular loads, snow loads have often been treated as primary loads in areas of heavy snowfall.

6.2 Deadweight

When the actual density is available, that value shall be used. If not, the density according to ISO 9194 for estimating the unit weight or the unit weight given in [Table 3](#) may be used for calculating deadweight.

Table 3 — Unit weight of concrete

Type	Unit weight (kN/m ³)
Plain concrete	23,0
Reinforced concrete	24,5
Prestressed concrete	24,5
Mortar	21,0

6.3 Imposed load

An imposed load of [0,5] kN/m² should be considered assuming the weight of people climbing up on the roof for inspection. When waterproof mortar, handrails, etc. are included, their actual weights are required to be added.

6.4 Hydrostatic pressure

Hydrostatic pressure shall be assumed to be proportional to the depth of water and act at right angle to the surfaces of the structure.

6.5 Prestress

6.5.1 General

Prestressing forces shall be applied using prestressing steel for mitigating tension in members. Water pressure causes hoop tension and bending moment in the horizontal and vertical directions, respectively, of the wall of a cylindrical tank. Also, a roof of a spherical dome type causes hoop tension at the dome ring due to the roof load including the deadweight of the dome.

a) Circumferential prestress

Hoop tension of a cylindrical tank derived from water pressure shall be counterbalanced by placing, prestressing and anchoring prestressing steel in the circumferential direction. It is advisable to determine the prestress to be applied in consideration of the effects of an earthquake and so forth.

b) Vertical prestress

In regard to bending moment in the vertical direction acting on the tank wall, prestress construction is generally adopted by placing vertical prestressing steel. Reinforced concrete construction having vertical steel reinforcement is also permitted.

c) Prestress along the dome ring

Horizontal thrust due to roof loads including the deadweight of the dome acting on the dome ring can be counterbalanced by applying a prestressing force by placing, prestressing and anchoring prestressing steel.

6.5.2 Prestressing force immediately after prestressing

The prestressing force immediately after prestressing shall be calculated in consideration of the following effects in addition to the applied tensile force.

a) Elastic deformation of concrete

The tensile stress losses of prestressing steel due to elastic deformation of concrete may be calculated by [Formula \(1\)](#):

$$\Delta\sigma_p = \frac{1}{2} n \sigma'_{\text{cpg}} \quad (1)$$

where

- $\Delta\sigma_p$ is the tensile stress loss of prestressing steel due to elastic deformation of concrete;
- n is the elastic modulus ratio, ($= E_p/E_c$);
- E_p is the elastic modulus of prestressing steel;
- E_c is the elastic modulus of concrete at the age of prestressing;
- σ'_{cpg} is the concrete stress at the centroid of prestressing steel due to prestressing.

b) Friction between prestressing steel and sheath

The tensile force of the prestressing steel at the design cross-section incorporating the effect of friction between the prestressing steel and the sheath can be expressed by [Formula \(2\)](#):

$$P_x = P_i e^{-(\mu\alpha + \lambda l)} \quad (2)$$

where

- P_x is the tensile force of prestressing steel at the design cross-section;
- P_i is the tensile force of prestressing steel at the jack position after considering the set length;
- μ is the friction coefficient per radian of angular change;
- α is the angular change of prestressing steel;
- λ is the friction coefficient per unit length of prestressing steel;
- l is the length from the tension end of prestressing steel to the design cross-section.

[Table 4](#) gives standard values of friction coefficients.

Table 4 — Friction coefficients

Type of prestressing steel	μ	λ
Wires and wire strands	0,30	0,004
Bars	0,30	0,003

c) Set length of anchorages

Tensile force losses of prestressing steel due to anchor setting vary depending on the prestressing method. The losses are negligible by the threaded type and button-head type. When using wedge-type anchorages, which lead to large set lengths, the resulting tensile force losses and affected ranges shall be investigated.

The tensile force loss due to anchorage setting when there is no friction between prestressing steel and sheath may be calculated by [Formula \(3\)](#):

$$\Delta P = \frac{E_p A_p \Delta l}{l_p} \quad (3)$$

where

- ΔP is the tensile force loss due to setting of prestressing steel;
- l_p is the length of prestressing steel;
- Δl is the set length;
- A_p is the cross-sectional area of prestressing steel.

When there is friction between prestressing steel and sheath, it is advisable to determine the tensile force loss due to anchorage setting by the diagram method as described below.

NOTE The diagram method takes the case of four pilasters shown in [Figure 3](#) in which two prestressing steel placed in one level and other two prestressing steel in the level above or below it as an analogy. Each prestressing steel has a length of half the circumference and an angular change of 180°, and the anchoring positions of the upper and lower prestressing steel are alternated in order to make the prestress force as uniform as possible.

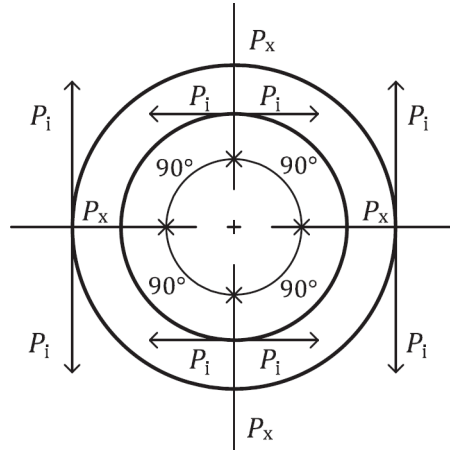


Figure 3 — Circumferential prestressing steel arrangement for four pilasters

The anchorage set length is expressed as [Formula \(4\)](#):

$$\Delta l = \frac{A_{ep}}{A_p E_p} \quad (4)$$

where A_{ep} is the area subjected to the effect of anchorage set.

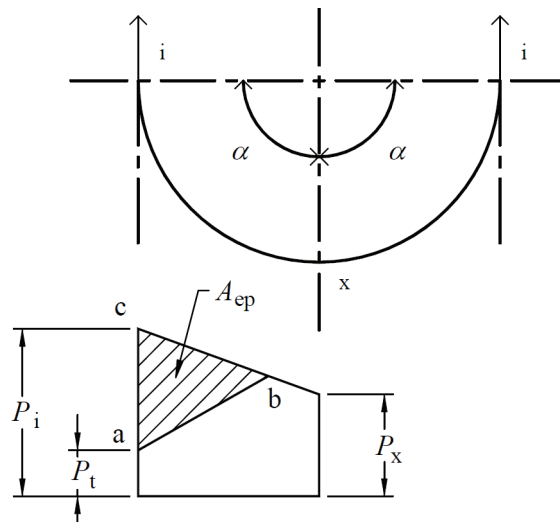


Figure 4 — Tensile force loss of prestressing steel due to setting (a)

Determine point b so that the area of triangle abc is equal to A_{ep} as illustrated in [Figure 4](#). This line expresses the distribution of the tensile forces of prestressing steel incorporating the tensile force loss due to anchorage setting. The example above shows the case where (a) the effect of anchorage setting does not reach the design cross-section. When (b) the effect reaches the boundary of the design cross-section, [Figure 5](#) applies.

Note Mutual friction between the base slab and the ground is negligible because it is generally small.

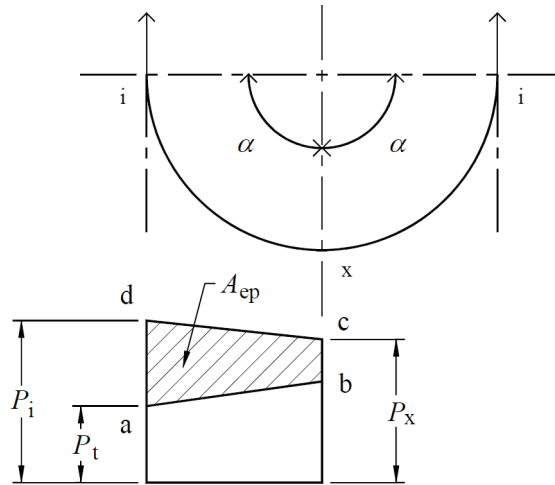


Figure 5 — Tensile force loss of prestressing steel due to setting (b)

6.5.3 Effective prestressing force

The effective prestressing force shall be calculated in consideration of the following effects in addition to the prestressing force immediately after prestressing calculated in accordance with 6.5.2.

a) Creep and drying shrinkage of concrete

The effective prestress shall be determined by calculating the tensile force loss of prestressing steel due to the creep and drying shrinkage of concrete and the relaxation of prestressing steel. The tensile stress loss of prestressing steel due to the creep and drying shrinkage of concrete may be calculated by [Formula \(5\)](#):

$$\Delta\sigma_{p\phi} = \frac{n\phi\sigma'_{cp} + E_p\varepsilon'_s}{1 + n\frac{\sigma'_{cpt}}{\sigma_{pt}}\left(1 + \frac{\phi}{2}\right)} \quad (5)$$

where

- $\Delta\sigma_{p\phi}$ is the tensile stress loss of prestressing steel due to creep, drying shrinkage and autogenous shrinkage of concrete;
- ϕ is the creep factor of concrete;
- ε'_s is the drying shrinkage of concrete;
- σ'_{cp} is the stress of concrete under sustained load at the position of prestressing steel (for a tank wall, σ'_{cp} may be regarded as prestress immediately after prestressing);
- σ_{pt} is the tensile stress of prestressing steel immediately after prestressing;
- σ'_{cpt} is the prestress immediately after prestressing at the position of prestressing steel.

b) Relaxation of prestressing steel

The tensile stress loss of prestressing steel due to relaxation of prestressing steel may be calculated by [Formula \(6\)](#):

$$\Delta\sigma_{p\gamma} = \gamma\sigma_{pt} \quad (6)$$

where

- $\Delta\sigma_{p\gamma}$ is the tensile stress loss of prestressing steel due to relaxation of prestressing steel;
- γ is the relaxation ratio of prestressing steel.

The effective tensile stress and effectiveness coefficient shall be calculated by the following [Formula \(7\)](#) and [\(8\)](#):

$$\sigma_{pe} = \sigma_{pt} - \Delta\sigma_{p\phi} - \Delta\sigma_{p\gamma} \quad (7)$$

$$\eta = \frac{\sigma_{pe}}{\sigma_{pt}} \quad (8)$$

where

σ_{pe} is the effective tensile stress of prestressing steel;

η is the effectiveness coefficient.

When the effective prestress is calculated during outline design by roughly giving the tensile stress of prestressing steel immediately after prestressing (σ_{pt}), the effectiveness coefficient (η) may be assumed to be 0,8 to 0,85. When judged as disadvantageous by design calculation, however, this should be precisely calculated.

6.5.4 Indeterminate forces due to prestress

When indeterminate forces are generated by prestressing forces, these shall be taken into account as necessary. When the tank wall and the bottom slab are structurally connected, indeterminate forces due to circumferential prestressing forces shall be assessed per [11.4.2.6](#).

6.6 Creep and drying shrinkage of concrete

In the case where the tank is to be filled with water at an early time (within three months after completion) after completion, the effects of the creep and drying shrinkage of concrete can be neglected in the calculation of cross-sectional forces.

In the case where the completed tank is to be left unfilled for a long time, indeterminate forces may be generated at the bottom edge of the tank wall, due to, for instance, differences in the age or the progress of drying shrinkage between the base slab and tank wall. The minimum reinforcement shall be specified in consideration of this effect (see [11.4.2.3](#)).

The effect of creep shall be incorporated when the structural system changes, such as the case where the form of supporting the bottom edge of the wall changes.

6.7 Temperature change

The design of a PC water tank shall incorporate the effect of uniform temperature rise/drop and the effect of temperature gap between the inside and outside of the tank wall. However, because of being slow, uniform temperature rise and drop may be considered to cause no temperature difference from one member to another.

When a PC water tank is empty, temperature differences between the inside and outside of the tank wall are marginal, and therefore, their effect may be disregarded. When the tank is filled with water, however, differences between the temperatures of water and air across the tank wall cause temperature stress. Such temperature differences vary depending on the region, water source, season, weather, etc. For these reasons, a design temperature difference (temperature gradient) of [5] °C may be adopted when no detailed data are available. Note that the effect of temperature shall be considered by generally assuming that external air temperature is higher than tank water temperature in summer and vice versa in winter.

6.8 Seismic action

The effects of an earthquake to be generally considered for the seismic design of a PC water tank shall include:

- displacement and strain of the ground during an earthquake;

- inertia forces derived from the deadweight of structures;
- earth pressure during an earthquake;
- dynamic water pressure during an earthquake;
- sloshing;
- lateral flow of the ground due to liquefaction;
- ground strain in an artificially altered sloping ground.

The peak acceleration should be determined for the calculation of inertia forces as the median spectral acceleration for one degree of freedom systems, which should be taken from the corresponding national design standard having jurisdiction over the site of the water tank. When no national design standard exists for the site being considered, the peak acceleration may be estimated from the seismic hazard maps provided in ISO 15673 and ISO 21725-1.

6.9 Wind load

The wind load, when required to be considered, shall be determined by multiplying the wind pressure by the wind force coefficient and the projection area.

When investigating the bottom end stress and safety against overturning and sliding of a PC water tank having a general shape, wind load is scarcely considered in particular because seismic force is generally greater than wind load. For a tank of particularly tall construction, the effect of wind pressure shall be investigated for a “tank empty” condition.

Wind pressure shall be calculated by [Formulae \(9\)](#) and [\(10\)](#)

$$P_w = qCA \quad (9)$$

$$q = 0,6\sqrt{h} \quad (10)$$

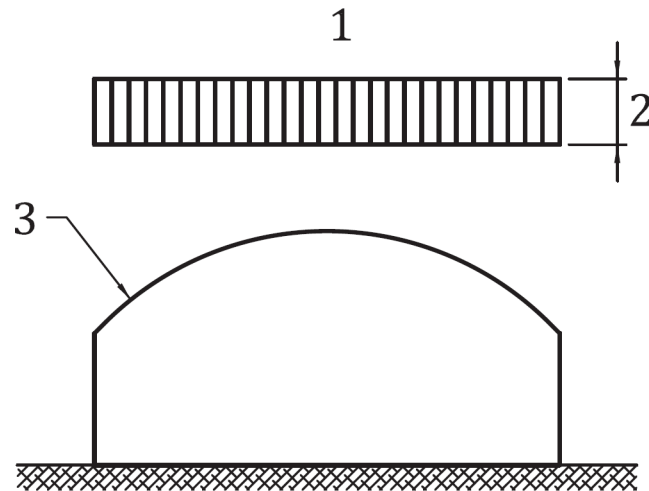
where

P_w	is the wind load (kN);
q	is the wind pressure (kN/m ²);
A	is the projection area (m ²);
h	is the height from the ground surface (m);
C	is the wind force coefficient (= 0,7 for a smooth cylindrical wall; = 1,0 for a rough cylindrical wall; = 0,4 for a smooth cylindrical wall; and = 0,6 for a rough cylindrical wall).

6.10 Snow load

The accumulated snow load shall be determined by multiplying the unit weight of snow by the maximum snow accumulation of the region. The unit weight of snow depends on geographical latitude or altitude.

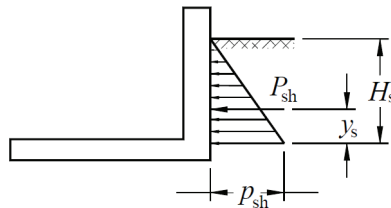
The unit weight of accumulated snow shall be established as not less than [30] N/m² on a normal basis for each cm of snow accumulation as shown in [Figure 6](#). The value may be reduced to not less than [20] N/m² for areas with a length of snow season of less than one month.

**Key**

- 1 snow load distribution
- 2 maximum snow accumulation
- 3 dome

Figure 6 — Snow load**6.11 Earth pressure**

In the case where earth pressure acts on the PC water tank, the earth pressure may be calculated by Rankine's formulae. By Rankine's formulae, the earth pressure is calculated using [Formulae \(11\)](#) to [\(14\)](#) (see [Figure 7](#)):

**Figure 7 — Earth pressure distribution**

$$p_{sh} = C_e w_s H_s \quad (11)$$

$$P_{sh} = \frac{1}{2} C_e w_s H_s^2 \quad (12)$$

$$y_s = \frac{H_s}{3} \quad (13)$$

$$C_e = \frac{1 - \sin \phi_s}{1 + \sin \phi_s} \quad (14)$$

where

p_{sh}	is the earth pressure;
P_{sh}	is the total earth pressure force;
C_e	is the earth pressure coefficient;
w_s	is the unit weight of soil (underwater unit weight);
y_s	is the height of the action point of earth pressure force;
H_s	is the total height of earth pressure action;
ϕ_s	is the internal friction angle of soil.

In case of constructing a PC water tank where the groundwater level is high, the groundwater pressure shall be considered in addition to earth pressure.

Note that the compressive force due to earth pressure shall not be added to the prestressing force. When the tank is empty, however, it shall be added to the prestressing force.

6.12 Uplift pressure force

In the case where uplift pressure forces act on the bottom of the tank, investigation shall be made regarding the uplift of the whole tank and safety of the base slab.

When the base slab of the tank is located below the groundwater level or in an ill-drained ground, measures shall be taken not to cause uplift pressure on the base slab. However, when the base slab is subjected to uplift pressure, examination shall be made in regard to uplift in a “tank empty” condition and safety of the base slab.

6.13 Other loads

In the case where the tank is subjected to loads other than those described in [6.2](#) to [6.12](#), these shall be separately considered.

7 Structural analysis

7.1 Calculation of member force

The roof, wall and base slab composing the PC water tank may be analysed as thin-wall shell construction. Analysis methods, which are described in detail in [Clause 11](#), include those using finite elements and analytical solutions.

The roof, wall and base slab constituting a PC water tank, which is generally made as an axisymmetric structure, shall be designed avoiding abrupt changes in the cross-section to the extent that it is possible, since such changes can damage the characteristics of a thin-wall structure. When an abrupt change in the cross-section is inevitable, the structural characteristics of the tank shall be thoroughly examined, and the member force shall be calculated by a method suitable for the structural characteristics.

For this type of a thin-wall shell structure, examination regarding out-of-plane shear forces may generally be skipped. Therefore, when using the finite element method (FEM) for structural analysis, this structure may be modelled as thin-wall shell elements disregarding shear deformation. However, sufficient care should be exercised when modelling abrupt cross-sectional changes or junctions between structural elements by FEM.

7.2 Concrete

7.2.1 Strength

The strength of concrete to be used for design shall be based on the strength at an age of 28 days.

The characteristic compressive strength of concrete for use in prestressed concrete members shall not be less than the following values:

- Post-tensioned: $f'_{ck} = [30]$ MPa;
- Pre-tensioned: $f'_{ck} = [35]$ MPa.

The characteristic compressive strength of concrete for reinforced concrete members shall not be less than [24] MPa.

The compressive strength of concrete to which prestress can be applied to shall be not less than 1,7 times the maximum compressive stress to be generated in the concrete immediately after prestressing.

7.2.2 Modulus of elasticity

The elastic modulus used for calculating the stress of reinforced concrete members shall be 14 GPa, accordingly, the elastic modulus ratio (n) may be set at 15.

The elastic modulus used for the calculation of indeterminate forces or elastic deformation of a reinforced concrete member and the design calculation of prestressed concrete members shall be determined depending on the characteristic strength of concrete.

7.2.3 Poisson's ratio

Poisson's ratio to be used for design calculation may generally be assumed to be 0,2 in the elastic deformation range.

7.2.4 Drying shrinkage

The degree of drying shrinkage of concrete to be used for calculating the prestress loss shall be determined depending on the age of concrete at prestressing.

7.2.5 Creep

The creep strain of concrete may be determined by [Formula \(15\)](#) on the assumption that it is proportional to the elastic strain due to the acting stress.

$$\varepsilon'_c = \varphi \frac{\sigma'_c}{E_c} \quad (15)$$

where

- ε'_c is the creep strain of concrete;
- σ'_c is the compressive stress of concrete under a sustained load.

The creep factor for calculating the prestress loss and indeterminate force shall be determined depending on the age of concrete when a sustained load is applied.

When the general creep factor is not applicable, the creep factor of concrete shall be separately determined in consideration of factors including the ambient temperature of the member, shape and size of the member

cross-section and age when the load is applied to the member. The creep factor at an effective age of t_e of concrete subjected to a load at an effective age of t_0 , $\varphi(t_e, t_0)$, may generally be determined by [Formula \(16\)](#).

$$\varphi(t_e, t_0) = \varphi_{d0} \beta_d(t_e - t_0) + \varphi_{f0} [\beta_f(t_e) - \beta_f(t_0)] \quad (16)$$

where

- φ_{d0} is the basic creep factor for delayed elastic strain and is generally assumed to be [0,4];
- φ_{f0} is the basic creep factor for flow strain and a value is selected from [Table 5](#) depending on the environmental conditions;
- $\beta_d(t_e - t_0)$ is a function related to the effective number of days after loading, $(t_e - t_0)$. A value read from [Figure 8](#) may be used;
- $\beta_f(t_e)$ is a function related to the effective age, t_e , and the virtual thickness of the member, h_{th} . A value read from [Figure 9](#) may be used;
- $\beta_f(t_0)$ is function β_f related to the effective age, t_0 , and the virtual thickness of the member, h_{th} .
- t_0 and t_e are the effective ages (days) of concrete when concrete is loaded and when the creep factor is calculated, respectively. Values corrected according to [Formula \(17\)](#) may be used depending on the concrete temperature and cement type.

$$t_e \text{ or } t_0 = \alpha \Sigma (T + 10) \Delta t / 30 \quad (17)$$

where

- α is a coefficient for the hardening rate of concrete. 2,0 and 1,0 for high early strength Portland cement and ordinary Portland cement, respectively;
- Δt is the number of days when the temperature is T ;
- T is the temperature difference (°C).

The virtual thickness of the member, h_{th} is defined in [Formula \(18\)](#).

$$h_{th} = \lambda_e A_c / u \quad (18)$$

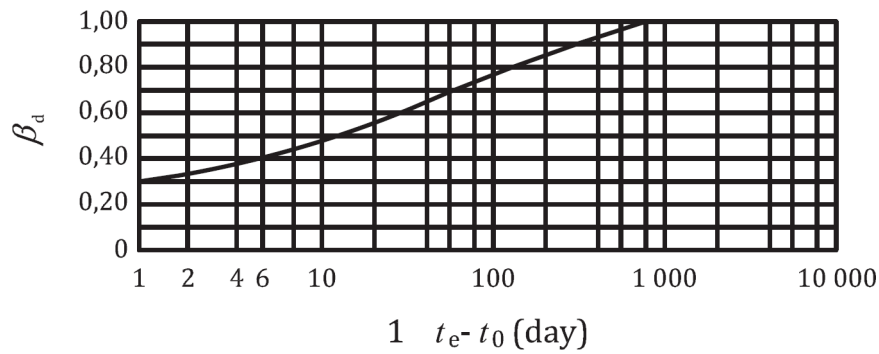
where

- h_{th} is the virtual thickness of the member;
- λ_e is the environmental factor (see [Table 5](#));
- A_c is the cross-sectional area of the member;
- u is the perimeter of the member in contact with ambient air.

In regard to the environmental conditions for determining φ_{f0} and h_{th} , the relative humidity in a “tank empty” condition may be assumed to be 70 %. In a “tank full” condition, the relative humidity may be assumed to be the average of underwater and 70 %. Also, the perimeter of u may be considered only on the outer side when the tank is full.

Table 5 — Basic creep factor for flow strain, φ_{f0} and λ_e

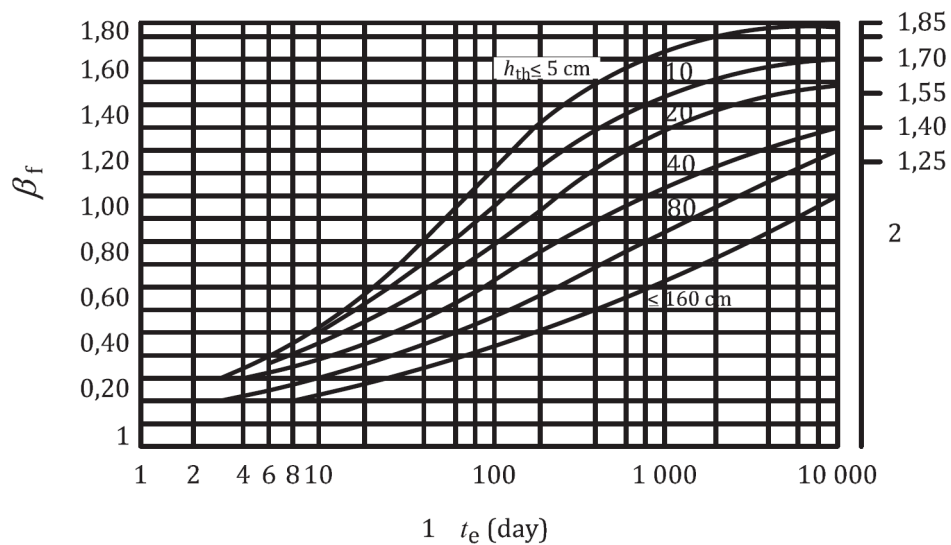
Environmental conditions	φ_{f0}	λ_e
Underwater	0,8	60
90 % R.H.	1,3	10
70 % R.H.	2,0	3
40 % R.H.	3,0	2



Key

1 effective time after loading

Figure 8 — $\beta_d(t_e - t_0)$



Key

1 effective time after loading

2 final value

Figure 9 — $\beta_f(t_e)$

7.3 Steel

7.3.1 Strength

Steel reinforcement (reinforcing bar), prestressing wire, prestressing strand, prestressing hard drawn wire, prestressing bar and welded wire fabric shall conform to the relevant ISO standards:

- Steel for reinforcement: ISO 6935-1 for plain bar and ISO 6935-2 for ribbed bar;
- Steel for prestressing steel:
 - ISO 6934-2 for cold-drawn wire;
 - ISO 6934-3 for quenched and tempered wire;
 - ISO 6934-4 for strand; and
 - ISO 6934-5 for hot rolled steel bar.

7.3.2 Modulus of elasticity

The elastic modulus of steel for design calculation may be set at 200 GPa.

7.3.3 Relaxation

As to the apparent relaxation ratio of prestressing steel for calculating the prestress loss, the values shall conform to the relevant ISO standard as presented in [7.3.1](#).

7.4 Calculation of tensile reinforcement

When tensile stress is generated in the cross-section of a prestressed concrete member during loading, it is necessary to place corresponding tensile reinforcement in the region under tensile stress.

For a member in which prestressing steel is not bonded with concrete, the following combination of loading action shall be considered:

(Primary load + particular load corresponding to primary load) + [1,35] × (effect of earthquake of Level 1 ground motion)

The cross-sectional area of tensile reinforcement to be placed in a cross-section of the region where tensile stress is to be generated may be calculated by [Formula \(19\)](#).

$$A_s = \frac{T_c}{\sigma_{sa}} \quad (19)$$

where

A_s is the cross-sectional area of tensile reinforcement;
 T_c is the resultant force of tensile stress generated in concrete;
 σ_{sa} is the tensile stress limit of reinforcement.

The stress distribution in a cross-section may be assumed as that shown in [Figure 10](#) and the resultant tensile force, T_c is calculated by [Formulae \(20\)](#) and [\(21\)](#).

$$x_t = \frac{|\sigma_c|t}{|\sigma_c| + \sigma'_c} \quad (20)$$

$$T_c = \frac{1}{2} x_t b |\sigma_c| \quad (21)$$

where

x_t is the distance from the tension edge of member to neutral axis;
 σ_c is the tensile stress of concrete;
 b is the width of member;
 t is the tank wall thickness.

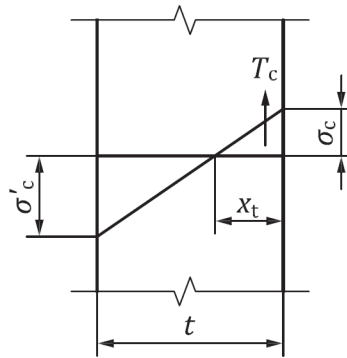


Figure 10 — Stress distribution diagram

Ribbed bars should be used for tensile reinforcement. σ_{sa} may be determined by multiplying the stress limit of reinforcement for general members by the extra coefficient given in [Table 6](#) according to the combination of loads to be considered. Since no tensile-crack-width-controlling effect is expected from prestressing steel placed near the centroid of a cross-section, only prestressing steel placed near the surface shall be regarded as tensile steel.

8 Stress limit

8.1 General

In regard to stress generated in a cross-section of each member under a primary load and particular load equivalent to a primary load, the stress limits of a reinforced concrete member and prestressed concrete member shall be the values specified in [8.2](#) and [8.3](#), respectively.

The stress limit for incorporating the subsidiary load and a particular load equivalent to a subsidiary load shall be the values obtained by multiplying the stress limits specified in [8.2](#) and [8.3](#) by the extra coefficients given in [Table 6](#).

The tensile stress limit of concrete in a prestressed concrete member for incorporating a subsidiary load and a particular load equivalent to a subsidiary load shall be the values specified in [8.3.4](#). The stress limit immediately after prestressing specified in [8.3.1](#) and [8.3.2](#) shall not be augmented.

NOTE The stress limits specified in this document are equivalent to the safety (ultimate limit state) and serviceability (water leakage, etc. for serviceability limit state) verification.

NOTE The extra coefficient specified in this document is to increase the stress limits in consideration with the probability of load combinations.

Table 6 — Combinations of loads and extra coefficients for stress limit

Combination of loads		Extra coefficient
a)	Primary load + particular load equivalent to primary load + effect of temperature (temperature difference)	[1,15]
b)	Primary load + particular load equivalent to primary load + wind load	[1,25]
c)	Primary load + particular load equivalent to primary load + effect of a Level 1 ground motion	[1,50]

8.2 Stress limit of reinforced concrete members

8.2.1 Stress limit of concrete

The compressive stress, shear stress and bond stress limits of concrete shall be determined to ensure performance requirements of a PC water tank.

The bearing stress limit of concrete shall be the value calculated by [Formulae \(22\)](#) and [\(23\)](#).

$$\sigma'_{ba} = \left(0,25 + 0,05 \frac{A_c}{A_b} \right) f'_{ck} \quad (22)$$

$$\sigma'_{ba} \leq 0,5 f'_{ck} \quad (23)$$

where

- σ'_{ba} is the bearing stress limit of concrete;
- A_c is the total area of the concrete surface;
- A_b is the area of concrete subjected to bearing load;
- f'_{ck} is the characteristic compressive strength of concrete.

8.2.2 Stress limit of reinforcement

The stress limit of reinforcement with a diameter of not more than 32 mm shall be determined taking into account the performance requirements of a PC water tank.

The stress limit shall be applied for members in contact with water in consideration of the fact that a PC water tank requires watertightness. However, those for general members should as a rule be applied to portions not in contact with water or effectively waterproofed portions.

When considering a combination of a primary load, particular load equivalent to a primary load and subsidiary load, the stress limit shall be the value obtained by multiplying the value for general members by the extra coefficient given in [Table 6](#).

8.3 Stress limit of prestressed concrete members

8.3.1 Stress limit of concrete

The compressive, shear and diagonal tensile and bond stress limits of concrete shall be determined taking into account the performance requirements of a PC water tank.

The bearing stress limit shall be the value specified in [8.2.1](#). As to the backsides of anchorages, verification of bearing stress may be omitted by confirming that the compressive strength of concrete specified in [7.2.1](#) is attained at the time of applying prestress.

8.3.2 Tensile stress limit of prestressing steel

The tensile stress limit of prestressing steel shall be determined taking into account the performance requirements of a PC water tank.

8.3.3 Stress limit of reinforcement

The stress limit of reinforcement shall be as specified in [8.2.2](#).

8.3.4 Augmentation of tensile stress limit of concrete

The tensile stress limit of concrete considering a subsidiary load shall be determined with a combination of the flexural and axial tensile stress limits.

When considering a particular load equivalent to a subsidiary load, an adequate value should be established on a case-by-case basis in consideration of a PC water tank.

9 Verification of safety against earthquake

9.1 Principles of seismic design

9.1.1 General

A PC water tank shall be designed to ensure the performance that a structure should retain during an earthquake with respect to the combination of the ground motion level and the importance of the facility.

For seismic design, the construction characteristics of the structure and the ground characteristics of the area shall be taken into consideration to select a method suitable for these characteristics.

In general, the PC water tank is often adopted to prevent a secondary disaster during an earthquake and so that water storing function shall be ensured such that storing water can be used as emergency water. Therefore, the PC water tank shall be designed as high degree of importance.

9.1.2 Ground motion levels

For seismic design, Level 1 ground motion and Level 2 ground motion shall be considered as necessary. Level 1 ground motion represents an event with a probability of encountering once or twice during the life of the facility, and Level 2 ground motion represents stronger ground motion with a lower probability of encountering.

NOTE Level 2 ground motion includes large-scale plate-boundary earthquakes occurring near land and inland near-field earthquakes. Though the probability of a waterworks facility encountering a ground motion of this level is generally low, its impact, once encountered, would be serious.

9.1.3 Levels of earthquake resistance

A PC water tank is required to retain the level of earthquake resistance specified in [Table 7](#) as a standard against each ground motion level. The functions of the PC water tank are retainable even with minor damage to the tank.

Table 7 — Earthquake resistance level required for a PC water tank

Ground motion level	Earthquake resistance level
Level 1	No damage
Level 2	No severe impact on human life and fatal accidents. The functions of the PC water tank are retainable even with minor damage to the tank.

9.1.4 Effects of earthquake

For seismic design of a PC water tank, the following effects of an earthquake shall be considered:

- displacement and strain of the ground during an earthquake;
- inertia force derived from the deadweight of the structure, etc.;
- earth pressure during an earthquake;
- dynamic water pressure during an earthquake;
- sloshing;
- lateral flow of the ground due to liquefaction;

- strain of the ground in artificially altered sloping ground.

However, the earth pressure during an earthquake can be ignored because it is a subsidiary load in the PC water tank constructed on ground where this document is applied. When water colliding with the roof does not affect the roof, the effect of the sloshing can be ignored.

9.1.5 Seismic design procedure

Seismic design shall basically follow these procedures:

- select the construction site;
- carry out ground survey and soil exploration at the site;
- investigate the ground conditions;
- calculate the earthquake resistance;
- verify the earthquake resistance level.

9.2 Input earthquake motion

9.2.1 Seismic design method

Resistance to Level 1 ground motion shall be calculated basically by elastic analysis and as a rule by the seismic coefficient method. It is necessary to appropriately establish the design seismic coefficient depending on the ground type and the natural period of the structure.

Resistance to Level 2 ground motion shall be calculated as a rule by the seismic coefficient method. However, in the case of a PC water tank with a large scale and complicated shape, it is advisable to carry out dynamic analysis as well, as necessity arises, to verify safety in consideration of its characteristics (natural period).

The natural period of the PC water tank in a “tank full” condition (T) may be determined by [Formulae \(24\)](#) and [\(25\)](#):

$$T = \frac{\pi H^2}{R} \sqrt{\frac{2q'}{3gE} \left\{ 1 + 12 \left(\frac{R}{H} \right)^2 \right\}} \quad (24)$$

$$q' = q_1 + \frac{q_0 R}{2t} \frac{\tanh\left(\frac{\sqrt{3}R}{H}\right)}{\frac{\sqrt{3}R}{H}} \quad (25)$$

where

- R is the radius of the tank;
- H is the total water depth of the tank;
- g is the gravitational acceleration;
- E is the elastic modulus;
- q_1 is the unit weight of the tank wall;
- q_0 is the unit weight of the liquid (water).

For a PC water tank having an irregular shape, the seismic coefficient method may not be capable of fully expressing its behaviour during an earthquake. In such a case, it is advisable to verify the results of the seismic design based on the seismic coefficient method by dynamic analysis in consideration of the characteristics (natural period) of the structure. During this process, nonlinear properties due to decrease of rigidity may be considered for modelling the structure. Analysis may also be conducted by the equivalent linear method.

A PC water tank to be built on ground generally has a simple shape of a cylinder and a relatively short natural period. For such a tank, design by the seismic coefficient method is sufficient without dynamic analysis.

9.2.2 Design seismic coefficients for the seismic coefficient method for Level 1 ground motion

The design horizontal seismic coefficient for Level 1 ground motion (K_{h1}) shall be determined as [Formula \(26\)](#):

$$K_{h1} = C_z K_{h01} \quad (26)$$

where

C_z is the correction factor by region (level of seismic hazard);

K_{h01} is the standard horizontal seismic coefficient at the position of the centroid of the structure.

The response of a waterworks facility to ground motion varies depending on the intensity, period characteristics and duration of the ground motion, ground type, type of the structure and type of the foundation. The standard horizontal seismic coefficients shall be based on the acceleration response spectrum curve for each ground type determined by analysing strong motion seismograms in each region. C_z and K_{h01} may be estimated referring to ISO 3010.

When considering the design vertical seismic coefficient (K_{v1}), the value shall be determined by $K_{v1} = K_{h1}/2$. For the seismic calculation of a normal structure, consideration of the effect of ground motion only in the horizontal direction is sufficient for constructing an earthquake-resistant structure. However, it may be desirable for certain types or parts of structures, such as anchorages to the foundations of tank structures having standpipes and the overhanging bottoms of elevated water tanks, to investigate the effects of vertical ground motion.

9.2.3 Design seismic coefficients for the seismic coefficient method for Level 2 ground motion

The design horizontal seismic coefficient for Level 2 ground motion (K_{h2}) shall be determined as [Formula \(27\)](#):

$$K_{h2} = C_s K_{h02} \quad (27)$$

where

C_s is the characteristic coefficient of the structure. This shall be appropriately established for the degrees of the response attenuation and plastic deformability of the structure. However, $C_s = 0,45$ may be assumed for a PC water tank of a general shape;

K_{h02} is the standard horizontal seismic coefficient at the position of the centroid of the structure.

The standard horizontal seismic coefficient for Level 2 ground motion at the position of the centroid of the structure as specified for each ground type is beyond the scope of this document. K_{h02} shall be estimated referring to ISO 3010.

The structure characteristic coefficient (C_s) should be determined by [Formula \(28\)](#):

$$C_s = D_\eta D_{he} \quad (28)$$

where

D_{he} is the correction factor dependent on damping constant. This may be assumed to be 1,0 when the damping constant is 5 %;

D_η is the response reduction ratio due to plastic deformability determined by [Formula \(29\)](#).

$$D_{\eta} = \frac{1}{\sqrt{2 \left(\frac{Q_a}{Q_y} + 1 \right) \eta + 1}} \quad (29)$$

where

Q_y is the yield load of member;

Q_a is the load at the deformation limit;

η is the mean cumulative plastic magnification expressed by [Formula \(30\)](#).

$$\eta = \frac{\delta_0}{\delta_y} \quad (30)$$

where

δ_0 is the cumulative plastic deformation;

δ_y is the yield deformation.

NOTE With regard to a general shaped PC water tank with a capacity of 1 000 m³ to 30 000 m³, it is possible to determine $D_{\eta} = 0,45$, that is, $C_s = 0,45$.

When considering the design vertical seismic coefficient (K_{v2}), the value shall be determined by $K_{v2} = K_{h2}/2$.

9.3 Verification of structural safety

9.3.1 Effects of earthquake

9.3.1.1 General

The effects of an earthquake to be considered shall include the following:

- inertia force derived from the deadweight of the structure, etc.;
- dynamic water pressure during an earthquake

The inertia force derived from deadweight, etc. and dynamic water pressure during an earthquake, which shall be specifically considered in the verification of seismic safety of a PC water tank are specified in detail.

9.3.1.2 Inertia force derived from deadweight, etc

The inertia force derived from the deadweight and imposed loads of the structure shall be determined by multiplying their respective weights by the design seismic coefficients specified in [9.2.2](#) and [9.2.3](#), giving sufficient consideration to the characteristics of the structure.

9.3.1.3 Dynamic water pressure during an earthquake

As dynamic water pressure during an earthquake, the following shall be considered:

- dynamic water pressure responding to short-period components of an earthquake (impulsive pressure);
- dynamic water pressure responding to relatively long-period components of an earthquake (convective pressure)

In addition to the above, pressure due to the elastic deformation of the tank and pressure due to rocking are conceivable as pressure acting on the tank during an earthquake. However, their effects on PC water tanks of a general shape are so small that these may be disregarded.

The Housner method and velocity potential method are representative methods of calculating dynamic water pressure during an earthquake. Other methods include the finite element method, boundary element

method and transfer matrix method. Any of these methods should be used for calculating dynamic water pressure during an earthquake.

The dynamic water pressure during an earthquake is divided into an impulsive and a convective component of water, which can be obtained from [Formulae \(31\)](#) and [\(32\)](#), respectively.

$$\alpha_s = \frac{g}{W_s} \int_0^H \int_0^{2\pi} P_{ws}(\xi) R \cos^2 \theta d\theta d\xi \quad (31)$$

$$\alpha_r = \frac{g}{W_r} \int_0^H \int_0^{2\pi} P_{wr}(\xi) R \cos^2 \theta d\theta d\xi \quad (32)$$

where

- α_s is the response acceleration of the convective component of water;
- α_r is the response acceleration of the impulsive component of water;
- W_s is the equivalent weight of the convective component of water
- W_r is the equivalent weight of the impulsive component of water;
- $P_{ws}(\xi)$ is the maximum convective pressure acting on the tank wall;
- $P_{wr}(\xi)$ is the maximum impulsive pressure acting on the tank wall;
- ξ is the vertical distance from the water surface;
- θ is the angle of seismic action to the horizontal plane;
- H is the water depth.

[Table 8](#) compares the formulae used in the Housner method and the velocity potential method.

Table 8 — Formulae for calculating dynamic water pressure

	Housner method	Velocity potential method
ω_s^2	$1,837 \frac{g}{R} \tanh\left(1,837 \frac{H}{R}\right)$	$k_s \frac{g}{R} \tanh\left(k_s \frac{H}{R}\right)$
W_s	$0,3189 \frac{R}{H} \tanh\left(1,837 \frac{H}{R}\right) W$	$\frac{2R}{(k_s^2 - 1)k_s H} \tanh\left(k_s \frac{H}{R}\right) W$
W_r	$\frac{\tanh\left(\sqrt{3} \frac{R}{H}\right)}{\sqrt{3} \frac{R}{H}} W$	$W - \sum_{s=1}^{\infty} W_s$
P_r	$K_h W_r$	$K_h W_r$
P_s	$\omega_s S_v \frac{W_s}{g}$	$\omega_s S_v \frac{W_s}{g}$
h_{sE}	$\left[1 - \frac{\cosh\left(1,837 \frac{H}{R}\right) - 1}{1,837 \frac{H}{R} \sinh\left(1,837 \frac{H}{R}\right)} \right] H$	$H - \frac{R}{k_s} \tanh\left(\frac{k_s H}{2R}\right)$
h_{rE}	$\frac{3}{8} H$	$\frac{1}{W_r} \left(\frac{WH}{2} - \sum_{s=1}^{\infty} W_s h_{sE} \right)$
h_{sI}	$\left[1 - \frac{\cosh\left(1,837 \frac{H}{R}\right) - 2,013}{1,837 \frac{H}{R} \sinh\left(1,837 \frac{H}{R}\right)} \right] H$	$H - \frac{R}{k_s} \left[\coth\left(k_s \frac{H}{R}\right) - 2 \operatorname{cosech}\left(k_s \frac{H}{R}\right) \right]$

Table 8 (continued)

	Housner method	Velocity potential method
h_{rl}	$\frac{1}{8} \left[\frac{4}{\frac{\tanh\left(\sqrt{3}\frac{R}{H}\right)}{\sqrt{3}\frac{R}{H}}} - 1 \right] H$	$\frac{1}{W_r} \left[\frac{W}{2} \left(H + \frac{R^2}{2H} \right) - \sum_{s=1}^{\infty} W_s h_{sl} \right]$
$P_{wr}(\xi)$	$\sqrt{3}\rho K_h H \left[\frac{\xi}{H} - \frac{1}{2} \left(\frac{\xi}{H} \right)^2 \right] \tanh\left(\sqrt{3}\frac{R}{H}\right)$	$\rho K_h R \left[1 - 2 \sum_{s=1}^{\infty} \frac{1}{k_s^2 - 1} \frac{\cosh\left(k_s \frac{H - \xi}{R}\right)}{\cosh\left(k_s \frac{H}{R}\right)} \right]$
$P_{br}(r)$	$\frac{\sqrt{3}}{2} \rho K_h H \frac{\sinh\left(\sqrt{3}\frac{r}{H}\right)}{\cosh\left(\sqrt{3}\frac{R}{H}\right)}$	$\rho K_h \left[r - 2R \sum_{s=1}^{\infty} \frac{1}{k_s^2 - 1} \frac{J_1\left(k_s \frac{r}{R}\right)}{J_1(k_s) \cosh\left(k_s \frac{H}{R}\right)} \right]$
$P_{ws}(\xi)$	$0,340 \, 2 \rho \left(\frac{R}{g} \right)^2 \omega_s^3 S_v \frac{\cosh\left(1,837 \frac{H - \xi}{R}\right)}{\sinh\left(1,837 \frac{H}{R}\right)}$	$2 \rho \frac{R}{g} \omega_s S_v \frac{1}{k_s^2 - 1} \frac{\cosh\left(k_s \frac{H - \xi}{R}\right)}{\cosh\left(k_s \frac{H}{R}\right)}$
$P_{bs}(r)$	$0,510 \, 4 \rho \left(\frac{R}{g} \right)^2 \omega_s^3 S_v \left[\left(\frac{r}{R} \right) - \frac{1}{3} \left(\frac{r}{R} \right)^3 \right] \frac{1}{\sinh\left(1,837 \frac{H}{R}\right)}$	$2 \rho \frac{R}{g} \omega_s S_v \frac{1}{k_s^2 - 1} \frac{J_1\left(k_s \frac{r}{R}\right)}{J_1(k_s) \cosh\left(k_s \frac{H}{R}\right)}$

where

- W is the total weight of contained water;
- ω_s is the natural circular frequency of the s -th mode;
- P_r is the horizontal impulsive force acting on the centre of gravity;
- P_s is the horizontal convective force acting on the centre of gravity;
- h_{sE} is the height above the base of the wall to the centre of gravity of the convective lateral force excluding base pressure;
- h_{rE} is the height above the base of the wall to the centre of gravity of the impulsive lateral force excluding base pressure;
- h_{sl} is the height above the base of the wall to the centre of gravity of the convective lateral force including base pressure;
- h_{rl} is the height above the base of the wall to the centre of gravity of the impulsive lateral force including base pressure;
- $P_{br}(r)$, $P_{bs}(r)$ are the maximum impulsive pressure and convective pressure acting on the base slab, respectively;
- subscript s is the mode number of solid oscillating mass point ($s = 1$ in the Housner method); $s = 1$ is also normally sufficient in the velocity potential method;

- k_s is the positive root that satisfies $\frac{d}{dk_s}[J_1(k_s)] = 0$ (see [Table 9](#));
- S_v is the velocity response spectrum;
- K_h is the design horizontal seismic coefficient (K_{h1} or K_{h2});
- J_1 is the vessel function (refer to [Table 10](#));
- r is the horizontal distance from the centre of the tank.

Table 9 — k_s

s	k_s
1	1,841
2	5,331
3	8,536
4	11,706
5	14,863

Table 10 — Vessel function, J_1

r/R	$J_1(k_s r/R)$										
	0,0	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1,0
$s = 1$	0,0	0,091 66	0,181 0	0,265 8	0,343 8	0,413 2	0,472 2	0,519 5	0,554 0	0,574 9	0,581 9
$= 2$	0,0	0,257 2	0,460 9	0,569 8	0,564 7	0,452 0	0,261 9	0,040 75	-0,160 5	-0,298 1	-0,346 1
$= 3$	0,0	0,389 1	0,578 2	0,481 5	0,173 2	-0,161 5	-0,338 7	-0,281 5	-0,056 49	0,177 6	0,273 3
$= 4$	0,0	0,490 6	0,532 2	0,132 4	-0,275 3	-0,302 9	0,002 40	0,257 5	0,188 4	-0,086 90	-0,233 3
$= 5$	0,0	0,556 0	0,349 2	-0,219 8	-0,287 1	0,117 9	0,254 2	-0,056 45	-0,229 4	0,011 55	0,207 0

Impulsive pressure is never simultaneous with convective pressure. Impulsive pressure is greater than convective pressure on general PC water tanks. Investigation of the effect of convective pressure may therefore be omitted for a tank with a small diameter causing small sloshing. Also, these can be combined by determining the square root of the sum of squares.

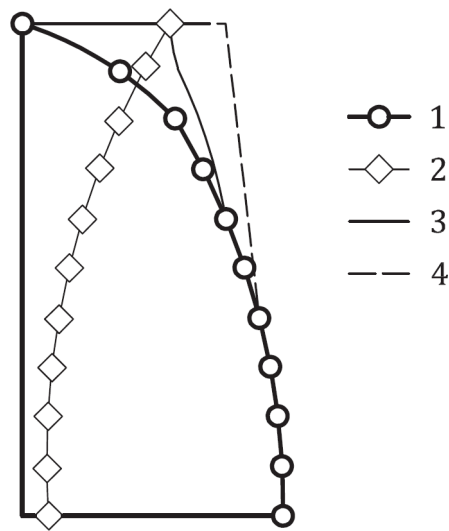
When approximating the distribution of dynamic water pressure during an earthquake by a simple form, the shape should envelope the object dynamic water pressure distribution to the extent that it is possible. [Figure 11](#) illustrates a typical example of approximated dynamic water pressure distribution. The pressures at the upper and lower edges should be determined by [Formulae \(33\)](#) and [\(34\)](#), respectively:

$$P_u = \frac{P_{1u} + P_l}{2} \quad (33)$$

$$P_l = \sqrt{P_{0l}^2 + P_{1l}^2} \quad (34)$$

where

- P_u is the dynamic water pressure at the upper edge;
- P_l is the dynamic water pressure at the lower edge;
- P_{0l} is the impulsive pressure at the lower edge;
- P_{1u} is the convective pressure at the upper edge;
- P_{1l} is the convective pressure at the lower edge.

**Key**

- | | |
|---|------------------------------|
| 1 | impulsive pressure |
| 2 | convective pressure |
| 3 | root mean square combination |
| 4 | trapezoidal rule |

Figure 11 — Approximation of dynamic water pressure distribution

9.3.2 Combination of loads

As to the combination of loads for verifying the degree of safety, only the “tank full” condition shall be considered because it is not likely the tank is kept empty for long time.

As to the combination of loads on a filled PC water tank, the imposed loads, the effects of creep and drying shrinkage of concrete, temperature and wind loads can be ignored from the list of loads given in [Table 2](#). However, loads that strongly affect the tank wall shall be considered as necessary.

9.3.3 Calculation of member forces

Member forces induced by Level 1 and Level 2 ground motions shall be calculated by assuming the tank body as a thin-wall shell structure in consideration of the characteristics of the loading action during an earthquake.

Dynamic water pressure and the inertia force of the structural framing that act during an earthquake are distributed non-axisymmetrically in the circumferential direction as shown in [Figure 12](#). It is, therefore, convenient to analyse the loads, displacements and member forces by expanding them in a Fourier series in the circumferential direction and using axisymmetric shell elements. However, since it is difficult to determine them in an analytical manner, the analysis may generally be carried out using the axisymmetric thin-wall shell finite element method, which can be expanded in a Fourier series.